

1 **A computational approach to evaluate strength in eggs: lay and crash implications**  
2 **for organic eggs production**

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20

21 **Abstract**

22

23 With the aim of characterizing the different stress patterns in several egg types and  
24 evaluate the resistivity of the eggshell while impacting in free fall, experimental tests  
25 and computational simulations have been performed on eggs of the species *Gallus*  
26 *gallus* (domestic hen), *Struthio camelus* (ostrich), and *Testudo* sp. (tortoise). The  
27 different types of failure were determined for each taxa and stress distribution maps  
28 were recorded and correlated between experimental results and computational  
29 simulations using Finite Element Analysis (FEA). For domestic hens, the numerical  
30 results obtained in both tests have highly correlation with the results obtained in  
31 previous works; for ostrich (*Struthio camelus*) and tortoise (*Testudo* sp.) eggshells, the  
32 new data represent a very good tool to understand in further works the failure  
33 mechanisms of the eggshells. More interestingly, the present study provides the first  
34 empirical and mathematic results that allow establishing confident safety interval related  
35 to the laying process in the poultry industry.

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38 Key-words: eggshell, strength, reproduction, failure mechanism

## 39 **1. Introduction**

40

41 The current growing demand in modern society for the called “organic foods” is  
42 shaping the way alimentary industry face the request of the markets. According to the  
43 most recent data provided by several international organizations (i.e. FAO, OECD, and  
44 FAPRI) a significant increase of the global demand for animal protein can be  
45 extrapolated in the years to come, being eggs the second alimentary source on the line  
46 just behind the poultry meat (Mulder, 2017). In this sense, organic eggs stand among the  
47 most requested organic products, leading the global proliferation of organic egg farms,  
48 places where animals can lay freely on the ground. Given the economical impact of this  
49 sector (Sumner et al., 2011), any advance in understanding the egg and eggshell  
50 mechanics helping to minimize the risks of egg failure during laying may represents a  
51 significant step-forward for the organic egg production.

52 Egg is a high complex biological structure composed of several concentric organic  
53 and bio-mineralized layers. In a simplistic way, it can be defined as a container that has  
54 an air chamber and viscous liquids (the yolk and the albumen) in its core that are  
55 surrounded by two membranes and a external covering, the eggshell. Eggshell strength  
56 is regulated by a certain number of variables such as genetics, the age of the laying  
57 female, feed composition, diseases, climatic conditions or management by the farmer  
58 (Solomon, 1990).

59 The characterization of the mechanical impact that suffers an egg on the substrate  
60 and its strength have certainly received little attention in literature (Nedomová et al.,  
61 2009a; Trnka et al., 2012; Juang et al., 2017). In experimental way, eggshell strength  
62 has been evaluated from a non-destructive and quasi-static compression test (Nedomová  
63 et al., 2009b; Voisey and Hunt, 1974; Nedomová et al., 2013a, b), using a transducer  
64 (Castilla et al., 2009) or introducing a dynamical test method using modal analysis  
65 (Coucke et al., 1994) in hen and ostrich eggs. The mechanics and mechanisms of failure  
66 of hen eggs have been examined experimentally under contact loading conditions  
67 (MacLeod et al., 2005). In computational mechanics, the dynamic mechanical behaviour  
68 of the egg has been evaluated with Finite Element Analysis (FEA) from simple  
69 structural models (Coucke et al., 1998; Upadhyaya et al., 1986) to highly non-linear  
70 transient dynamic analysis, including the study of the rupture by impact loading  
71 (Nedomová et al., 2009b). FEA has also been used to evaluate the effects of variations  
72 in certain geometrical and material parameters of the egg on the structural and acoustic

73 frequency response functions (Perianu et al., 2010) or even to study the microstructure-  
74 controlled stability of selected eggshells of Indian dinosaurs (Srivastava et al., 2005).

