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Challenging common notions on how eggs break and the role of strength versus toughness

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One experiment commonly used to teach young students about the response of structures to dynamic loading is the "egg drop challenge", in which students design a device to protect an egg from cracking after a fall from a specified height. Relevant to this activity is the choice of orientation of the egg to decrease the probability of fracture. In this study, we contest the commonly held belief that an egg is strongest when dropped vertically on its end. Through hundreds of experiments and a set of static and dynamic simulations, we demonstrate a statistically significant decrease in the likelihood that an egg breaks when oriented horizontally as opposed to vertically, and offer a concrete and intuitive explanation as to why this is the case. These results and the associated analysis demonstrate the importance of specificity of language and the dangers of appealing to "common sense" in the physics classroom while having wide-ranging implications due to the ubiquity of shell structures in nature and in the man-made world.

In Jonathan Swift's Gulliver's Travels[1], the empires of Lilliput and Blefuscu engage in quarrels over the optimal orientation to crack an egg. The ideas, hardened by centuries of commitment and generations of repetition, gave rise to an independent conventional wisdom in either society. In our own society, there exists a similar "common sense" idea about the best orientation for dropping an egg.

Such ideas about the strength of shells have implications beyond the chicken egg. In nature, shell structures are ubiquitous, serving as a protective layers for soft-bodied organisms; turtle shells and sea shells[2], to human skulls, and even the outer membranes of viruses and bacteria[3]. Insights on the mechanical failure of these structures may thus enable progress in a myriad of applications ranging from the design of protective equipment to drug delivery[4].

For this reason, in science classrooms worldwide, the *egg drop challenge* is used by educators to introduce young students to the basic ideas of structural mechanics and impact and to develop their physics intuition[5]. In this challenge, teams are given materials like cotton balls, plastic bags, and straws to design a device that prevents an egg from cracking when dropped from a specified height. A review of instructional materials from various STEM institutions[6,7] and online tutorials[8–11] (see Supplementary Table S1) reveals that while factors such as the materials provided, the drop height, and the design solutions vary widely, one aspect remains largely unquestioned: the idea that an egg is "stronger" when oriented vertically as opposed to horizontally (as illustrated in Fig. 1), and therefore less likely to break. This idea appears to be based on an appeal to common wisdom, often inspired by the enduring design of structural arches and domes from ancient civilizations[12,13] to the present day[14–18]. Similar to the shape of a hanging chain—an observation famously captured by Robert Hooke[19] in 1675 with the aphorism, "As hangs the chain, so stands the arch"—under static loading, a steep arch effectively transmits vertical loads along its curve (Fig. 1a), eliminating perpendicular forces and taking advantage of the "strong" direction of the structure. It may thus seem obvious that this notion would apply also to the structure of an egg, *but is it true?*

In this work, by cracking over 200 eggs in total, and employing high-precision instrumentation to record their response in both static and dynamic conditions, along with predictive numerical simulations, we answer this question. Through our static tests, we find that the peak force required to break an egg is independent of orientation, but due to the decreased stiffness in the horizontal orientation, an egg can absorb more kinetic energy before failure. These results are verified through a series of

