Subjective Evaluation of Crash Behavior of Muscle at Subsonic Level for Simulation of Bird Strike

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Abstract

Because any impact test method for materials at the subsonic level has not been developed so far, numerical simulations of crash problems at this level have been inaccurate. This inaccuracy causes serious problems, especially in the analysis of bird collisions with airplanes. Therefore, a shock impact test system using an airsoft gun is developed to evaluate material behavior at the subsonic level that will support technological design of anti-bird-strike structures of airplanes. The viscoelastic characteristics of specimens are evaluated by analyzing the stress response using the extended Hertzian contact theory and wave equation at the moment when a simple ball bullet is shot at the specimen using the airsoft gun. In the experimental results of the test, an obvious relationship between quasi-static and impact responses of the specimen is observed subjectively. The evaluated viscoelastic relationship is applied to simulate the impact test by using LS-DYNA with the fundamental viscoelastic constitutive equation and the material parameters derived from the impact test, and the simulation of the crash is completed using the identified parameters.

Keywords: Bird Strike, Airplane, Viscoelastic, Biomechanics, Dynamic Stress, SPH Method

Introduction

While the number of aviation accidents caused by bird strikes increases each year [1], aircraft miniaturization and lightening are being advanced to improve economic efficiency; consequently, safety design technology for airplanes becomes difficult to develop. Therefore, a shock impact test system using an airsoft gun is developed in this study to evaluate the design technology of anti-bird-strike structures of airplanes. A simple ball bullet is shot at the test specimen using an airsoft gun and the stress response in the load cell of the test system is evaluated by the extended Hertzian contact theory and the wave equation, which are used to analyze the viscoelastic characteristics of the specimen. In the experimental results, an obvious relationship between quasi-static and impact responses of the specimen is observed subjectively, and the hardening effect caused by the impact is clearly observed in the results of muscles of chicken. The evaluated viscoelastic relationship is applied to simulate the impact test by using LS-DYNA with the fundamental viscoelastic constitutive equation and the material parameters derived from the impact test, and a phantom imitating a real bird will be developed as a standard specimen for an anti-bird-strike test using the shock impact test system.

Experimental System

Shock Impact Test by Ball Collision

To evaluate the deformation behavior of materials at the subsonic level, an impact system using a ball bullet is adopted for the development of an impact test using an airsoft gun. The bullet used is the product made of polystyrene resin containing lime. The system developed is shown in Figure 1 with other measurement instruments used in the evaluation. The airsoft gun used in this system is an airsoft gun (toy gun) made by Tokyo Marui Co., Ltd., Japan. The M14 model of the airsoft gun is adopted because it has the capability to shoot a ball bullet at almost 100 m/s. The shot bullet collides with the specimen on a load cell vertically, causing stress waves in the cell. Furthermore, the wave in load cell is measured using a strain gauge pasted onto the side of the cell and logged through the dynamic strain meter CDV-700A (Kyowa Electronic Instruments Co., Ltd.) and the AD board LPC-320724 (sample frequency: 1.556 MHz; Interface Corp.) using a MS-Windows PC. The collision is also observed with a high-speed camera.