75 According to previous works performed in hen eggs, the eggshell breaks at a certain  
76 stress point (Nedomová et al., 2009a), namely fracture stress. Fracture stress is  
77 independent of egg properties (i.e. geometry, size, and eggshell thickness), and on the  
78 loading force orientation and it is affected only by the eggshell material properties. In a  
79 scenario where impact is produced below the fracture stress point the physic integrity of  
80 the egg is poorly compromised, with minor or without cracking, while impacts  
81 occurring up to the fracture stress point produce different types of failure

82 Herein, experimental tests and computational simulations were performed in order  
83 to evaluate the resistivity of the eggshell while impacting in free fall. Different impact  
84 tests in tortoises, domestic hen, and ostrich eggs were performed to determine the  
85 different types of failure among different groups of animals. These experimental results  
86 were confronted and correlated with those obtained from computational simulations  
87 using Finite Element Analysis (FEA), providing stress distribution maps. Thus, the  
88 main goal of the present study is to provide new key information to characterize the  
89 different stress pattern in eggs of different groups.

90

## 91 **2. Material and Methods**

92

### 93 *2.1. Sample*

94

95 The experimental program was conducted on twelve tortoise (*Testudo* sp.) eggs,  
96 seventeen hen (*Gallus gallus*) eggs, and six ostrich (*Struthio camelus*) eggs. They have  
97 been selected for representing different eggshell-types structures (Mikhailov, 1997).

98 Free-range hen eggs were obtained from a local product gross-store, while ostrich  
99 eggs were acquired from an ostrich farm. Non-fertilized tortoise eggs were provided by  
100 the Centre de Recuperació d'Amfibis i Reptils de Catalunya (CRARC, Catalonia,  
101 Spain), after careful examination of a large sample of specimens collected during the  
102 brooding season of *Testudo* sp., while hen and ostrich eggs were obtained from  
103 commercial sources.

104

### 105 *2.2. Experimental tests*

106

107 The impact test procedure consisted in releasing the egg from a height which  
108 determined the incident kinetic energy and hence the incident velocity. Tests were  
109 performed by crashing the specimens on a rigid support ( $E=10000$  MPa). In order to  
110 evaluate the impact damage resistance, specimens were dropped from different height  
111 levels ranging from 50 to 1500 mm (Fig. 1). Prior to each test, specimens were  
112 geometrically characterized (length, width, mass). Falling egg height and impact  
113 velocity were recorded (Tables 1-3). After the impact, the thickness of eggshells were  
114 measured, and values were used to create the computational model (see below). With  
115 the aim of visualize the impact event details, a high-speed camera MotionBLITZ Cube4  
116 was used. The frequency of the camera was 1878 Hz representing a time resolution of  
117 529  $\mu$ s per frame. The initiation and propagation of the failure modes were  
118 characterized thanks to the recorded results. The crash of the eggs were divided into  
119 three different types of failure (Fig. 2):

120 Type A: Total crash and spill of the yolk.

121 Type B: Crack and spill of the yolk. The egg bounces.

122 Type C: Partial crack and no spill of the yolk. The egg bounces.

123

### 124 2.3. Computational Simulations

125

126 A transitory Finite Element Analysis (FEA) was developed to simulate the  
127 dynamical impact of the eggshell on the substrate (Fig. 3) using the Finite Element  
128 Package ANSYS 14.5 in a Dell Precision™ Workstation T7600 with 32 GB (4X8GB)  
129 and 1600 MHz. The maximum Von Mises stress was recorded in the eggshell  
130 depending on the different impact velocities for the different substrate materials.

131

#### 132 2.3.1 Egg geometry

133

134 The geometry of each egg type was 3D digitally recorded and following is described  
135 in detail the approach used. Several authors have provided different equations in order  
136 to express the mathematical function describing the vast variability of the contour of the  
137 hen egg shapes (i.e. Narushin, 1997, 2001; Baker, 2002; Denys et al., 2003; Stoddard et  
138 al., 2017; Severa et al., 2013; Troscianko, 2014; Attard et al., 2018; Duursma et al.,  
139 2018). Nevertheless, most of them fall back in assuming that an ellipsoid profile or  
140 modified ellipse equations is the best method for describing this particular avian egg

141 shape. Herein the geometry of the hen eggshell was obtained from digital photographs  
142 and translated to a CAD model using Rhinoceros® (McNeel & associates, version 5.0,  
143 Seattle, WA).