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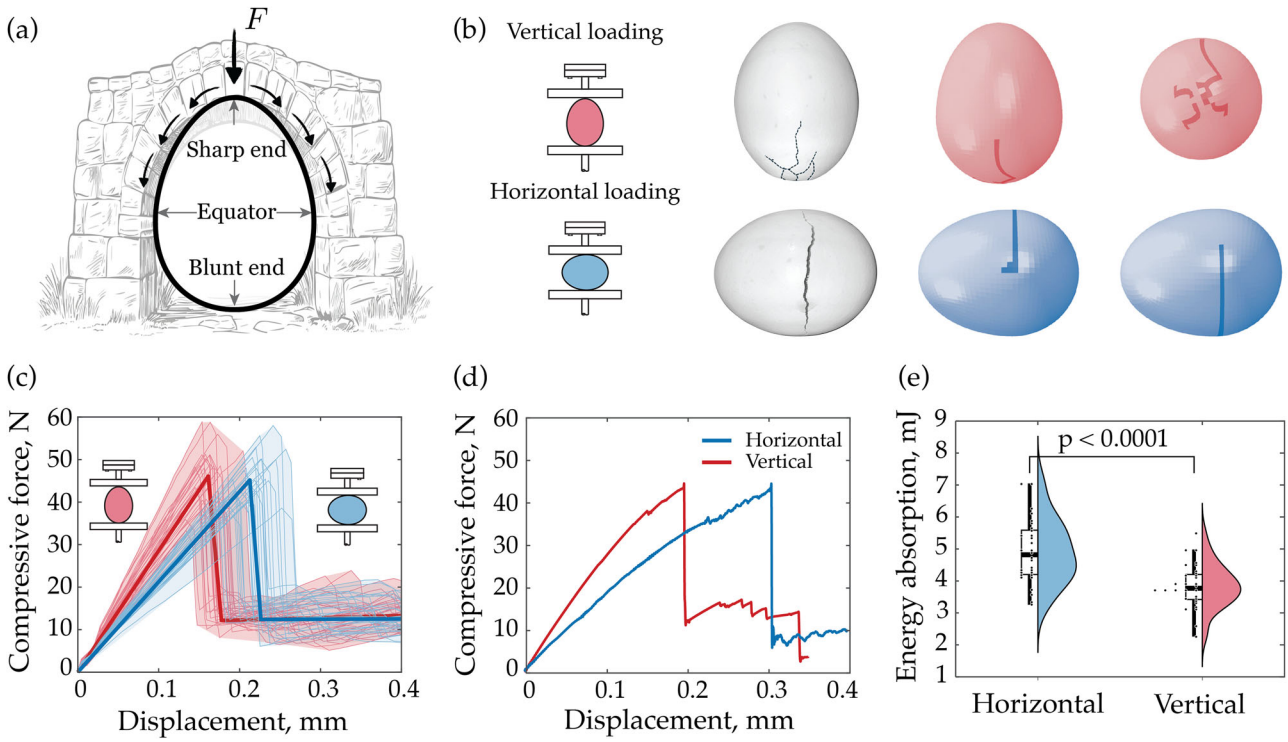


Fig. 1 | Static compression. a The eggs load bearing capabilities are often described in analogy to those of structural arches, which effectively redistribute loads[29]. In this work, we investigate just how valid this analogy is. **b** Eggs are statically loaded in two orientations: vertically (red, top) and horizontally (blue, bottom). The experimental crack patterns are shown in the second column. For improved visualization, the crack lines in the vertical orientation are enhanced. The right two columns display similar crack patterns obtained from numerical simulations. **c** Experimental force-displacement curves. Thin lines represent individual tests, while thick lines show the average curves for each orientation. The continuous regions of the curves before and after cracking are averaged separately. **d** Simulated force-displacement curves. **e** Violin plot of the energy absorbed before cracking. The plot displays the median, interquartile range, and the distribution of data points. There is a statistically significant difference between the absorbed energy for different orientations ($p < 0.0001$).

drop-tests, which show a decreased likelihood of fracture in the horizontal orientation, and through a series of static and dynamic numerical simulations of a simple egg structure.

Results and discussion

Peak force is independent of orientation

The ability of an egg to withstand static loads can provide insights into its ability to resist impact. Hence, as a first step, we conducted 60 compression tests to determine whether positioning an egg horizontally or vertically (as illustrated in Fig. 1b) affects the maximum force it can withstand before cracking (experimental details are described in "Methods" section). In each test, we place an egg on the bottom platen of a universal mechanical testing machine, stabilized by a paper support. We then control the displacement of the top platen, compressing the egg, while simultaneously recording the force. As seen in Fig. 1c, the force-displacement response increases linearly until the onset of fracture where a peak force is recorded along with the corresponding displacement, at which a sudden transition to brittle fracture is observed as the force drops sharply. Surprisingly, regardless of how the eggs are placed, the peak forces are found to be similar: around 46.0 ± 6.61 N ("mean-value" ± "standard-deviation") for the vertical and 45.2 ± 5.52 N for the horizontal.

To validate these results and determine the mechanisms which explain the results in Fig. 1, we developed a three-dimensional mechanical model of an egg that accounts for the shell and a viscous liquid yolk. For simplicity, we refer to the entire contents of the egg (both the yolk and albumen) as the "yolk" from here on. We further model the shell as a linearly elastic material with a brittle fracture response. Elastic properties of the egg are obtained from the literature (see "Methods"). We note that the simplified model in this work is not intended to capture all of the ensuing physics or to reproduce the exact fracture patterns, but instead to identify the essential structural mechanisms that explain our observations.

