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A Study on Optimality of Fiber Direction of Bursting Fruit with Spiral Motion

Jiro Sakamoto[1], Yasuhiro Endo[2], Yuta Koshimura[3]

[1] Kanazawa University, Kanazawa, Ishikawa, Japan, sakamoto@se.kanazawa-u.ac.jp
[2] Aishin Engineering Co., Kariya, Aichi, Japan
[3] Tsudakoma Co., Kanazawa, Ishikawa, Japan

1. Abstract

Plant seeds are moved in a variety of ways. Wind, insects or animals carries them sometimes. Dispersion by bursting pericarp is a typical movement of plant seeds that is self-active and independent of other creatures. Hereafter, pericarp means wall of fruit, which contains and disperses the seeds. If a pericarp can burst powerfully and spread seeds widely, it is advantageous in expanding the breeding grounds of a plant. So, the bursting mechanism of a pericarp of existent plants seems to be adapted mechanically and structurally. We clarified that fruit of the Impatiens have outstanding function to disperse seeds far away in previous study. The impatience is a kind of autochore plant, that the fruit accumulates stress to burst by swelling, and the pericarps perform roll up motion while bursting. It became clear that pre-burst stress distribution of the pericarp is advantageous to make it large and fast motion for spreading seeds. Knowledge obtained in the study is useful to understand the autochore mechanism. In addition to this, there are various kinds of autochore plant that have different bursting mechanism of fruit. We focused on bursting fruit of the Vicia angustifolia in this study. Fruit of the Vicia angustifolia accumulates stress to burst by drying up, and the pericarps scatter seeds by their spiral motion. Laminated structure and fiber tissue arrangement in the pericarp seems very important to consider the bursting mechanism. In this study, the bursting motion was captured by a high-speed video camera. Anisotropic mechanical properties of the pericarp were determined, and the finite-element model considering the anisotropy was created based on 3D scanning of actual fruit of the Vicia angustifolia. Computer simulation of the pericarp bursting motion by finite-element method was compared to actual motion to validate the finite-element model, and mechanics of the fruit bursting was considered. Configuration and time at maximum deformation occur in the simulation was consistent with actual motion. It was validated that structure and mechanical properties of the FE model was effective. Parametric study changing the fiber direction in the pericarp was carried out to evaluate optimality of the fiber direction for spreading seeds. It was clarified that optimal fiber direction was found to achieve faster and larger motion of the pericarp, and the optimal fiber direction was almost same as actual one. Furthermore, FE model of total fruit composed of a pair of pericarps and included seeds was developed and effectiveness of the model was ensured.

2. Keywords: Fibrous Composite, Laminated Structure, Biomechanics, Plant Fruit, and Spiral Motion.

3. Introduction

Plant seeds are moved in a variety of ways. Wind, insects or animals carries them sometimes. Dispersion by bursting pericarp is a typical movement of plant seeds that is self-active and independent of other creatures [1]. Hereafter, pericarp means wall of fruit, which contains and disperses the seeds. If a pericarp can burst powerfully and spread seeds widely, it is advantageous in expanding the breeding grounds of a plant. So, the bursting mechanism of a pericarp of existent plants seems to be adapted mechanically and structurally. We clarified that fruit of the Impatiens have outstanding function to disperse seeds far away in previous study [2]. The impatience is a kind of autochore plant, that the fruit accumulates stress to burst by swelling, and the pericarps perform roll up motion while bursting. It became clear that pre-burst stress distribution of the pericarp is advantageous to make it large and fast motion for spreading seeds [3]. Knowledge obtained in the study is useful to understand the autochore mechanism. In addition to this, there are various kinds of autochore plant that have different bursting mechanism of fruit.

We focused on bursting fruit of the Vicia angustifolia in this study. Fruit of the Vicia angustifolia accumulates stress to burst by drying up, and the pericarps scatter seeds by their spiral motion. Laminated structure and fiber tissue arrangement in the pericarp seems very important to consider the bursting mechanism. In this study, the bursting motion was captured by a high-speed video camera. Orthotropic mechanical properties of the pericarp were determined, and the finite-element model considering the orthotropy was created based on 3D scanning of actual fruit of the Vicia angustifolia. Computer simulation of the pericarp bursting motion by finite-element method was compared to actual motion to validate the finite-element model, and mechanics of the fruit bursting was considered. Furthermore, parametric study changing the fiber direction in the pericarp was carried out to evaluate optimality of the fiber direction for spreading seeds.