144 As a result, the average values from the measured hen (*Gallus gallus*) egg  
145 specimens (Table 1) were: 55.96 mm in length, 43.86 mm in maximum width, and an  
146 average eggshell thickness of 0.44 mm. Tortoise egg can be described as a revolution  
147 ellipsoid. In this case, the tortoise (*Testudo* sp.) eggshell was created using the CAD  
148 interface of ANSYS FEA package. The average obtained from the measured egg  
149 specimens (Table 2) was used: an average length of 34.4 mm, an average width of 27.97  
150 mm, and an average thickness of 0.4 mm. Finally, the shape of the ostrich (*Struthio*  
151 *camelus*) egg can be described as a revolution ellipsoid. As in the previous case, the  
152 ostrich eggshell was created using the CAD interface of ANSYS FEA package, using  
153 the average values obtained from the measurements of the analysed specimens (Table 3)  
154 it was established an average length of 158.4 mm, and an average width of 126.0 mm.  
155 Assuming that the flexible testacea membrane that surrounds the inner part of the  
156 eggshell could be omitted for this simulation purpose, the thickness of the eggshell  
157 considered was an average value of 1.75 mm.

158

#### 159 *2.4. Solid grounds selection and modelling*

160

161 Different impact substrates were considered in the computational model. Each  
162 substrate was selected for having different elastic values associated to different soils-  
163 types (from hard to soft), and meshed with hexahedral solid elements in the FEA model.  
164 The values were chosen taking into account that saturated clay soils have a Poisson  
165 coefficient around 0.45 (Simeonovova and Buchar, 2002; Nedomova et al., 2009b).  
166 However, the Elastic Modulus is around  $E=5$  to 25 MPa for soft clays, while that of  
167 hard clays ranges from 50 to 100 MPa (Bowles, 2006), and reaching up to 10000 MPa  
168 in rigid floors. Because of that, we established four cases of study where the Case1  
169 represents an impact on a hard soil of 10000 MPa, Case 2 of 1000 MPa, Case 3 of 100  
170 MPa, and Case 4 is characterised by a soft soil of 10 MPa.

171 All the eggs were meshed with shell elements of constant thickness considering as a  
172 homogeneous isotropic linear elastic material with  $E = 0.0035$  GPa and  $\nu = 0.45$   
173 (Simeonovova and Buchar, 2002; Nedomova et al., 2009b). The yolk, the albumen and  
174 the air inside the egg chamber were considered as an hydrostatic pressure of a liquid of

175 1.025 g/cm<sup>3</sup> (Rahn and Paganelli, 1989). Different tests were considered modifying the  
176 impact velocity. The value of the velocity is associated to a height according to the  
177 energetic equilibrium between potential and kinetic energy (Fig. 1).

178 In order to model the interaction between the eggshell and the soil in the very  
179 moment of the impact, a frictionless contact was defined between the bodies. A  
180 frictionless contact assumes that a gap was allowed in the normal direction and sliding  
181 was freely allowed in the tangential direction. In the gap direction, an augmented  
182 Lagrange contact formulation with large Normal Stiffness symmetric behaviour were  
183 assumed in which only the contact surfaces were constrained from penetrating the target  
184 surfaces (Wriggers, 2002). This formulation implies a non-linear solution. A  
185 convergence iterative procedure based on a Newton-Rhapson iterative algorithm was  
186 used.

187

### 188 **3. Results**

189

190 The experimental impact tests, with a rigid support ( $E=10000$  MPa), showed that in  
191 the tortoise (*Testudo* sp.) eggs (Table 2) the boundary between the total crash of the egg  
192 (type A) and its crack and spill of the yolk (type B) appears when the fall height is  
193 around the 1000-750 mm with a velocity of 4000 mm/s, while the boundary between  
194 failure type B and partial cracking of type C occurs around 125-110 mm of fall height,  
195 producing a velocity around 1500 mm/s (Table 2).

196 In the case of the domestic hen (*Gallus gallus*), the boundary between the failure  
197 type A and B appeared between a fall height of 300-400 mm and a velocity of 2500  
198 mm/s (Table 1), while between type B and C occurred in a fall height of 125-110 mm  
199 and a velocity of 1500 mm/s (Table 1). Finally, in the ostrich (*Struthio camelus*) eggs  
200 the fall heights reduced: the boundary between type A and B was around 250-300 mm  
201 and a velocity of 2300 mm/s, while the type B-C boundary occurred in a fall height  
202 around 50-75 mm and a velocity of 1,200 mm/s (Table 3). Figure 2 shows frames of the  
203 recorded videos of the experimental tests with the different casuistry for defined types  
204 A, B and C (see also Supplementary Information).