To examine if the experimentally observed differences between vertical and horizontal orientations are captured also in our purely mechanical model, we calibrate the fracture parameters based on the averaged response from the vertical compression tests (details on the simulation and material parameters are provided in "Methods" section). The simulation for the horizontal orientation is then conducted using the same material parameters. As shown in Fig. 1(d) the simulation predicts the same qualitative trend as the experiments; the peak force is indistinguishable for the different egg orientations, and the egg is more compliant when placed horizontally.

These results challenge the common belief that eggs are stronger when loaded vertically. However, the question remains: *what determines the best orientation to drop an egg?*

Eggs are tougher when loaded on their equator

Though we find that the maximum force an egg can sustain, F, is independent of its orientation, the displacement of the egg at the onset of cracking, Δ, varies significantly (Fig. 1c, d). We find that eggs loaded horizontally exhibit ~ 30% greater displacement upon cracking (0.213 ± 0.022 mm) compared to eggs loaded vertically (0.161 ± 0.015 mm). Namely, the stiffness of the egg, defined as $k = F/\Delta$, is smaller in the horizontal direction. Since the peak force is independent of orientation, this implies that the loading orientation influences the level of energy absorption, which is equivalent to the area under the force-displacement curves up to the point of fracture, i.e., $E = F\Delta/2$, assuming linear dependence between compressive force and displacement. Accordingly, on average, eggs loaded horizontally can absorb ~ 30 % more energy before failure. Notice that the distribution of the experimentally measured energy absorption, shown in Fig. 1e, exhibits a statistically significant difference with normal statistical distribution for 30 tests in each loading direction, thus further supporting the observation that eggs loaded horizontally can absorb more energy before

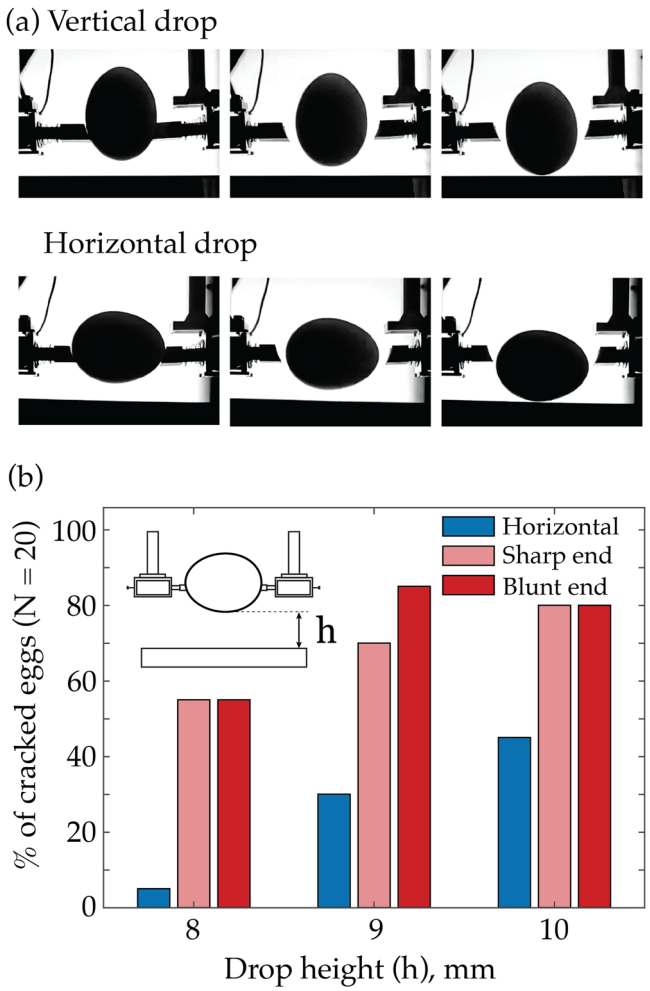


Fig. 2 | Dynamic drop experiments. a Sequence of experimental snapshots for vertical (top) and horizontal (bottom) drops. **b** Percentage of eggs cracked when dropped from three different heights in various orientations. Corresponding force-time curves are provided in Supplementary Fig. S7 and on Github[20]. Corresponding videos are found in Supplementary Movie 1.