4. Materials and Method

4.1. Structure of the Vicia angustifolia Fruit

The Vicia angustifolia (Vicia sativa subsp. nigra) is leguminous plant, known as Common Vetch, height of grass is 60-150 cm, and it can be often seen at the roadside in whole Japan. Fruit of the Vicia angustifolia consists of a pair of pericarps the length of which is about 4.5 cm and it includes seed of from 6 to 10. Color of the fruit turns black from green, as it ripen and dry, shown in figure 1(A) and (B). When dryness of the fruit progresses more, a pericarp junction is fracture, and then seeds are scattered by high-speed spiral motion of the pericarps. Figure 1(C) shows spiral shape of a fruit after bursting. In generally, the pericarp of seed plant is constituted by three layers, which are endocarp, mesocarp and epicarp, as shown in figure 2. Fiber tissue exists along a specific direction in the endocarp and epicarp of the Vicia angustifolia. Microscope observation of the tissue showed angle of the fiber direction to long axis of the fruit is about 40 degree in endocarp and -50 degree in epicarp. The fiber directions of endocarp and epicarp are orthogonal each other as shown in figure 2(B). It can be considered that pericarp of the Vicia angustifolia is a fiber reinforced cross-ply laminate.

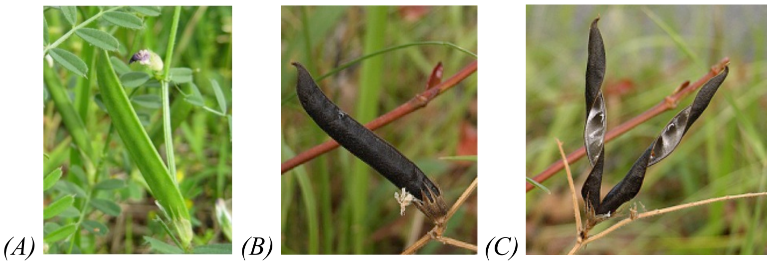
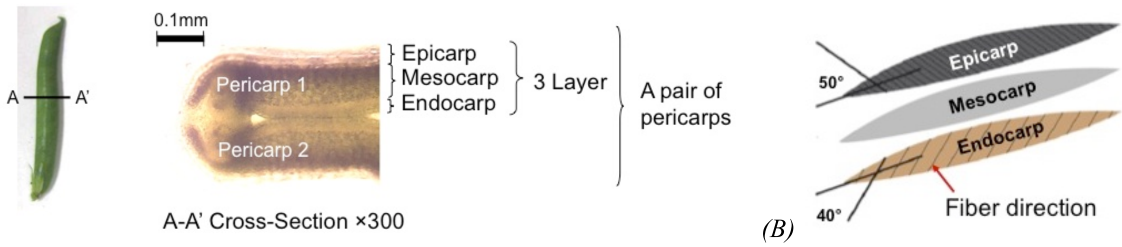


Figure 1. A fruits of Vicia angustifolia before drying (A), before bursting (B) and after bursting (C).



(A) (B)

Figure 2. The composite structure of a fruit pericarp of Vicia angustifolia. (A) The microphotograph of A-A' cross-section of the fruit. (B) The three layered structure of the fruit pericarp.

4.2. Bursting Motion of the Fruit

The bursting motion of the fruit was recorded by a high-speed video camcorder (nac Image Technology, MEMRECAM fx-k3) with 3000 frames per second. An example of bursting motion images of a fruit is shown in figure 3. In the experiment, a pericarp was picked with stalk just before bursting, and the stalk of the pericarp was fixed on a steel rod using adhesive tape. Orientation of the fruit was set as same as natural condition where tip of the fruit has turned to the slant top. A hot wind was given to the fruit by using a hair dryer to dry and induce fruit burst. According to the images, after the pericarp sheet junction was ruptured, the pericarps opened bilateral symmetrically and then simultaneously twisted spirally to longitudinal direction. When the fruit tip turns to the top, the pericarps twist in the direction of outside, so they can eject seeds upwards. Inside the fruits, seeds were arranged mostly at equal intervals. The pericarp tip moved most quickly. Therefore, a seed at the tip side was ejected farther away, and a seed was ejected closer at the root side. It is probably effective to scatter seeds by the wider range. The bursting motion happens in a very short period. The elapsed time from rupture of the pericarp junction until spiral motion completed was about 2 msec.

