Physical Properties of Egg Shells

1. RELATIONSHIP OF RESISTANCE TO COMPRESSION AND FORCE AT FAILURE OF EGG SHELLS[1]

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(Received for publication May 14, 1966)

INTRODUCTION

EGG SHELL strength has been measured by compression, impact and puncture, but only compression lends itself to the development of a non-destructive measurement of shell strength. If a linear relationship exists between compression force and the induced deformation of the shell, and if the slope of this line is related to force applied at failure of the shell, then a non-destructive test could be developed. The deformation under non-destructive forces would be used to predict the force at failure.

Brooks and Hale (1955) studied this relationship and found that deformation under force applied parallel to the major axis was correlated with force at failure by a r value of −0.71. They demonstrated that differences of deformation within eggs was too small to account for differences between eggs and that shape exerted a small influence on this criterion while egg weight had no effect. They also observed that the relationship between force and deformation was almost linear. Removal of forces less than the force required to cause shell failure resulted in a return of the egg to its original dimensions. Schoorl and Boersma (1962) in a similar study, found a correlation of −0.88 between deformation and force at failure. They used means of all eggs from individual hens rather than data from individual eggs to obtain their correlation. These workers also observed a linear relationship between deformation and force applied. Gainsford (1965), using the apparatus of Brooks and Hale (1955), reported a correlation coefficient of −0.80 between deformation and force at failure.

Rehkugler (1964) found that egg shells were not perfectly elastic and determined elastic constants for shell material based on the deformation of a ring or semi-circular section of shell (1963). Shuster (1959) measured deformation of the egg under a one kilogram force and found deformation to be significantly correlated ($r = 0.506$) with resistance of the shell to puncture.

The object of the work reported here was to determine whether a non-destructive compression test could be used to predict the strength of egg shells with greater accuracy if other physical properties of the shell were also taken into account.

MATERIAL AND METHODS

Eggs used in these studies were from S.C. White Leghorn hens, fed a practical type diet, containing 3.0% calcium, 0.67% total phosphorus (0.42% inorganic), and 680 I.C.U./lb. vitamin D_3.

Experiment 1. Eggs were collected and candled the morning they were laid. Cracked eggs were discarded. The remaining eggs were weighed to within 0.1 gm. and passed through NaCl solutions of varying specific gravity (1.060–1.100 in increments of 0.002), to determine their

[1] Contribution No. 230, Animal Research Institute and Contribution No. 91, Engineering Research Service.

specific gravity by flotation. Eggs were stored overnight in a refrigerator at 4.5°C. (40°F.). The following day the eggs were removed from the refrigerator, allowed to reach room temperature, and their major and minor axes measured to within 0.1 mm. The eggs were recandled to eliminate eggs damaged by handling.

The eggs were tested in a universal test machine[2] which compressed each egg between flat plates. The surfaces in contact with the eggs were ground to a smooth finish, chrome plated and polished (maximum roughness < 15 microns). The force on the egg during compression was recorded on a strip-chart (Fig. 1) over the range 0–15 lb. by a force transducer and electronic recording system. The eggs were compressed at 0.2 in./min. and when the shell failed, the compression bar was reversed and the egg removed. This procedure was carried out on 151 eggs with the major axis parallel to the compression surfaces (force applied to equator) and 78 eggs with the major axis perpendicular to the compression surfaces (force applied at poles). After testing the eggs were candled and the direction of the fractures, at the equator, recorded by a numerical rating (Table 1). The location of the fracture was noted to be either at the moving or stationary surface of the test machine.

The radius of curvature of the shell along the fracture and at right angles to it was measured with templates varying in radii of curvature by 0.031 in. The fracture was marked at the start, mid-point and finish. The internal contents were discarded and the shell membranes removed by the method of Tyler and Geake (1953). The shells were dried to constant weight and the shell weight recorded. Shell thickness measurements were taken at three random

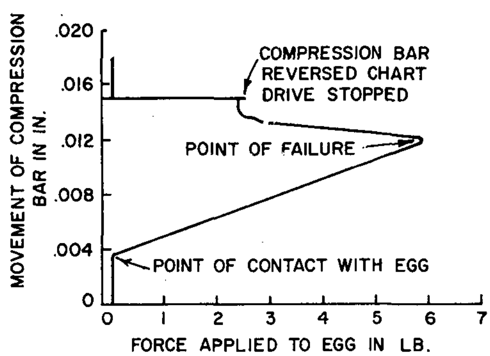


FIG. 1. Force-deformation curve for an egg under a quasi-static force.