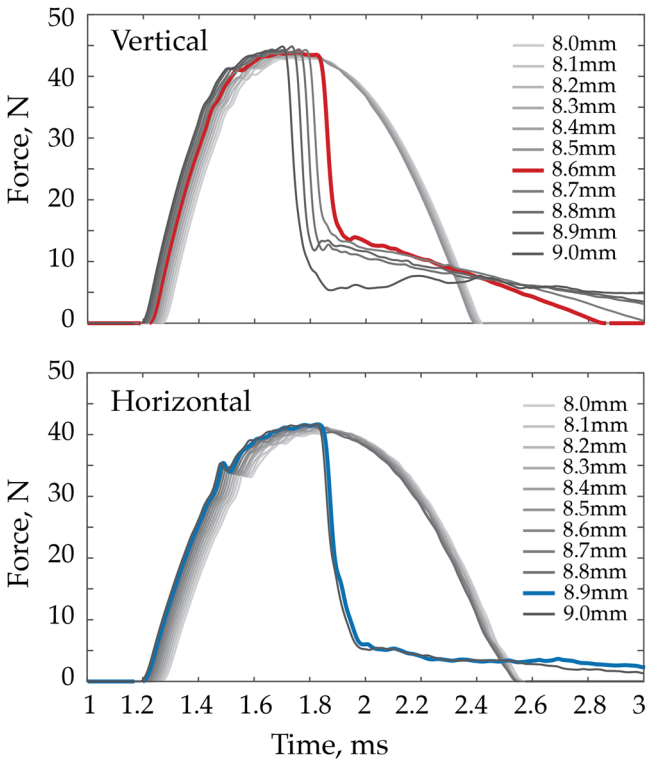


Fig. 3 | Dynamic drop simulations. Force-time curves for egg drops from various heights in vertical (top) and horizontal (bottom) orientations. Curves with sharp drops represent cracking.

cracking. Defining the toughness of an egg as the amount of energy it can absorb before failure, we can thus conclude that based on our results *eggs are tougher when loaded horizontally*.

Crack patterns are another notable difference observed between vertically and horizontally loaded eggs. As seen from both the experiments and the numerical model (Fig. 1b), horizontal compression typically results in cracks that propagate along the equator of the egg thus splitting it open, while vertical compression often leads to cracks that propagate in a spiral pattern from the contact point of the blunt end leading to shell caving.

While various material and geometric factors may contribute to the overall toughness of an egg, our simplified model that considers an isotropic shell of uniform thickness can capture the observed trends in both the force-displacement responses and the fracture patterns. This strengthens the assumption that these minimal mechanical considerations are sufficient and that other mechanisms play a secondary role in determining the egg's toughness. Furthermore, it re-enforces the overall conclusion that eggs are tougher when loaded on their equator.

Dynamic drop tests corroborate static results

It remains to be seen if the static toughness of an egg can predict its ability to withstand a drop. To this end, we conducted a series of drop tests. Using solenoid-based supports mounted on a universal mechanical testing machine (see Methods), eggs were dropped from various heights onto a fixed support that is connected to a force sensor (Fig. 2a). An indication of cracking can be seen from a drop in the measured force-time response, and confirmed via visual inspection (see Supplementary Fig. S2). Following a series of initial tests dedicated to identifying the range of relevant drop heights for different orientations, we performed 60 tests for each orientation; 20 for each of the three different heights, 8, 9, and 10 mm, as shown in Fig. 2b.

Note that, in contrast to static compression, for the dynamic tests we distinguish between impact on the blunt and sharp ends, in the vertical configuration. In both the static and dynamic loading cases, placing the egg with its blunt or sharp end down in the vertical orientation does not change the results. However, during the static tests, fracture consistently occurs on the sharp side of the egg, regardless of the vertical orientation, shedding some light on the intricacies and nuance involved in the seemingly eternal conflict between the kingdoms of Lilliput and Blefuscu.

While no statistically significant difference is observed in comparing results for eggs dropped in either of the vertical orientations, a clear difference is seen when comparing the vertical and horizontal configurations. The number of eggs that cracked when impacted on their equator was lower than those impacted on their poles. Namely, these results suggest that *an egg dropped on its equator can likely sustain greater drop heights without cracking*.