4.3. Experiments to Determine Mechanical Properties

Tensile test was carried out to obtain mechanical properties of the Vicia angustifolia pericarp. The endocarp specimen was taken by separating from pericarp, and then tensile tests were done along to the direction of fruit longitudinal axis and the fibrous direction. Since the mesocarp and epicarp were not able to separate, the tensile test for whole pericarp in longitudinal direction was performed. Each tensile test specimens are shown in figure 4. Mechanical properties were determined by using tensile test result of the endocarp and whole pericarp, and by assumption using literature value [4]. Tensile test machine (Shimazu Co., Autograph AG-5000B) was used while crosshead speed is 1mm/min. 5 specimens were tested for each case, and the average values were used.

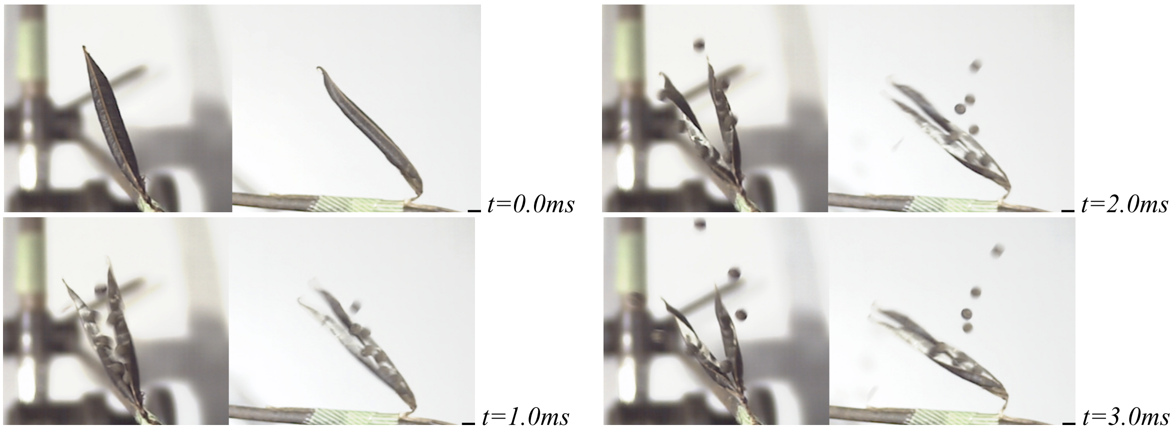


Figure 3. Sequential images during a fruit burst taken by high-speed video camcorder from two directions.

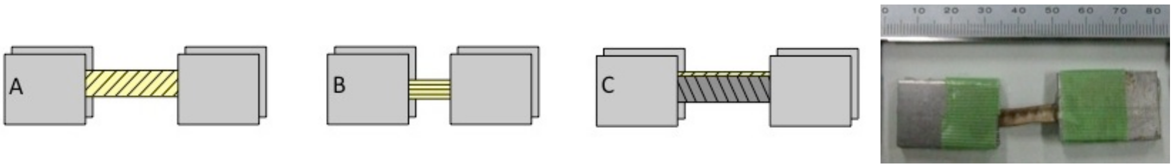


Figure 4. The tensile test specimens of Vicia angustifolia pericarp. Specimen A is endocarp one along fruit longitudinal direction. Specimen B is endocarp one along its fiber direction. Specimen C is pericarp one composed endocarp, mesocarp and epicarp along fruit longitudinal direction. Right photo is a pericarp specimen (specimen C).