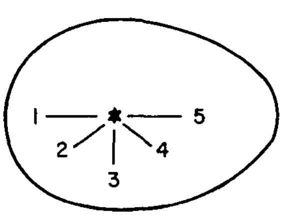
locations about the equator of the egg and at the three previously marked locations along the fracture.

From these data, stiffness of the shell, percent shell and shape index (minor axis/major axis) were calculated. In this, and subsequent papers in this series, the term stiffness is equal to the slope of the force-deformation line. Poles refer to the apex of the large and small ends of the egg. Equator refers to the plane where the minor axis is greatest.

Experiment 2. In this experiment, 209

TABLE 1. *Direction and frequency of fractures under quasi-static loading conditions at the equator.*

FRACTURE DIRECTION	FREQUENCY OF OCCURRENCE	
	EXP. 1	EXP. 2
1	44	52
2	5	2
3	48	84
4	4	4
5	50	67
TOTAL	151	209



SYSTEM OF ENUMERATING FRACTURE DIRECTION

[2] Instron, Type B, Universal Testing Machine, Instron Engineering Corp., Canton, Mass., U.S.A.

eggs were tested with the major axis parallel to the compression surfaces (force applied at equator). Specific gravity, shape, curvature of shell were not recorded in this experiment.

The data were submitted to regression analysis. Simple and partial correlation coefficients were obtained as well as standard partial regression coefficient and coefficients of multiple correlation.

RESULTS AND DISCUSSION

Typical force-deformation lines (point of contact to point of failure) appeared linear to the eye (Fig. 1). In these experiments the maximum deviation from linearity could not be determined precisely as the distance between the force transducer and the compression bar was not recorded during deformation. It was assumed for the calculation of stiffness that the chart and compression surface velocities were proportional and the transducer position was fixed. In reality there was a slight deflection of the transducer under force.

When compression was applied at the equator it was noted that a small (3 mm. approx.) circular fracture occurred similar to that described by Tyler and Moore (1965) but differing in that usually one major fracture emanated from the point of contact. Tyler and Moore (1965) indicated that several fractures emanated from the point of contact. When force was applied at the poles, it was found that several fractures emanated from the point of contact.

Table 1 gives the direction in which the fracture occurred for both experiments with force applied at the equator. Using the "Z" test for binomial distribution it was found that the probability of the fracture occurring in directions 1 or 5 was equal while the probability was not equal that the fracture would occur along the major or minor axis. The majority of fractures occurred along the major axis. This observation agrees with the work of Tyler and Moore (1965). A satisfactory explanation for the small number of fractures which travel in the areas between the major and minor axis cannot be offered. Tyler and Moore point out that the path a fracture takes is not governed by crystal orientation as fractures pass through crystals. Tests for normal approximation to the binomial distribution indicate that the probability of the curvature of the shell along the fracture being less than the curvature of the shell at right angles to the fracture was 0.5, therefore, curvature of the shell does not influence fracture direction. This is contrary to what was expected since the majority of fractures occurred along the major axis. Similar tests of probability on thickness of shell along the fracture indicate that the fracture would run from thick shell to thin shell as many times as it would run from thin shell to thick shell.

In a previous paper (Voisey and Hunt, 1964) it was noted that fractures occurred predominantly at the moving surface. In these experiments it was found that the probability of the fracture occurring at either face was equal and the occurrence of the fracture at one face or the other was independent of shell thickness. The discrepancy between this test and our previous work appears to be related to the surface finish of the compression plates. In the previous paper a rough machined surface (maximum roughness = 50 microns) was used at the moving surface while in this work two identically plated and polished surfaces were used.

Simple correlation coefficients and means for the physicial properties of eggs are presented in Table 2 for the forces applied at the poles and at the equator. Mean force at failure was lower for forces applied at the equator but was more highly correlated with stiffness of the egg than when the force was applied at the poles (Figs. 2

TABLE 2.—*Simple correlation coefficients and means of physical characteristics of egg shells for force applied at the equator or poles**

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	Means
X_1	—	0.8338	0.1313	0.7462	−0.0773	−0.0020	0.6993	0.6487	0.1754	7.464
X_2	0.6246	—	0.1253	0.8226	0.1393	−0.1575	0.8059	0.7662	−0.0232	9.240
X_3	0.0372	0.0045	—	0.1312	−0.0106	0.1435	−0.0166	0.2899	0.0222	56.8
X_4	0.4546	0.5078	0.0026	—	0.2083	−0.1927	0.8932	0.7645	−0.1064	1.084
X_5	0.0568	−0.1317	−0.0542	−0.1062	—	−0.9030	0.2070	0.1632	−0.4041	40.6
X_6	0.0534	−0.1266	−0.0716	−0.0997	0.9726	—	−0.2063	−0.0928	0.1840	33.2
X_7	0.4748	0.5128	−0.1572	0.9033	−0.1343	−0.1202	—	0.7468	−0.1696	8.947
X_8	−0.0656	0.3346	0.2170	0.8002	−0.1800	−0.1802	0.8505	—	−0.2148	0.316
X_9	−0.0656	−0.1046	0.0091	−0.0001	0.2086	0.2001	−0.0460	−0.1046	—	0.7252
Means	8.324	14.19	57.8	1.084	20.8	20.8	8.986	0.321	0.7184	

Upper triangle and Means column: Force applied at equator of egg. Lower triangle and Means row: Force applied at poles of egg.