Similar to the static tests, mechanical analysis is sufficient to explain and predict the result of the drop test. Using the same material properties and modeling framework as developed and calibrated for the static case, we conduct numerical simulations to obtain the force versus time responses for eggs dropped from different heights (Fig. 3). As confirmed by examining the failure criteria in the simulation, curves with sharp drops in force indicate cases where the egg cracks upon impact, while smooth curves indicate cases where the egg deforms elastically and thus recovers by bouncing back after engaging with the support[20]. Notably, fracture is first observed when eggs are dropped from a height of 8.6 mm for the vertical orientation. Orienting the egg along its equator allowed it to reach 0.3 mm higher than in the vertical

orientation without cracking, confirming a real albeit small advantage of dropping the egg along its equator.

Examining the curves for the intact eggs in Fig. 3 we find that the contact time with the platen (i.e., the extent of time in which the force measurement is non-negative), is larger for the horizontal orientation. This result suggests that the egg is more compliant in this configuration, also for the case of dynamic impact, thus corroborating the prediction based on egg toughness. This increased compliance is most likely attributed to the egg's structure, given that the same material properties are used in both orientations. This influence of geometry is also reflected in the fracture patterns that emerge and the corresponding stress distribution (see Supplementary Fig. S3). Nonetheless, in all three orientations, the cracks originate from the point of contact and propagate outwards as seen from both the experiments and the simulations. To numerically investigate the initiation of cracking, the material properties of the egg are calibrated based on the static experimental results and can thus be considered as equivalent material properties for the shell with the internal membrane. The simulations are able to illustrate the dynamic cracking even for higher drops (see Supplementary Fig. S4).

Conclusions

The presented results support the idea that an egg is less likely to crack when dropped on its equator. This result is contrary to the conventional wisdom that an egg is "stronger" in the vertical direction. *So what went wrong?*

To understand this we can examine the common steps in logic made by popular science communicators and institutions on the strength of an egg. Below is a set of basic descriptions of the common arguments found in popular science media (see Supplementary Table S1), and an analysis of their validity, based on our experiments and simulations. These are not exact quotes but represent common threads in explanation among the examined sources.

Eggs are stiffer when loaded in the vertical direction.

This is true. Both our experiments and our numerical simulations verify that the stiffness k of an egg is higher when loaded in the vertical direction.

This means that eggs can sustain more force when loaded in the vertical direction.

Even conceptually, this is not necessarily true. The peak force F may depend on a number of material and geometric factors, which are independent of the stiffness. For instance, the stiffness of a column is determined by its cross-sectional area, but the force at which it buckles is determined by its area moment of inertia. Therefore, a column with a larger area, but smaller moment of inertia will be stiffer but attain a lower peak force[21]. In our experiments, we found no statistical difference between the peak force in the vertical and horizontal directions, consistent with our numerical simulations.

Because an egg can sustain a higher force in the vertical direction, it is less likely to fracture during impact.

This is incorrect. Even if eggs could sustain a higher force when loaded in the vertical direction, it does not necessarily imply that they are less likely to break when dropped in that orientation. In contrast to static loading, to remain intact following a dynamic impact, a body must be able to absorb all of its kinetic energy by transferring it into reversible deformation. For an egg, assuming a linear force-displacement relationship (supported by the data in Fig. 1c, d), we can write the total energy absorption (i.e., the egg toughness) and kinetic energy, K at impact as

$$E = F^2/(2k), \qquad K = mgh$$

respectively, g refers to the acceleration due to gravity. With K and F independent of orientation, and given that k is higher for an egg loaded in the vertical direction, one *should* expect that E is higher for an egg when loaded in the horizontal orientation; it would thus be less likely to break when impacted on its equator and experiencing lower force. This is in agreement with the results of our dynamic experiments and simulations.

It is evident now that the flaw in the common argument is with the definition of a "strong" egg, [see Supplementary Table S17]. The preponderance of STEM communicators understand that an egg is stiffer in one direction, but they equate this with "strength" in all other senses. However, eggs need to be tough, not stiff, in order to survive a fall. We understand this intuitively. When we fall we know to bend our knees rather than lock them straight, which could lead to injury. In a sense, our legs are "weaker", or more compliant, when bent, but are tougher, and therefore "stronger" during impact, experiencing a lower force over a longer distance.

Our results and analysis serve as a cautionary tale about how language can affect our understanding of a system, and improper framing of a problem can lead to misunderstanding and miseducation. We hope that this revised framing of the problem will help equip budding scientists and engineers with a better understanding of the way in which objects and structures react to impact and dynamic loads.