4.4. Finite-Element Modeling

Scan of a pericarp shape before bursting was carried out by 3D scanning machine (Roland, 3D Laser scanner LPX-600) . The scanning surface data was outputted in STL form to the Patran (MSC Software Co.), which was preprocess software of finite-element analysis (FEA). The B-Spline curves were applied to the nodes of STL data, and then the curved surface model was created using the Patran. The surface model is shown in figure 5(A), and the finite-element model based on the surface model is shown in figure 5(B). Finite-element modeling and analysis were performed using the Marc & Mentat (MSC Software Co.). The mesocarp was discretized to solid elements, and the endocarp and epicarp were discretized to shell elements that have orthotropic material properties. The angle of the epicarp fiber direction to the longitudinal direction θ was set as 50 degree, and the endocarp fiber direction was set as orthogonal it. The same material properties as the endocarp were given to the junction part between pericarps. Contraction of the fiber by drying was given as equivalent heat contraction in the FEA. Orthotropic contraction ratio of the Quercus acuta Thunb (Fagales) [4], which is related species to the Vicia angustifolia (Fabales), was used for the endocarp elements. Contraction ratio of the epicarp elements was empirically assumed as 2/5 of endocarp one.

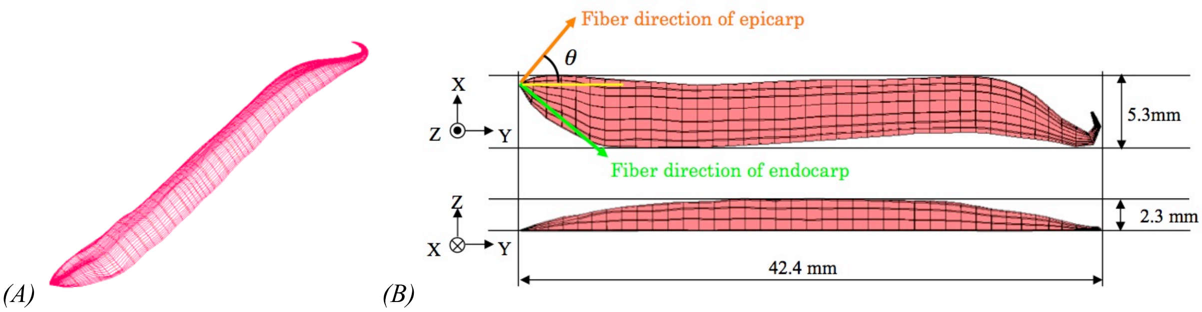


Figure 5. (A) The surface model of the Vicia angustifolia fruit taken by 3D laser scanner. (B) Finite-element model of the fruit pericarp based on the surface model.

5. Results and Considerations

5.1. Mechanical Properties of the Pericarp

Elastic modulus of specimen A, B and C was 3.2GPa, 4.0GPa and 2.3GPa on the average, respectively. Young's modulus of endocarp in fiber direction E_1 was equal to elastic modulus of specimen B. Orthotropy of Young's modulus of endocarp E_1/E_2 was assumed 8 as same as wood tissue [4], because endocarp tissue after dry up was similar to wood tissue. Relationship of shear modulus G and E_1 was also assumed as $G=0.08E_1$ according to same literature. Epicarp was also followed to the assumption. Orthotropic Young's modulus and Poisson's ratio of endocarp were determined by using the assumption and tensile test results of specimen A and B. Mesocarp tissue was assumed as isotropic, soft and incompressible, so the Young's modulus was given as 1/10 E_2 of endocarp and the Poisson's ratio was given as 0.49. Mechanical Properties of epicarp were calculated using theory of elasticity for cross-ply laminate. Elastic modulus of each layer in fruit longitudinal direction was satisfied following equation.

$$E_C = \frac{E_{end} t_{end} + E_{mes} t_{mes} + E_{epi} t_{epi}}{t_{end} + t_{mes} + t_{epi}} \qquad (1)$$

Where, E_{end}, E_{mes} and E_{epi} is elastic modulus of endocarp, mesocarp and epicarp in fruit longitudinal direction, and t_{end}, t_{mes} and t_{epi} is their thickness, respectively. E_C is elastic modulus of pericarp specimen C. The mechanical properties giving to the FEA are shown in Table 1.