X_1 = Force at failure, lb.
X_2 = Stiffness (slope of compression line) lb./0.01 in.
X_3 = Egg weight, gm.
X_4 = Specific gravity.
X_5 = Curvature along fracture, radii in 32nds of an inch.
X_6 = Curvature at right angles to fracture, radii in 32nds of an inch.
X_7 = Percent shell.
X_8 = Shell thickness, mm. Mean of three equatorial readings.
X_9 = Shape index, minor axis/major axis.

* Data are from experiment 1 with 151 observations on each property for force applied at equator and 78 observations for force applied at the poles.

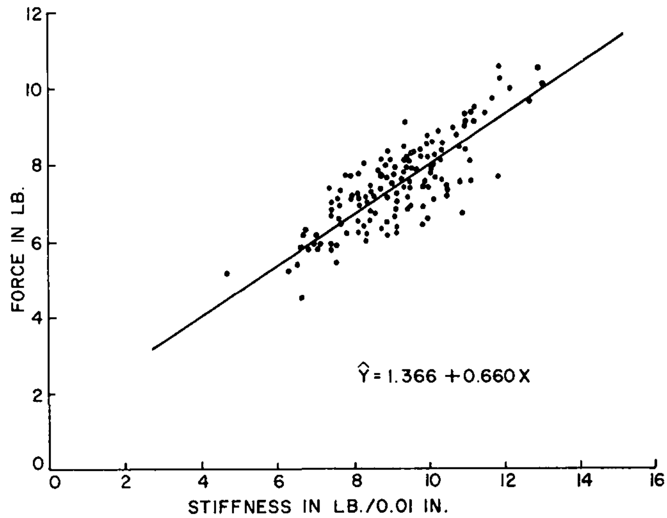


FIG. 2. Relationship between force and stiffness of shell for force pplied at the equator.

and 3). Higher correlations for force at failure occurred with all properties when the force was applied at the equator as compared to the poles. This was especially true for shell thickness about the equator where the correlation with force applied at the equator was 0.649 while for force applied at the poles it was —0.066. Schoorl and Boersma (1962) found similar results in that deformation at the equator was more highly correlated with equatorial shell thickness than with mean shell thick-

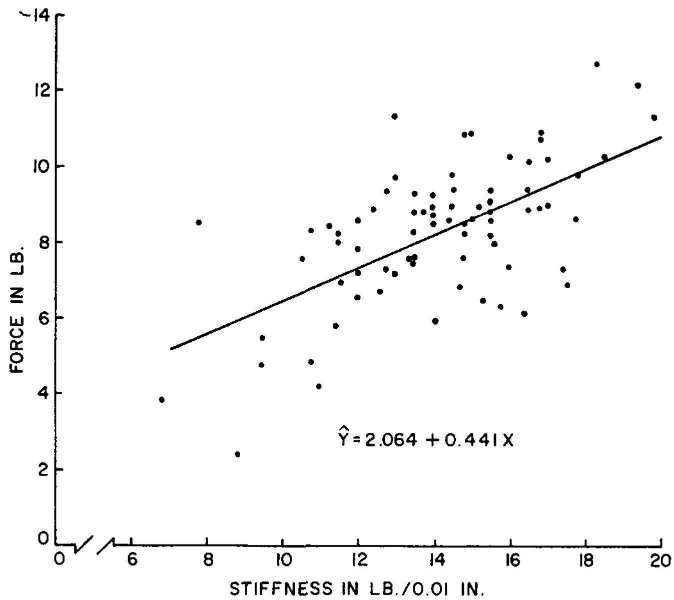


FIG. 3. Relationship between force and stiffness of shell for force applied at the poles.

ness derived from measurements taken over all the egg surface. Whether thickness measurements, at the site of loading, are a useful measure of shell resistance to fracture or whether shell thickness is not a significant factor in resistance to fracture under quasi-static loads in the polar region of egg shells, could not be ascertained from their experiment. The correlation for force at failure on stiffness was greater in both experiments ($r = 0.8338$, expt. 1; $r = 0.7487$, expt. 2) than that reported by Brooks and Hale (1955) and slightly below that reported by Schoorl and Boersma (1962) but still only accounts (100 r^2) for 69.5% and 56.1% of the variation in experiment 1, and 2 respectively. The other correlations reported for force applied at the equator agree favourably with those reported by Brooks and Hale (1955) and Shuster (1959).