Methods

Egg selection and measurement

We purchased USDA Grade AA Cage Free Large Eggs in cartons of 60 eggs from Costco under the Kirkland Signature brand. Prior to testing, eggs were allowed to reach room temperature. We inspected eggs for any potential defects. If we determined the presence of a pre-existing crack (through a visual inspection for hairline cracks on the shell), we discarded the egg and did not include it in subsequent testing. Of the eggs tested, properties that we recorded to inform finite element simulation were length, L, defined as the distance in the long-axis direction from the sharp end to the blunt end; width, B, defined as the maximum diameter of the egg perpendicular to the long-axis, and mass, m. We measured the lengths via a TOL-10997 Digital Caliper with accuracy of ±0.02 mm. Thickness of the eggshell, t, was measured using a Mitutoyo Digital Micrometer H-2780 with accuracy of ±0.001 mm. Mass was measured using a Bonvoisin laboratory scale with accuracy of ±0.01 g. We calculated the average length to be 56 mm, the average width to be 44mm, and the average mass to be 59 g.

Physical experiments

We used an Instron 5943 universal testing machine to measure force in both the static and dynamic tests, and for controlling the displacement in the static tests. The precision in tracking the displacement is ±0.01mm, and the resolution for the load measurement is ±0.05N.

Static compression tests. For testing, we rested a single egg on a fixed platen and then compressed it by moving the top platen, which was connected to the 1kN load cell. We oriented the eggs in one of two directions, vertical or horizontal. To ensure correct alignment of the egg with the center of the moving platen, specially designed supports were constructed from letter-size copy paper as shown in Supplementary Fig. S1. We found that increasing friction between the egg and platen during testing did not alter the central conclusions of our original experiments, as can be seen in Supplementary Fig. S10. When testing, the BlueHill software recorded reaction forces, time, and displacement of the moving platen, at 10 mm/min, into the egg up to and past cracking. Data collected from the tests is provided in Supplementary Note 2.

Drop tests. Opposite the static compression tests, we fixed the 1kN load cell to the bottom platen and the Bluehill software was configured to record the force at a sampling rate of 1 kHz. To consistently drop the eggs at the correct orientation with minimal rotation, we 3D printed a solenoid-based device out of Polylactic acid (PLA). With no top platen, we fitted the device into the moving cross-head of the Instron 5943

universal testing system. The device holds two UXCELL 0.8N, 10 mm stroke push-pull electromagnet solenoids, with 3D-printed angled egg supports to stabilize the egg prior to dropping. To actuate the solenoids, thereby dropping the egg, we wired both solenoids to a pair of 9V batteries, connected in series, to a Single-Pole Single-Throw (SPST) rocker switch. Experimental setup is shown in Supplementary Fig. S5.

A drop test is carried out as follows: First, we place the egg atop the solenoid supports and reset the 1kN load cell such that the force reading is 0.0N. To precisely set the drop height, we use the cross-head of the Instron system, to lower the device until the egg lightly touches the load cell and the force reading is 0.1N, indicating first contact. We then reset the gauge length extension to zero and translated the egg assembly upwards to heights of 8.0, 9.0, and 10.0 mm for testing. With the egg in place, we begin data collection and toggle the SPST rocker switch to "ON" triggering the solenoid arms to simultaneously retract and release the egg for impact onto the bottom platen.

We dropped the eggs in three different orientations: horizontal on their equator, vertical on their sharp end, and vertical on their blunt end. Twenty eggs were tested per orientation and the drop procedure was repeated at heights of 8.0mm, 9.0mm, and 10.0mm for a total of 180 eggs tested. Cracked eggs were identified through analysis of force-time curves recorded by the Instron system and subsequent visual inspection. A sharp drop in force was interpreted as a crack event. Conversely, if the egg bounced (as reflected in the force-time plot as a wave with decreasing amplitude) the egg was likely intact, although some did crack. To ensure accuracy, we visually inspected all eggs for hairline fractures after a few days. If we detected a fracture, the egg was classified as cracked. Raw Data from the dynamic tests can be found in Supplementary Note 3.