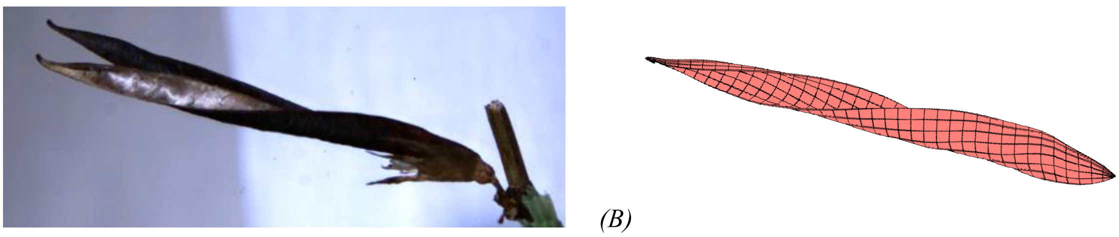
Table 1. Material properties. Young's modulus (E_1, E_2), shear modulus (G) and Poisson's ratio (ν_{12}, ν_{21}) of endocarp, mesocarp and epicarp of the pericarp.

Layer	Thickness[mm]	E_1 [MPa]	E_2 [MPa]	G [MPa]	n_{12} [-]	n_{21} [-]
Endocarp	0.15	4016	502	321	0.56	0.07
Mesocarp	0.01	50.2	50.2	17.9	0.49	0.49
Epicarp	0.08	3232	404	258	0.56	0.07

5.2. Finite-Element Analysis

Deformation of pericarp after bursting is shown in figure 6 comparing actual one and the finite-element model obtained static analysis as equivalent drying contraction. One spire was observed in each deformation, and these configurations conform each other very well. Figure 7 shows a sequence of the pericarp motion and its principal stress distribution in bursting simulation by dynamic analysis. The maximum deformation occurred about 2msec after starting of burst, and then deformation of reversion was observed until end of the simulation (3msec). The bursting time and spiral motion of the pericarp in the simulation agree well to the actual one shown in Figure 3.

Since burst deformation of the actual pericarp was reproducible by the created finite-element model, it was thought that the mechanical properties, the shape and composite of structure, and the boundary conditions given to the model were appropriate. For especially, the spiral deformation probably depends on material properties such as orthotropic elasticity and contraction. Although several assumptions were introduced to determine the material properties, these assumptions seem to be reasonable. The finite-element model must be effective to discuss influence of fiber tissue direction to bursting motion and performance of seed spreading.



(A) *(B)*

Figure 6. Profile comparison between (A) actual pericarp and (B) the finite-element model after bursting. Equivalent drying contraction was applied to the finite-element analysis in static condition.

5.3. Influence of Fiber direction on Pericarp Deformation

Burst motion simulation by using the finite-element model was performed with changing fiber direction to evaluate its influence on pericarp motion. θ, which was the angle of epicarp fiber to fruit longitudinal axis, was changed from 0 to 90 degree. It was assumed that fiber direction of endocarp kept orthogonal to one of epicarp in this simulation. Configuration and time when the pericarp deformation archived maximum as shown in figure 8 was evaluated. Larger spiral deformation occurred in case of θ=45, 50 and 55 degree in comparison with the other case. When θ approach 0 or 90 degree, spiral deformation of the pericarp become smaller. No deformation was occurred in case of θ=0 and 90. Reason of no deformation on θ=0 and 90 is considered that fiber direction is orthogonal to principal axis of pericarp curvature. Although bending deformation easily occurs in direction of curvature axis, such deformation is interfered by stiff fiber tissue in the case. Times to achieve maximum deformation were almost same of the all case, except for θ=0 and 90 degree. It means pericarp motion speed is faster in case of θ=45, 50 and 55 degree. If pericarp deformation is larger and motion speed is faster, it is advantageous to spread seed far away in wide area. Optimal fiber direction of epicarp is suggested as around θ=50 in this case. Natural fiber direction in epicarp of the Vicia angustifolia pericarp is also about 50 degree.