205 Regarding the results obtained with computational simulations, results reveal the  
206 tendency to level off certain value of threshold for high impact velocities, and abrupt  
207 changes for very low values of velocity (Supplementary Tables S1-S3). Figure 3 shows  
208 the resulting maximum von Mises stress values during the impact of eggs against rigid

209 soil ( $E=10000$  MPa), whereas Figure 4 shows maximum Von Mises stress versus height  
210 and impact velocity defined in the FEA model where the egg is dropped off depending  
211 on the hardness of soil for hen (Fig. 4 A and D), tortoise (Fig. 4 B and E), and ostrich  
212 (Fig. 4 C and F). Von Mises stress corresponds to the moment of the impact between  
213 the eggshell and the soil, and the maximum Von Mises stress reached in the  
214 computational model. Height and velocity are related according to the law of  
215 conservation of energy, which balances the kinematic energy ( $E=1/2mv^2$ ; being  $m$  the  
216 mass of a body and  $v$  its velocity) and the potential energy ( $E=mgh$ ; where  $m$  is the  
217 mass,  $g$  is the acceleration due to gravity, and  $h$  is the height). Regarding the ostrich  
218 egg, the non-linear solution of the impact for a soil  $E=10$  MPa did not reached the  
219 mathematical convergence (see Fig. 4 C and F).

220 There is also a close dependence between eggshell rupture force and impact velocity  
221 that can be described as a logarithmic function, as occurs in many engineering materials  
222 and according to previous observations (Trnka et al., 2012).

223 The type of failure, based in the casuistry defined via experimental tests, was  
224 correlated between the results obtained in both computational and experimental models.  
225 Given that a detailed analysis of returned data requires complex considerations, the  
226 following results focus in describing the aforementioned correlations under extreme  
227 experimental conditions, which are those when the test is running simulating a hard soil  
228 with an elastic modulus of  $E=10000$  MPa. For hen eggs, the failure type C was only  
229 obtained below an impact velocity of 1000 mm/s (Table 1), which can be correlated  
230 with a value below the 554 MPa in the computational simulation (Fig. 4D). These  
231 results agree with previous impact analyses obtained also using hen eggs (Nedomová et  
232 al., 2009). In tests with tortoise eggs, the type of failure C was observed below an  
233 impact velocity of 1500 mm/s (Table 2), correlated with a value of Von Mises stress  
234 below the 520 MPa (Fig. 4E). Finally, in the case of the ostrich eggs, type C was  
235 recorded below an impact velocity of 1200 mm/s (Table 3), related with a value below  
236 the 420 MPa in the computational simulation (Fig. 4F), and representing the lowest  
237 value in comparison with the hen and the tortoise cases.

238 Regarding the computational analysis, Figure 3 reveals different distribution of Von  
239 Mises stress depending on the type of failure. These observed distributions of stress can  
240 be correlated with the different types of failure observed in the experimental test when  
241 the fracture of the eggshell is with a partial crack, a major crack, or a total crash of it.



242 According to that, in tortoise eggshell, in the failure type A, the maximum values of  
243 stress were located in a wide point and important values of stress were located in the  
244 bottom half of the eggshell generating the total crash of the eggshell. For the failure  
245 type B the peak stress was concentrated but appearing important stress values in the  
246 surrounds of the impact point. This different distribution generated a crack in the  
247 eggshell without the total crash of the shell. Finally, the failure type C revealed very  
248 low concentrated peak stress, only placed just in the point of impact. This value was  
249 lower than the threshold of 520 MPa and for instance, the eggshell was not breaking due  
250 to the impact. In the hen eggshell, for type A, the maximum values of stress were  
251 located in a wider point and important values of stress were located in the bottom half  
252 of the eggshell generating the total crash of the eggshell. In the failure type B the peak  
253 stress was concentrated but appearing important stress values in the surrounds of the  
254 impact point (as in the same case in tortoises). This different distribution generated a  
255 crack in the eggshell without the total crash of the shell. Finally, in the failure type C,  
256 very low concentrated peak stress was placed just in the point of impact. This value was  
257 lower than the threshold of 550 MPa, and therefore the eggshell was not broken due the  
258 impact.