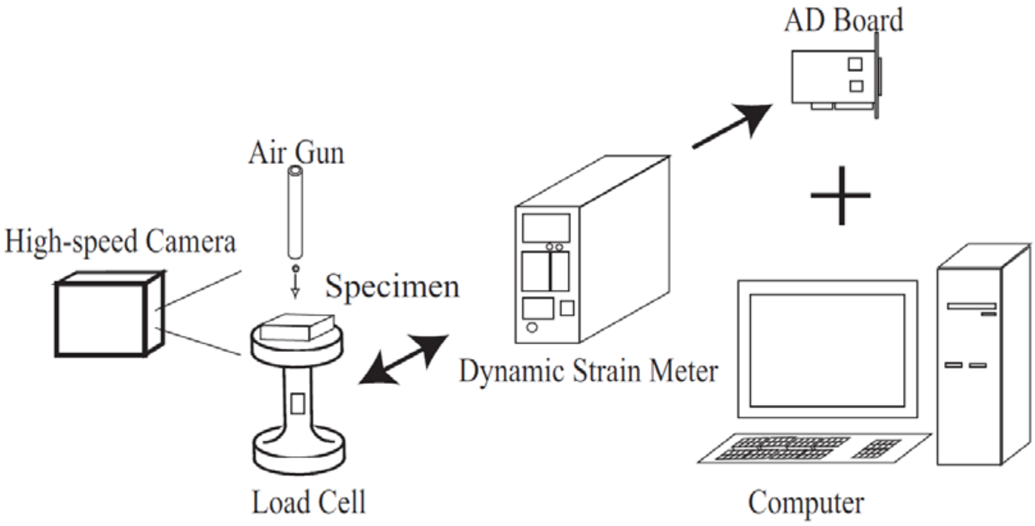


Figure 1. System of impact test

Evaluation Procedure for Deformation Characteristics of Materials

The famous Hertzian contact stress theory [2] is extended to evaluate the collision behavior of the impact test system. The fundamental form of the theory can be written in the following form as the relationship between contact force F and indentation depth δ for the contact problem of a rigid ball and elastic body with a planar surface:

$$F = \frac{4}{3}\frac{E}{1-\nu^2}\left(\frac{\phi}{2}\right)^{\frac{1}{2}}\delta^{\frac{3}{2}} = A\delta^{\frac{3}{2}} \tag{1}$$

Here, variables E, ν, and ϕ indicate Young's modulus, Poisson's ratio, and the diameter of the ball indenter, respectively.

Equation (1) is the theoretical solution for a semi-infinite elastic body, but the specimen on the load cell in Figure 1 should have a finite body because of the measurement of the stress wave in the load cell. The extended relationship [3]-[4] of the Hertzian contact stress theory is then adopted to analyze the contact problem of the finite elastic body. The extended Hertzian contact stress theory has the following form with thickness coefficient B:

$$\hat{F} = \frac{4}{3}\frac{E}{1-\nu^2}\left(\frac{\phi}{2}\right)^{\frac{1}{2}}\{\delta(1+B\delta)\}^{\frac{3}{2}} = A\{(1+B\delta)\delta\}^{\frac{3}{2}} \tag{2}$$

As for the ball collision problem illustrated in Figure 2, the contact force $\hat{F}$ at the specimen on the load cell causes a stress wave to propagate through the cell to the bottom. The propagation can be represented by wave equation (3) with constant c as a function of time t and position x as follows:

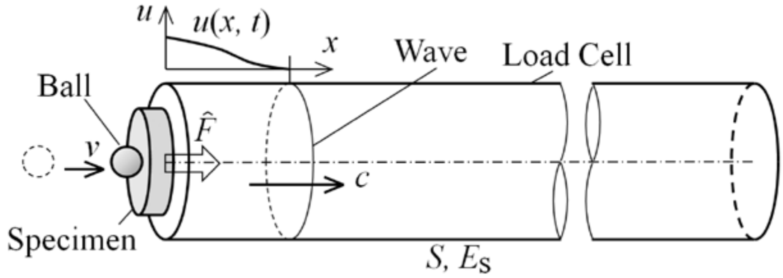


Figure 2. Wave analysis model of ball impact on specimen at the bar end of load cell

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \tag{3}$$

By using equation (2) as a boundary condition for the wave equation (3), the solution *u*(*x*, *t*) can be derived with constants *a*, *b*, and *c* as follows:

$$\begin{aligned} u(x,t) = & \; a\{3\log\{\sqrt{1+b(ct-x)} + \sqrt{b(ct-x)}\} \\ & + \sqrt{b(ct-x)\{1+b(ct-x)\}} \\ & \{16b^3(ct-x)^3 + 24b^2(ct-x)^2 + 2b(ct-x) - 3\}\} \end{aligned} \tag{4}$$

Equation (4) can be used to analyze the wave profile in the cell for the mechanical evaluation of the specimen on the cell. Then, coefficients *A* and *B* can be derived with the following relationship using *a*, *b*, and *c*, which were identified by using the above procedure.

$$A = -\frac{64ab^{\frac{5}{2}}c^{\frac{3}{2}}E_s S}{v^{\frac{3}{2}}} \tag{6}$$

$$B = \frac{bc}{v} \tag{7}$$

Here, variables E_S and *S* indicate Young's modulus and the section area of the load cell, respectively.