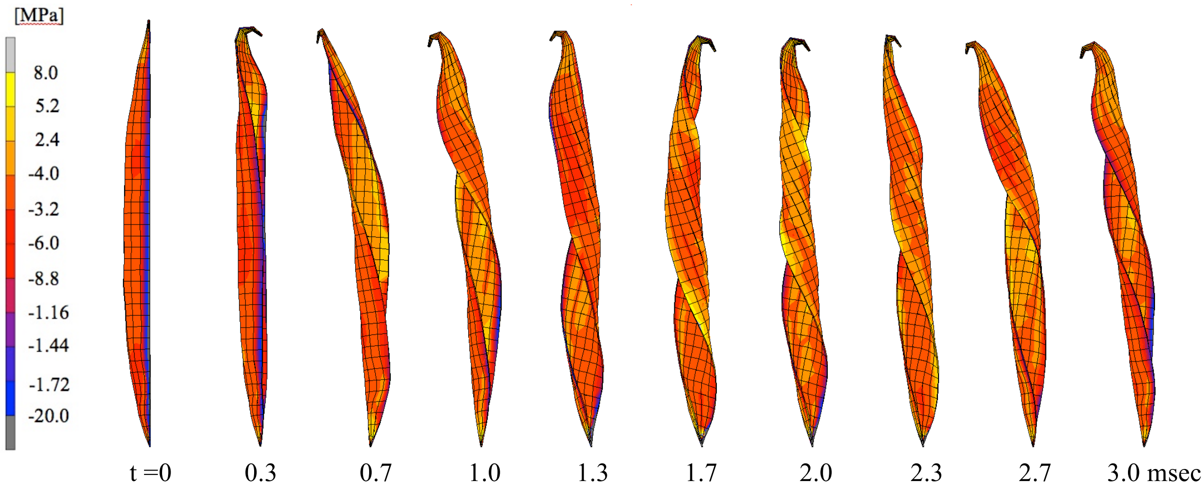


Figure 7. Deformation and stress distribution of the pericarp in dynamic bursting simulation by the finite-element analysis. Equivalent drying contraction was applied with fixed junction of the pericarp and the junction was suddenly released.

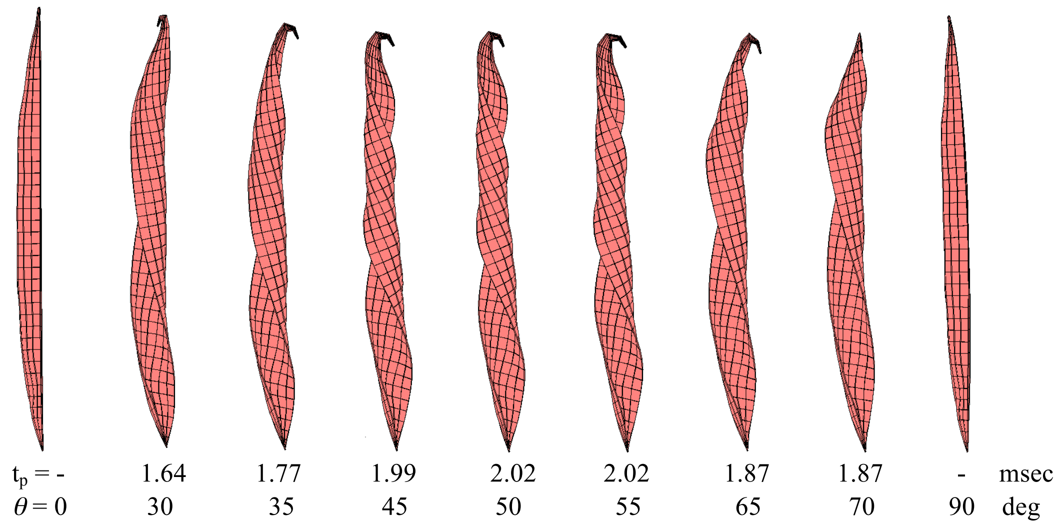


Figure 8. Configuration and time at maximum deformation with changing fiber direction (θ) of epicarp to longitudinal direction.

5.4. Simulation of Fruit Burst and Spreading Seeds

The burst motion simulation described above had limitations. Only one pericarp was considered however fruit of the Vicia angustifolia composed of two pericarps. Bursting motion of the pair of pericarps is symmetrical, so that the simulation considering one pericarp is reasonable. One of important limitation is no consider seeds inside of the fruit. Fruit of the Vicia angustifolia has generally from 6 to 10 sphere seeds, average diameter and weight of the seed is 2.8mm and 14.5mg by our measurement. The seeds are arranged in one row along fruit longitudinal axis. To discuss optimality of the fruit structure for spreading seed, it is necessary to make a finite-element model of total fruit composed of two pericarps and includes seeds. We made a finite-element model of the Vicia angustifolia fruit and performed simulation of fruit burst and spreading seeds. Pericarp models of both sides were created giving them symmetrical shape and direction of fibers. Icosahedron seed models were created to approximate sphere seed, because of time consuming of computation. Seven seed models put in the fruit model. The finite-element model of fruit and seeds is shown in figure 9. Contact condition without friction was set between seeds and pericarps. Interface of each pericarp was tied in initial condition, and then equivalent heat contraction correspond to drying was given to the pericarps. Tying of pericarp interface was released lastly. Stalk side nodes of the pericarps was always fixed in the simulation. The simulation of fruit burst and spreading seeds is shown in figure 10 comparing images taken by high-speed video. In the simulation and the experiment, deformation of pericarps and time of seed ejection correspond well each other. The finite-element model of fruit is valid and effective to discuss performance of seed spreading.

