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

Albert G. Sellés[a,b,*], Jordi Marcè-Nogué[a,c], Bernat Vila[a,b,d], Marco A. Pérez[e], Lluís Gil[f], Àngel Galobart[a,b], Josep Fortuny[a]

a. Institut Català de Paleontologia Miquel Crusafont – Escola Industrial 25, E-08201 Sabadell, Barcelona, Spain.

b. Museu de la Conca Dellà, c/Museu 4, E-25650 Isona, Lleida, Spain.

c. Center of Natural History (CeNak), Universität Hamburg, Martin-Luther-King-Platz 3, Hamburg 20146, Germany.

d. Departament de Geologia, Facultat de Ciències, Universitat Autònoma de Barcelona, Carrer de l'Eix central, 08193, Cerdanyola del Vallès, Barcelona, Catalonia, Spain.

e. IQS School of Engineering, Universitat Ramon Llull, Via Augusta 390, 08017 Barcelona, Spain.

f. Department of Strength of Materials and Structures in Engineering. Universitat Politècnica de Catalunya UPC-ESEIAAT, c/ Colom 11, 08222, Terrassa, Spain.

*Corresponding author: albert.garcia@icp.cat

Abstract

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

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

1. Introduction

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

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

The characterization of the mechanical impact that suffers an egg on the substrate and its strength have certainly received little attention in literature (Nedomová et al., 2009a; Trnka et al., 2012; Juang et al., 2017). In experimental way, eggshell strength has been evaluated from a non-destructive and quasi-static compression test (Nedomová et al., 2009b; Voisey and Hunt, 1974; Nedomová et al., 2013a, b), using a transducer (Castilla et al., 2009) or introducing a dynamical test method using modal analysis (Coucke et al., 1994) in hen and ostrich eggs. The mechanics and mechanisms of failure of hen eggs have been examined experimentally under contact loading conditions (MacLeod et al., 2005). In computational mechanics, the dynamic mechanical behaviour of the egg has been evaluated with Finite Element Analysis (FEA) from simple structural models (Coucke et al., 1998; Upadhyaya et al., 1986) to highly non-linear transient dynamic analysis, including the study of the rupture by impact loading (Nedomová et al., 2009b). FEA has also been used to evaluate the effects of variations in certain geometrical and material parameters of the egg on the structural and acoustic frequency response functions (Perianu et al., 2010) or even to study the microstructure-controlled stability of selected eggshells of Indian dinosaurs (Srivastava et al., 2005).

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

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

2. Material and Methods

2.1. Sample

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

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

2.2. Experimental tests

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

Type A: Total crash and spill of the yolk.

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

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

2.3. Computational Simulations

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

2.3.1 Egg geometry

The geometry of each egg type was 3D digitally recorded and following is described in detail the approach used. Several authors have provided different equations in order to express the mathematical function describing the vast variability of the contour of the hen egg shapes (i.e. Narushin, 1997, 2001; Baker, 2002; Denys et al., 2003; Stoddard et al., 2017; Severa et al., 2013; Troscianko, 2014; Attard et al., 2018; Duursma et al., 2018). Nevertheless, most of them fall back in assuming that an ellipsoid profile or modified ellipse equations is the best method for describing this particular avian egg shape. Herein the geometry of the hen eggshell was obtained from digital photographies and translated to a CAD model using Rhinoceros® (McNeel & associates, version 5.0, Seattle, WA).

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

2.4. Solid grounds selection and modelling

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

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

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

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

3. Results

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

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

Regarding the results obtained with computational simulations, results reveal the tendency to level off certain value of threshold for high impact velocities, and abrupt changes for very low values of velocity (Supplementary Tables S1-S3). Figure 3 shows the resulting maximum von Mises stress values during the impact of eggs against rigid soil (E=10000 MPa), whereas Figure 4 shows maximum Von Mises stress versus height and impact velocity defined in the FEA model where the egg is dropped off depending on the hardness of soil for hen (Fig. 4 A and D), tortoise (Fig. 4 B and E), and ostrich (Fig. 4 C and F). Von Mises stress corresponds to the moment of the impact between the eggshell and the soil, and the maximum Von Mises stress reached in the computational model. Height and velocity are related according to the law of conservation of energy, which balances the kinematic energy ($E=1/2mv^2$; being m the mass of a body and v its velocity) and the potential energy ($E=mgh$; where m is the mass, g is the acceleration due to gravity, and h is the height). Regarding the ostrich egg, the non-linear solution of the impact for a soil E=10 MPa did not reached the mathematical convergence (see Fig. 4 C and F).

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

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

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

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

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

4. Discussion

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

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

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

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

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

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

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

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

5. Conclusion

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

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

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

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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

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

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

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

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

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

FIGURE CAPTIONS

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

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

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

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