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Professor Hayashi's brilliant activities in composites research

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Professor Hayashi's brilliant activities in composites research

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1. INTRODUCTION

We deeply miss Professor Tsuyoshi Hayashi who passed away on February 2, 1998 at the age of 87. Through more than 60 years' activities, Prof. Hayashi made a significant academic contribution to the fields of aircraft structures, composites, biomaterials and others. He presented hundreds of research papers, published more than 10 books, served in a number of committees, and was invited frequently to domestic and international conferences.

Because of his great activity and his warm character, he was often amiably called the 'Godfather' among our composite community. It is practically impossible to cover all of his achievements in a short article, as his accomplishments spanned so many different areas.

Since the author is one of Professor Hayashi's last students, he is not very familiar with Professor Hayashi's early work. However, he feels obligated to review and commemorate Professor Hayashi's achievements, some of which are reported here.

In this article, we focus mainly on the three subjects in which he excelled: orthotropy, short fiber composites, and hybrid composites.

2. ORTHOTROPY

Professor Hayashi's research career started with a study on buckling of stiffened thin-walled structures and soon shifted to a study on buckling of wooden structures. That was just before and during World War II when Japan experienced a chronic shortage of almost all goods and materials. Japan could not import, for example,

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aluminum for aircraft. For this reason, wood was used as an alternative material to metal for aircraft structures. Professor Hayashi conducted mechanical tests on almost all kinds of woods available in Japan at that time. This, in fact, turned out to be beneficial for Professor Hayashi for his later career because he was forced to study the nature of anisotropy, which is one of the most important characteristics of composites.

In 1946, he submitted his doctoral dissertation entitled 'Theory of Elasticity of Orthotropic Structures' to the University of Tokyo and received his Doctor of Engineering degree in 1947. Although the author does not have Professor Hayashi's original dissertation at hand, most of its contents can be retrieved from the memorial book at his 61st anniversary published in 1973 [1].

The contents of his thesis cover a wide range of topics. The table of contents are:

Chapter 1. Introduction,

Chapter 2. Fundamental equations for orthotropic bodies,

Chapter 3. General solution for shear, bending and torsion problems of orthotropic bodies,

Chapter 4. Stress analysis of stiffened plates treated as orthotropic plates,

Chapter 5. Buckling theory of orthotropic plates,

Chapter 6. Buckling theory of orthotropic cylinders,

Chapter 7. Conclusions.

Research on anisotropic elasticity in the field of crystals began in the last century, which is much earlier than Professor Hayashi's work. In the Introduction part of his dissertation, Prof. Hayashi reviewed previous works by W. Voigt, M. T. Huber, E. Seydel, M. Yamana, D. D. Dschou, O. S. Heck, G. I. Taylor, R. E. Green, K. Ikeda, and others. However, this does not in any way undermine the originality of Professor Hayashi's work.

Here is an example of such originality. Everybody knows nowadays the following expression for computing the shear modulus for orthotropic plates from experiments:

$$\frac{1}{G_{\mathrm{LT}}} = \frac{4}{E_{45}} - \frac{1}{E_{\mathrm{L}}} - \frac{1}{E_{\mathrm{T}}} + 2\frac{\nu_{\mathrm{LT}}}{E_{\mathrm{L}}}, \tag{1}$$

where G_{LT} is the shear modulus with respect to the LT coordinate, E_{L} and E_{T} are Young's moduli in the L and T directions, E_{45} is Young's modulus in the direction of 45° from the principal direction, and ν_{LT} is Poisson's ratio (see Fig. 1). Thus, if we measure the material constants in the right-hand side in equation (1), we can calculate the shear modulus, G_{LT}.

Another equation to get the shear modulus is

$$G_{\mathrm{LT}} = \frac{E_{45}}{2(1 + \nu_{45})}, \tag{2}$$

which is much more convenient than equation (1) because only E_{45} and ν_{45} are needed.