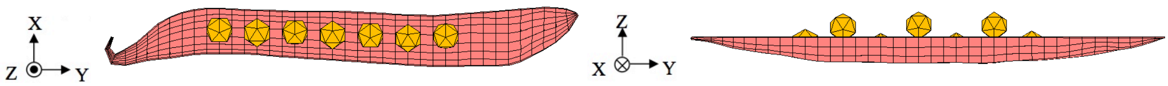
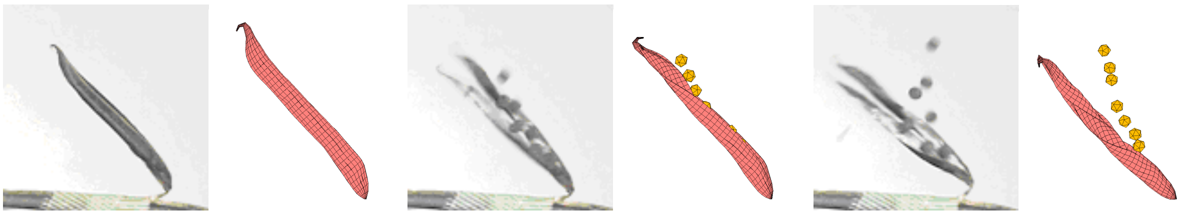


Figure 9. The finite-element model of the Vicia angustifolia fruit considering seeds. Left is lateral view and right is frontal view. Only half side pericarp is shown to make observation of the seeds.



t=0msec *t=1msec* *t=2msec*

Figure 10. Sequential images during a fruit burst taken by high-speed video camcorder and the computer simulation

Computer simulations of the spreading seeds were performed by varying the fiber direction θ, to consider optimality of the fiber direction in the pericarp. We assumed the fruit model located 150mm height from the ground and its longitudinal direction was 60 degree from horizontal line same as normal natural condition shown in figure 11. Ejecting velocities of the seeds and their ejecting directions were computed by using the computer simulation on the assumption. Drop positions of the seeds on the grounds were calculated from the ejecting velocities and directions as point mass motion. Air drag and roll over on the ground were neglected in the calculation. We evaluated frying distances and Voronoi area of the seeds dropped on the ground. Voronoi regions are determined by distances to a specified family of objects (points) in the space. It relates to territory or influential zone. Voronoi area was calculated to the square region 2.4x2.4 [m^2] in this study.
Calculated frying distances of the seeds for the case of fiber direction 30, 35, 50, 65 and 75 degree are shown in figure 12. It was difficult to find an optimality of a fiber direction on the frying distances of the seeds in this chart. Although no advantage was observed in the actual fiber direction 50 degree in comparison with the others, same tendency was found in the fiber direction 35 and 50 degree. Top three seeds flew long distance from 0.8 to 1.7m. On the other hand, bottom four seeds flew short distance less than 0.4m. The farther seed group has advantage to expand vegetation region, and the closer seed group can keep their original territory. It is also important a seed drops at same place of the fruit, because Vicia angustifolia is a yearly plant that the parent died before next growth season.
Examples of Voronoi region are shown in figure 13(A) for the fiber direction 35 and 50 degree. The seeds were dispersed along X direction in the case of θ=35 degree. On the other hand, the seeds were dispersed along both directions of X and Y in the case of θ=50 degree. Figure 13(B) shows standard deviation of Voronoi area of the seeds that denote unevenly of each seed's territories. Even territories are better for growth of the seeds because they can prevent to fall together. Dispersion of the seed territories is minimum in the case of θ=50 degree. It was suggested that actual fiber direction of the pericarp was advantageous to spread seeds on the ground uniformly.