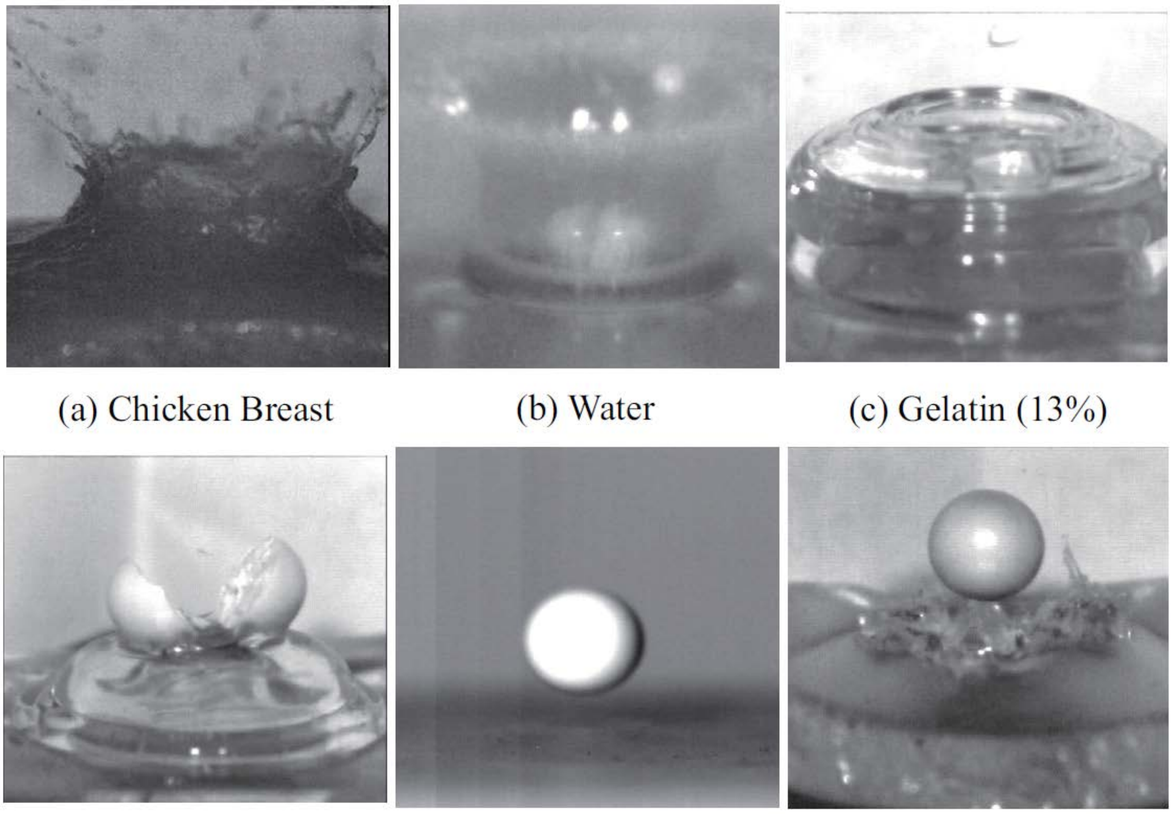
From coefficient *A*, Young's modulus *E* is derived by using equation (1). However, the effect of viscosity is included in the deformation behavior that is observed in the shock impact test. Coefficient *D* is then used to represent the deformation behavior of the specimen in this paper. Coefficient *D* is defined as follows by Hooke's law with the consideration of the viscous effect, and is referred to as the deformation-resistant modulus in this paper:

$$D = \frac{3}{4}A(1-\nu^2)\left(\frac{\phi}{2}\right)^{-\frac{1}{2}} \tag{5}$$

Experimental Results and Numerical Simulation

Experimental Result

In Figure 3, the experimental results measured by the system shown in Figure 1 are shown as examples of ball collisions. Here, six materials are shown: chicken breast, water, 13% gelatin, 25% gelatin, silicone rubber, and epoxy-based resin. The impact crown at the moment of the collision is shown for each material, but their shapes are different, indicating that the deformation characteristics of the materials are also different.



(a) Chicken Breast (b) Water (c) Gelatin (13%)

(d) Gelatin (25%) (e) Silicone Rubber (f) Epoxy-Based Resin

Figure 3. Moment of ball collision

These experimental results are evaluated by Young's modulus E and D shown in Figure 4. Here, Young's modulus E is measured using a fundamental material indentation tester SoftMeasure HS-3001 (Horiuchi Electronics Co., Ltd.) [5] for all materials except water. Young's modulus of water, which is a liquid, could not be measured because of its characteristic lack of elasticity. In these results, it is shown that every material becomes hard at the subsonic level.

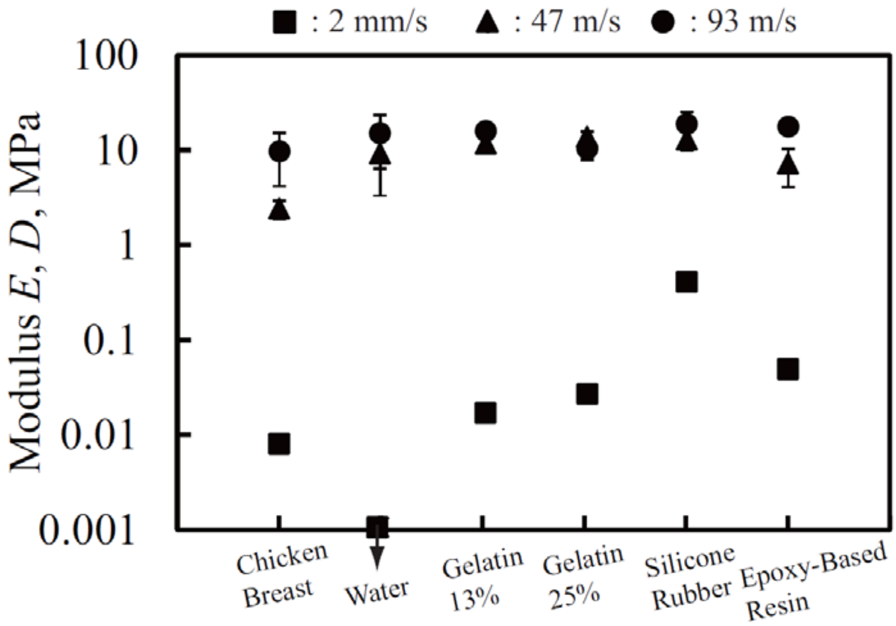


Figure 4. Effect of deformation velocity

Numerical Simulation

The differences observed in each material are analyzed by the relationship shown in the following section. The analyzed result is applied to deformation analysis using LS-DYNA (Livermore Software Technology Corp.), which uses the evaluated results of the materials. In this analysis, the constitutive equation of Hermann and Peterson [6] is adopted to represent the viscous effect of the materials. The equation defines shear elasticity $G(t)$ in terms of the relationship among short-run shear elasticity G_0, long-run shear elasticity G_∞, and coefficient β (equation (6)). Furthermore, normal elasticity $D(t)$ is defined for applying equation (5) in terms of short-run normal elasticity D_0 and long-run normal elasticity D_∞ in this paper:

$$G(t) = G_\infty + (G_0 - G_\infty)\, e^{-\beta t} \tag{6}$$

$$D(t) = D_\infty + (D_0 - D_\infty)\, e^{-\beta t} \tag{7}$$

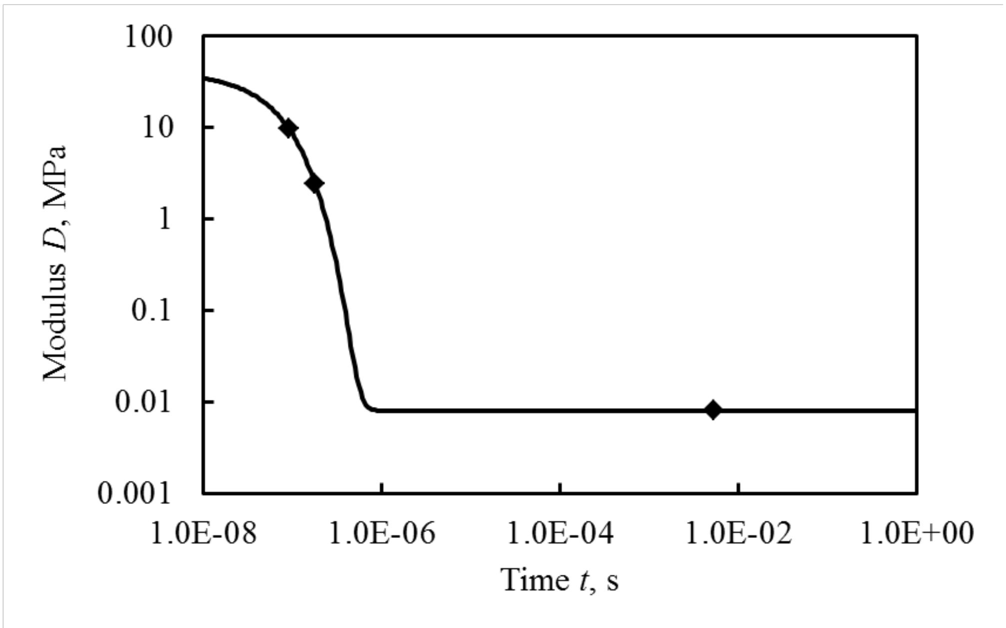
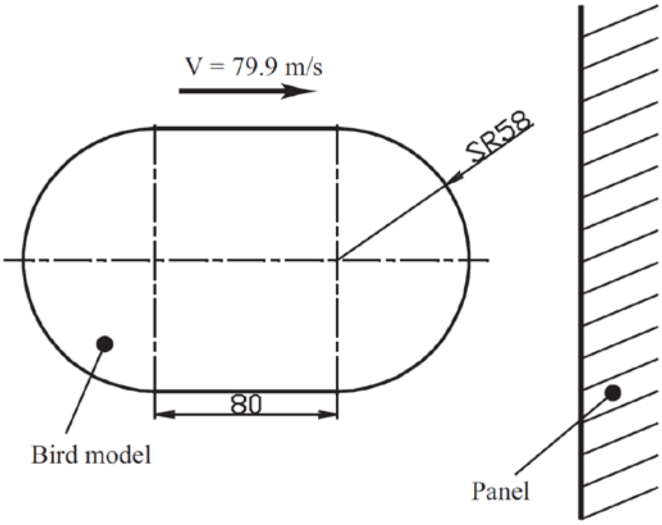


Figure 5. Identified viscoelastic property

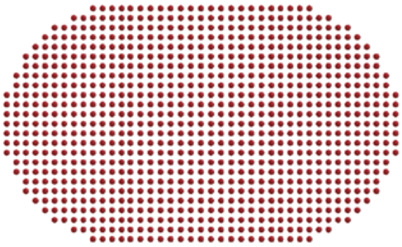
If the experimental result shown in Figure 4 is used, the relationship between the equations of Hermann and Peterson in the form of equation (7) can be defined as shown by the example in Fig. 5. The relationship defined in this manner can be applied to various simulations by using LS-DYNA. As an application of the defined relationship, a simulated collision imitating a bird strike is shown in Figure 6. This simulated result is calculated by the SPH method. In this simulated result, the situation representing the deformation of the viscoelastic body, which imitated a real bird finely deformed by the collision, is captured well. Thus, it is possible to analyze various problems related to bird collisions using the simulation procedure shown here.