Numerical experiments

Full 3D simulations were conducted using the Finite Element Analysis software, Abaqus/Explicit. We structured the egg with an exterior eggshell modeled as a linear elastic material, and an interior yolk modeled as a viscous fluid. The average measured dimensions of the experimental eggs were used to define the model egg geometry. For the yolk, we adopted mass density and viscosity values as reported in the literature[22,23], i.e., 1.02 g/cm^3, and 1322MPa · s, respectively. The shells Young's modulus, Poisson's ratio, and mass density were also taken to agree with reported values[24–26] i.e., 49GPa, 0.3, and 2.241 g/cm^3, respectively. We postulated shell fracture as brittle failure with material parameters calibrated to match the average experimental curve for static compression in vertical loading (Fig. 1): the failure stress as 23MPa, the Mode I fracture energy–defining the energy required for failure–as 3.728 mJ. The calibrated failure stress of 23MPa matches closely to the value of 19.9MPa determined from Liu et al.[27]. Additionally, we simulated the half-shell experiments performed in Liu et al.[27] and were able to capture the same trends. More details of these simulations can be found in Supplementary Note 4. To specify the post-cracking shear behavior, we defined the shear retention factor-crack opening strain relationship as crack opening strain of 0 corresponding to shear retention factor of 1, and crack opening strain of 0.002922 corresponding to shear retention factor of 0. For more information about the latter parameters, the reader is referred to ABAQUS documentation[28].

The eggshell domain was discretized using unstructured S4R elements with an element size of 2mm with reduced integration and finite membrane strain. Note that when a crack propagates through an element, the failed element may experience severe distortion. In this case, it is removed from the mesh once the damaged criterion is satisfied. To accommodate this we enabled element deletion in the ABAQUS element controls. Mesh dependence analysis confirms that the current approach captures the correct qualitative trends (see Supplementary Fig. S2).

We analysed the interaction between the yolk and the eggshell via the Coupled Eulerian-Lagrangian (CEL) technique. To specify the exact location of the yolk inside the eggshell, we used a predefined material assignment after creating a discrete field using the volume fraction tool. ABAQUS tracks the material flow in each element by using volume fraction, which represents the percentage of the element's volume filled with material at any given moment. We discretized the yolk domain using a structured mesh of 8-node brick elements of EC3D8R Eulerian family element type with an element size of 2 mm. The top and bottom supports are modeled as 3D discrete rigid plates, which we discretized via unstructured mesh of 4-node 3D bilinear rigid quadrilateral elements (R3D4).

Static compression tests modeling. To simulate static compression, we bounded the egg by top and bottom supports. The top support translates in the vertical direction at a constant velocity, 100 mm/min, while the bottom support remains stationary. To prevent rotation of the egg we constrained the top and bottom tips of the egg to move only along the vertical axis. It is worth mentioning that both 10 mm/min and 100 mm/min velocities were tested experimentally, with no significant difference observed in the results. To reduce simulation time, we adopted the 100 mm/min velocity in our simulations, as using 10 mm/min would have led to excessively long computational times, which are impractical for model calibration with the Coupled Eulerian-Lagrangian (CEL) approach. Simulations were conducted using dynamic explicit stepping with a time period of 0.35 seconds and geometric nonlinearities were captured by choosing the NLGEOM option.

Drop tests modeling. To model a dynamic drop, we used the same setup as for static compression, but without the top support. We dropped the egg from a prescribed height onto the stationary bottom support. We adopted the same material parameters, egg dimensions, loads, mesh types, and number of elements as in the compression tests. We modeled the egg when it reached a height of 0.5 mm from the floor by prescribing an initial velocity using energy conservation, $v = \sqrt{2gh}$, which matched the experimental drop values. We use a dynamic explicit step with a time period of 0.005 s. For smooth tracking of fracture, we defined the output frequency of intervals as 50.

Data availability

All of the experimental data is provided in the Supplementary Information and available online via GitHub (cohen-mechanics-group/nature-comms-phys-egg).

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Author contributions

A.S., B.M.U., S.R., H.Bd.R., S.K.M., and T.C. contributed to the conceptualization and methodology. T.C. provided resources, project administration, supervision, and funding acquisition. A.S., B.M.U. and S.K.N. contributed to data curation. A.S., S.A.Q., A.J., B.M.U., J.E.B., and S.K.N. were responsible for validation, formal analysis, and investigation. A.J., S.A.Q., H.Bd.R., and S.K.N. contributed to visualization. S.A.Q. developed the software. Writing, including original draft preparation and review and editing, was carried out by A.J., S.A.Q., B.M.U., J.E.B., H.bd.R., S.K.N., and T.C.

Competing interests

The authors declare no competing interests.

Additional information

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