To measure the contribution of other physical properties of egg shell to quasi-static force, a stepwise regression program which extended the regression model by one variable at a time was used. The variable selected at each stage was the variable accounting for the largest residual sum of squares.

Table 3 gives the results of this program for force applied at the poles and equator for expt. 1 and 2. Regardless of the point of application, stiffness accounts for the greatest contribution to variance for the prediction of force at failure. The contribution (100 r^2) of stiffness for force applied at the poles is much less (39%) than when the force is applied at the equator (69.5%). That shape as suggested by Frank *et al.* (1964) is a more important factor than other physical properties of the shell is exemplified by significant F values for curvature along the fracture in both tests of experiment 1 and by the significant F value of shape index when force was applied at the equator in experiment 1. Physical measures of shell are not consistent in the order of their contribution to variance in the regression equations derived from these experiments for force applied at the poles and the equator. Part of this inconsistency may be attributed to the high degree of correlation between physical properties of the shell.

TABLE 3.—*Variance and contribution of variables to regression of force at failure*

Regression due to	d.f.	MS	100 R^2
Y = Force at failure with force applied at poles—Exp. 1			
Stiffness	1	103.30	39.0
Percent shell	1	8.58	42.3
Curvature along fracture	1	6.35	44.7
Egg weight	1	1.70	45.3
Shape index	1	.33	45.5
Shell thickness	1	.41	45.6
Residual	71	2.03	
Y = Force at failure with force applied at equator—Exp. 1			
Stiffness	1	124.80	69.5
Curvature along fracture	1	6.85	73.4
Specific gravity	1	4.53	75.9
Shape index	1	3.87	78.0
Curvature at fracture	1	.65	78.4
Percent shell	1	.41	78.6
Residual	143	.29	
Y = Force at failure with force applied at equator—Exp. 2			
Stiffness	1	136.00	56.1
Shell thickness	1	.77	56.4
Percent shell	1	.90	56.7
Residual	202	.52	

Experiments 1 and 2 generated two simple regression equations, $Y = 1.366 - .660X$ and $Y = 2.009 - .571X$, respectively where Y is an estimate of failure force for force applied at the equator and X is shell stiffness. In both cases "b" was significant (0.1%) but differences between regression coefficients were also significant, If it is assumed that the Y intercept is zero then the two sets of data yield exactly the same regression coefficient of 0.812. The difference between the egg samples of experiment 1 and 2 is that the eggs were collected from the same flock of birds for both experiments, but experiment 2 was conducted at a later date and the birds were therefore older. It must also be pointed out that the same number of eggs from specific hens were not used in each experiment.

The simple correlation coefficient of failure force on stiffness and the fit of the data for forces applied at the equator suggests value in the technique of using stiffness to predict force at failure. The contribution of shape or physical properties of shell is small and therefore the work involved in measuring a second physical property does not appear worth while in evaluating egg shell strength by compression.

The difference in regression equation for experiments 1 and 2 suggests that age, individual hen and strain should be studied before a general prediction equation can be suggested.

SUMMARY

The use of egg shell stiffness (slope of the force-deformation line) to predict force at failure has been investigated under quasi-static loading conditions. Correlations of 0.8338 (Expt. 1) and 0.7487 (Expt. 2) were obtained for force at failure on stiffness when force was applied at the equator while a correlation of 0.6246 was found for force applied at the poles. Incorporation of shape characteristics or physical properties of the egg such as specific gravity, percent shell, mean shell thickness at the equator and egg weight had a small effect on improving the prediction equation for force at failure. Shape characteristics appear to be more important than physical properties.

For both experiments when force was applied at the equator, the regression equations had highly significant regression coefficients but there was also a highly significant difference between coefficients. Neither equation passed through the origin or approached it. If regression lines were calculated to pass through the origin then the coefficients were identical for the two sets of data. The difference between the egg samples used in the two sets of data was date of lay. Further work is required on age, environment and strain effects.

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NEWS AND NOTES

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ONTARIO NOTES

The Government of the Province of Ontario has honored Shaver Poultry Breeding Farms, Ltd., Galt, Ontario, Canada, for "outstanding contribution" to the growth and expansion of the Province's economy. The Company was presented with the

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