259 Finally, for the ostrich eggshell in the type A, the maximum values of stress were  
260 placed in a wide point and important values of stress were located in the bottom half of  
261 the egg generating the total crash, while in the failure type B the peak stress was  
262 concentrated but appearing important stress values in the surrounds of the impact point  
263 (as in the same type in tortoises and hens). This different distribution generated a crack  
264 in the eggshell without the total crash of the shell. Finally, the type C showed a very  
265 low concentrated peak stress sited just in the point of impact. This value was lower than  
266 the threshold of 420 MPa, and for instance, the eggshell did not break due to the impact.  
267

#### 268 **4. Discussion**

269  
270 Reproduction is one of the fundamental biological processes of any organism, from  
271 which depends the survivorship of a species. Of its success depends the proper  
272 conditions for the development of the offspring, but also it is the basis of the poultry  
273 industry. Several studies have emphasised on the increasing role that organic food play  
274 in global market. Among them organic eggs represent an important economical sector,  
275 which is valued on up to US\$ 2700 Mn by the end of 2025 only in Europe (data from

276 Konzept Analytics, 2018; QYResearch Group, 2018). Forecasts indicate that this trend  
277 will increase in the future.

278 Because of that, any advance in minimizing the loss in the production of free-cage  
279 eggs may represent a major economical impact. The egg quality and incubation/nesting  
280 environment conditions are crucial factors for success laying (Grant, 1982). In this  
281 regard, the results of the present study set the bases for establishing confident intervals  
282 of oviposition height, from which eggs can suffer or avoid critical damages.

283 The final aim of the egg is the functionality of the structure in land environments  
284 and to provide the proper inner conditions and its security (e.g. mechanical impacts or  
285 microbial invasion) during the embryo development. Theoretically, the optimal  
286 morphology of a maximum volume with minimum eggshell perimeter is a sphere.  
287 However, the great diversity of egg morphologies shows that other variables are playing  
288 a key role in the final egg morphology and function. Several functional geometries are  
289 known from living and extinct reptiles including circular to elongated eggs morphology  
290 with a huge size variability. It should be remarked that the final egg is the meeting point  
291 between the producer of the egg (e.g. pelvis morphology, size of the producer, cost for  
292 calcite/aragonite production, potential to lay the egg in the substrate, to produce a nest  
293 etc) and the requirements of the embryo to properly develop (quantity of required  
294 calcite, inner egg microstructure, eggshell thickness, air transport between the  
295 membrane and the eggshell, etc). Of particular interest, eggshell thickness probably  
296 plays an important role, as revealed by Ar and colleagues (1979), who demonstrated  
297 that eggs have a positive allometry regarding the eggshell thickness revealing that more  
298 resources are required to build up the eggshell thickness as they grow. In particular, the  
299 eggshells have a power law of 1.5 related to support the gravitational loads of their  
300 mothers, but also to support other loads or impacts, as show the results herein presented.

301 Nesting-site selection is a common behaviour among turtles (Hays et al., 1995),  
302 lizards (Trauth, 1983; Warner and Shine, 2008), crocodiles (Combrink et al., 2017), and  
303 birds (Clark and Shutler, 1999). In all cases, female choses the most suitable soil to lay  
304 its eggs, and often exploiting the surrounding resources in order to increase the chance  
305 of the reproduction success. Depending on the nest type, clutch requirements or  
306 incubation behaviour, the female shows preferences for softer or harder substrates.  
307 Given that each organic farm can be build up on different substrates, here we simulated  
308 this variability by using different substrate with distinct elastic modulus in order to  
309 cover a wide spectrum of possibilities.

310 Some Asian and South American countries are known for being great consumers of  
311 turtle eggs. Although there are some attempts in farming turtles, the current demand of  
312 turtle eggs is mainly satisfied by poaching. It is out of our scope to discuss the ethic  
313 basis or the risk for human health for consuming turtles' meat or eggs, but the debate is  
314 currently intense (D'Cruze, 2012). From a biological perspective, all turtles excavates  
315 on the substrate to create a hole where lays the eggs, known as egg chamber. After that,  
316 eggs are buried and covered with sand for incubation. Taking as example the herein  
317 studied terrestrial tortoise of the genus *Testudo*, the female excavates the nest using the  
318 hindlimbs, which in turn determines the maximum depth of the hole. The hindlimbs in  
319 this genus range around 50-60 mm (Djurakic et al., 2011) that in the light of our results  
320 reveals that the eggs could support an impact two times higher before to be crashed (egg  
321 cracking produced up to 110-120 mm). Interestingly, the tortoise eggs present an  
322 important variability of sizes (Deeming and Ferguson, 1991; Deeming, 2004), with an  
323 eggshell thickness comparable to the hens, although its mean size is clearly smaller (one  
324 third part). It should be noted also that the turtle eggs must support the weight of the  
325 substrate during the incubation period, although in this case the mechanic fatigue is  
326 playing a role out of the scope of the present article. In fact, the resistivity of turtle egg  
327 is remarkable being the one that supports the highest impact height (750-1000 mm) on  
328 hard substrate ( $E=10000$  MPa) before total failure (boundary between Type A and B) of  
329 the parameterised egg types (see Fig. 4).