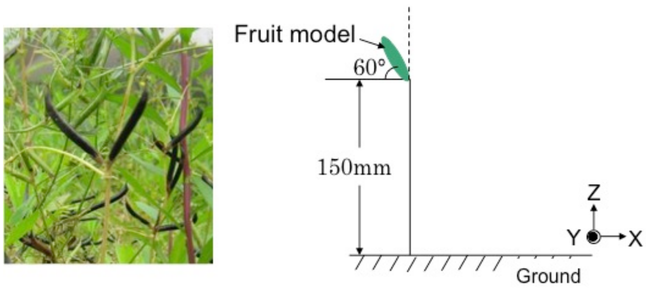


Figure 11. The position of the fruit model in the computer simulation spreading seeds. Left photograph shows natural position of fruits of Vicia angustifolia. X is forward, Y is side and Z is upward direction of the fruit model in the simulation.

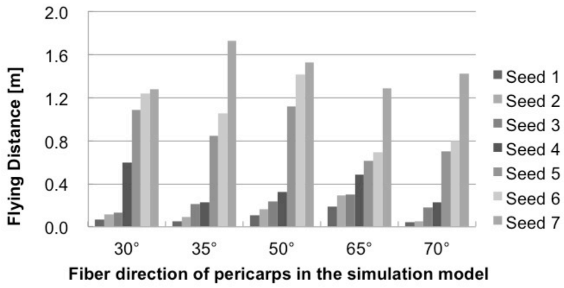


Figure 12. Frying distances of each seeds vs. fiber direction of the pericarp in the computer simulation

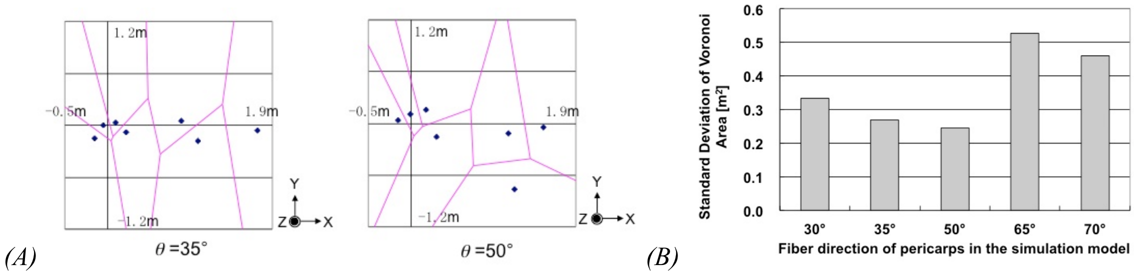


Figure 13. Evaluation of seed spreading by using their Voronoi area in the simulation (A) Examples of seed distributions and their Voromoi regions (θ=35 and 50 degree) (B) Standard deviation of Voronoi area of the seeds vs. fiber direction of the pericarp.

6. Conclusion

We focused on bursting motion of the Vicia angustifolia fruit to clarify optimality of the structure, especially for fiber tissue effect in the pericarp. Bursting motion of the fruit was captured by a high-speed video camcorder, and orthotropic mechanical properties of the pericarp were determined based on tensile test, orthotropic theory and theory of elasticity for cross-ply laminate. The finite-element model considering the orthotropy was created based on 3D scanning of actual fruit. Computer simulation of the pericarp burst motion by the finite-element method was compared to actual motion. Configuration and time at maximum deformation occur in the simulation was consistent with actual motion. It was validated that structure and mechanical properties of the FE model was effective. Parametric study changing the fiber direction in the pericarp was carried out to evaluate optimality of the fiber direction for spreading seeds. It was clarified that optimal fiber direction was found to achieve faster and larger motion of the pericarp, and the optimal fiber direction was almost same as actual one. Furthermore, FE model of total fruit composed of a pair of pericarps and included seeds was developed and effectiveness of the model was ensured. Flying distances of the seeds and Voronoi area of the seeds dropped on the ground were evaluated by the computer simulation of spreading seeds with varying the fiber direction of the pericarp. The actual fiber direction of the pericarp could be optimal to spread the seeds uniformly.

7. Acknowledgements

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8. References

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