Table 1. Material properties of bird-strike model

G_0[MPa]	G_∞[MPa]	β
1.34×10	2.67×10^{-3}	1.58×10^7

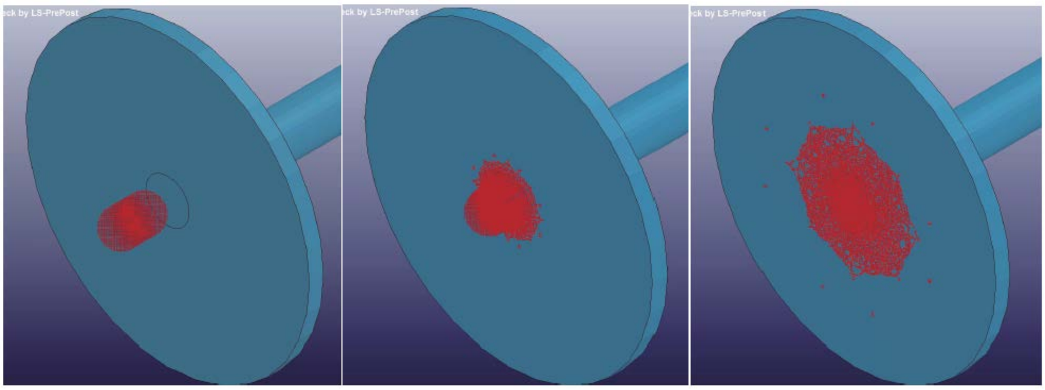


(a) Schematic showing bird-strike model for flat panel impact



(b) SPH bird model with 16041 particles

Figure 6. Numerical model of bird strike



(a) t = 0 [ms] (b) t = 1.5 [ms] (c) t = 3 [ms]

Figure 7. Simulated bird strike(M = 1.81 kg, V = 79.9 m/s)

Conclusion

The ball collision impact test system introduced in this paper can be used to quantitatively evaluate material deformation at the subsonic level. Dynamic evaluation of the impact of bird strike on the airplane can be realized in more detail by numerical analysis using the results presented this paper. Many problems related to bird strike will be analyzed by using this method in the future.

Acknowledgement

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References

[1] FAA-USDA report, Wildlife Strikes to Civil Aircraft in USA, 1990-2011, *Report of the Associate Administrator of Airports Office of Airports Safety and Standards, Airport Safety and Certification*, (2012), 6:8-13.
[2] Hertz, H., Ueber die Berührung fester elastischer Körper, *Journal für die reine und angewandte Mathematik (Crelle's Journal)*, (1882), 92: 156-171.
[3] Tani, M. Sakuma, A. and Shinomiya, M., Evaluation of Thickness and Young's Modulus of Soft Materials by using Spherical Indentation Testing, *Transactions of the Japan Society of Mechanical Engineers, Series A*, (2009), 75-755:901-908 (in Japanese).
[4] Tani, M. and Sakuma, A., Applicability Evaluation of Young's Modulus Measurement using Equivalent Indentation Strain in spherical Indentation Testing for Soft Materials, *Transactions of the Japan Society of Mechanical Engineers, Series A*, (2010), 76-761:102-108 (in Japanese).
[5] Sakuma, A., Desktop Robot to Measure the Elasticity of Any Objects by Palpation Mechanics, *Journal of the Japan Society of Mechanical Engineers*, (2013), 116-1134:355 (in Japanese).
[6] Gladman, B., *LS-DYNA® Keyword User's Manual (Version 971) - Volumes II*, (2013), 2-61.