330 On the contrary, free-living ostrich commonly selects sandy dry riverbeds to nest  
331 (Sauer and Sauer, 1966), thus tending to choose relatively hard substrate to lay the eggs.  
332 Female sits directly in the substrate when laying, with a null or very minor nest  
333 production (Bertram, 1992). Interestingly, these big and thick-shelled eggs are the first  
334 to be broken as revealed by the results (between 50-75 mm to be crashed),  
335 demonstrating the importance for the ostrich female to lay very close or directly placed  
336 on the floor. In an intermediate position, the hens lay the eggs in a nest in a squat  
337 position causing an impact of few centimetres. In this case, the eggs could support also  
338 an impact higher than the ostrich but lower than the tortoises. The total rupture of the  
339 hen egg (boundary between Type A and B failures) takes place between 30 and 40 cm  
340 (Table 1 and Supplementary Information), which values are similar to the average  
341 height of domestic hens in erected position. It is also worthy noting that the frontier  
342 between safety (Type C) and failure (Type A) scenarios is established between 500 and  
343 550 MPa, whatever the type of egg (see Fig. 4). These results led to speculate that these

344 values might represent a universal boundary for the safety integrity of all amniotes eggs,  
345 but more analyses are needed to confirm this observation.

346 In sum, the parental decision of the optimal place for the laying is the result of  
347 several key variables that could be divided on three different perspectives: A) from the  
348 female producer and its (biomechanical) capabilities to create the nest or clutch, B) from  
349 the egg to support the loads of the parent weight (or support the weight of the substrate),  
350 and C) its capability to resist the impact on the substrate during the laying, considering  
351 that different substrates (from softer to harder) could provide different conditions for the  
352 nest (or clutch) and the egg incubation.

353

## 354 **5. Conclusion**

355

356 In organic egg production minimize the egg losses is a key factor that imply to  
357 maximize the safety factors and reduce the number of failure eggs. In order to provide a  
358 model helping to achieve those goals we evaluated the eggshell strength in a free-fall  
359 scenario. Both experimental and computational tests were proved to be equally  
360 effectives and useful, but computational simulation raises as a more preferable model  
361 instead experimental tests given that it represents a non-destructive method.

362 From a more applicable perspective, the present study provides the first empirical  
363 and mathematic results that allow establishing confident safety interval related to the  
364 laying process. According to our models, tortoises and hens cannot lay their eggs up to  
365 11-12 cm from the surface without compromising the structural integrity of the  
366 eggshells. These values decrease dramatically for the large eggs of ostrich, which can  
367 suffer severe damaging if the egg is laid up to 5-7 cm from the ground surface. These  
368 results can have, indeed, a considerable impact in the organic egg industry, helping the  
369 farmers to minimize the risk of losing eggs and therefore gaining more profits.

370 Furthermore, our models also set the bases for the development of a framework that  
371 allow evaluating other scenarios without (i.e. wildlife conservation) compromising any  
372 sample or even for assessing the biomechanical response of elements from the fossil  
373 record (i.e. dinosaur eggs).

374

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376

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497

Fall Height [mm]	Impact velocity [mm/s]	Maximum Egg length [mm]	Maximum Egg Width [mm]	Mass [g]	Eggshell Thickness [mm]	Type of failure
1500	5424.94	54.37	44	58.3	0.47	A
1400	5240.99	57.75	43.36	61.6	0.49	A
1300	5050.35	56.14	44.32	61.2	0.44	A
1200	4852.22	55.85	44.69	61.3	0.41	A
1100	4645.64	56.59	44.3	61	0.41	A
1000	4429.45	55.72	43.16	57.6	0.44	A
900	4202.14	54.88	44.27	59.7	0.43	A
800	3961.82	52.56	42.98	56.5	0.47	A
700	3705.94	55.29	44.49	59.1	0.41	A
600	3431.03	55.48	43.76	59.3	0.41	A
500	3132.09	56.79	43.78	61	0.45	A
400	2801.43	55.26	44.71	61.5	0.42	A
300	2426.11	57.86	43.5	61.1	0.41	B
200	1980.91	55.29	44.54	61.6	0.44	B
150	1715.52	55.74	44.08	59.8	0.46	B
100	1400.71	56.86	42.87	57.9	0.47	B
50	990.45	59	42.94	59.9	0.4	C

498 **Table 1.** Results obtained in the impact of the hen eggshell

499

Fall Height [mm]	Impact velocity [mm/s]	Maximum Egg length [mm]	Maximum Egg Width [mm]	Mass [g]	Eggshell Thickness [mm]	Type of failure
1000	4429.45	40.5	29	11.8	0.41	A
1000	4429.45	34.5	29.9	18.4	0.44	A
750	3836.01	39	31.3	20.3	0.4	B
500	3132.09	33	29.7	17.6	0.43	B
250	2214.72	35.9	25.6	13.2	0.4	B
150	1715.52	32.7	29.7	15.5	0.4	B
125	1566.05	31.6	24.3	10.5	0.4	B
125	1566.05	31.8	23.3	10.3	0.36	B
110	1469.08	34.2	23.9	10.6	0.34	C
100	1400.71	31.8	29.3	16.5	0.41	C
100	1400.71	36.4	30.3	18.5	0.4	C
50	990.45	32.2	29.4	17.3	0.41	B

500 **Table 2.** Results obtained in the impact of the tortoise eggshell

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502

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507

Fall Height [mm]	Impact velocity [mm/s]	Maximum Egg length [mm]	Maximum Egg Width [mm]	Mass [g]	Eggshell + membrane Thickness [mm]	Eggshell Thickness [mm]	Type of failure
1000	4429.45	152.2	129.9	1465.2	2.09	1.84	A
900	4202.14	154.1	125.2	1404.6	1.85	-	A
500	3132.09	159.0	118.9	1330.4	1.88	-	A
350	2620.50	165.7	126.0	1391.5	1.63	1.56	A
300	2426.11	156.8	131.6	1552.5	1.98	1.82	A
250	2214.72	162.8	124.3	1502.7	1.9	1.78	B
150	1715.52	159.0	118.9	1330.4	1.88	-	B
100	1400.71	152.2	129.9	1465.2	2.09	1.84	B
75	1213.05	165.7	126.0	1391.5	1.63	1.56	B
50	990.45	156.8	131.6	1552.5	1.98	1.82	C
50	990.45	154.1	125.2	1404.6	1.85	-	C
40	885.89	162.8	124.3	1502.7	1.9	1.78	C

508 **Table 3.** Results obtained in the impact of the ostrich eggshell.

509 **FIGURE CAPTIONS**

510

511 **Figure 1.** Scheme of the Transient dynamic Analysis performed for the tortoise, hen,  
512 and ostrich eggs. Abbreviations: d-short axis; D-long axis; Hn-high of falling; s-shell;  
513 su-shell units; t-thickness of the eggshell; tm- testaceous membrane; v-initial velocity.

514

515 **Figure 2.** Example of types A, B, and C of the casuistry of the crash of the egg in the  
516 substrate for the hen (*Gallus gallus*) egg.

517

518 **Figure 3.** Von Mises stress distribution for computational cases defined via impact  
519 velocities according to the type of fracture A, B, and C when the maximum value of  
520 stress was reached.

521

522 **Figure 4.** Maximum Equivalent Von Mises stress versus height and defined in the FEA  
523 model where the egg is dropped (A, B, C) and impact velocity depending on the type of  
524 soil (D, E, F). Tests with performed by hen (*Gallus gallus*; A, D), tortoise (*Testudo* sp.;  
525 B, E), and ostrich (*Struthio camelus*; C, F) eggs. Failure types are represented as a  
526 continuous degraded colour transition, being the type A associated to “red”, type B to  
527 “yellow”, and type C to “green”.