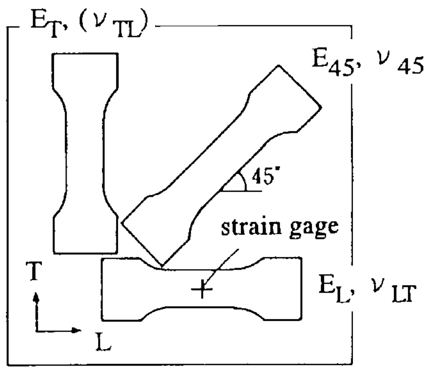

Figure 1. How to 'calculate' GLT.

These equations were first derived by Prof. Hayashi, not by those in the crystal research field. However, these equations were not presented in his dissertation but appeared in the paper published in 1941 [2]. Lekhnitskii's book [3] is often cited in the anisotropy literature but Professor Hayashi's work was conducted much earlier. In addition, he used the nomenclatures and terminologies that were familiar to us working in composites research. In other words, Professor Hayashi guided those of us who were trained as engineers, to open our eyes to the world of anisotropic elasticity theory.

To the knowledge of the author, FRPs were first developed in the US in the early 1940s and naturally Professor Hayashi was not aware of such a development at that time; he used woods for his experiments.

However, his contribution at that time is still alive and valuable. Because his dissertation was written in Japanese, it was not widely distributed worldwide even though it contained many novel findings.

3. SHORT FIBER COMPOSITES

In 1958, Professor Hayashi presented a paper written in Germany that discussed fiber-matrix interaction by a model where one short fiber was embedded in an infinite matrix [4]. In the field of short fiber composites, Cox's work [5] is recognized as the first, and it was to be followed by many other researchers. Cox's analytical model was essentially a shear-lag analysis. On the other hand, Professor Hayashi approached the subject from a viewpoint of theory of elasticity. The basic equation is the following integral equation with singularity:

$$\int_0^1 \frac{u}{u^2 - p^2}\tau(u)\,\mathrm{d}u + \lambda \int_p^1 \tau(u)\,\mathrm{d}u = C_0, \tag{3}$$

where $\tau(u)$ is the shear stress along the fiber/matrix interface. The singularity was

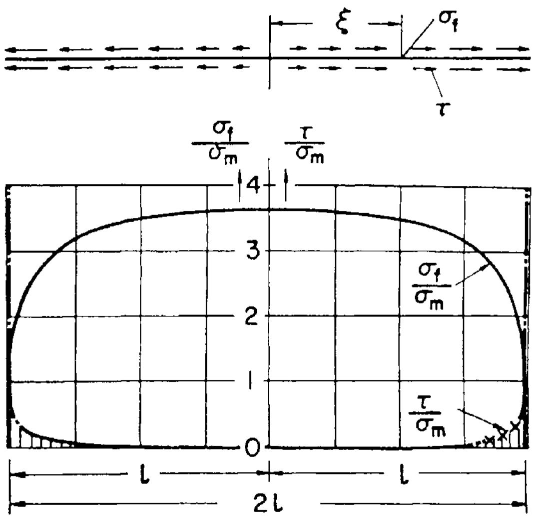

Figure 2. Axial and interfacial shearing stresses in a short fiber model [6].

removed by introducing Cauchy's principal value. Using Fourier series expansion and Galerkin's method, he obtained a set of algebraic equations. At that time, digital computers were not widely available so Professor Hayashi and his co-workers used a hand-held mechanical calculator known as the 'Tiger Calculator' in Japan. He later refined this formula [6]. Figure 2 is an example of the fiber axial stress and fiber/matrix interfacial stress distributions.

His paper was referred to by many researchers. For example, in the work of Cohen *et al.* [7] that discussed the stress distribution of multi-fiber model, they cited Hayashi's work. On the other hand, Bürgel *et al.* [8] did not cite Hayashi's work even though their basic equation shown below is essentially the same as equation (3):

$$\int_{-1}^{1} \frac{f(\xi')}{\xi - \xi'} \, d\xi' + \frac{1}{K(\xi)} \int_{-1}^{\xi} f(\xi') \, d\xi' = 1. \tag{4}$$

Although the present author does not criticize Bürgel for not quoting Hayashi's work, the author feels sorry again on behalf of Professor Hayashi as he published the result in the proceedings of a conference, not in an academic journal.

4. HYBRID COMPOSITES

The year 1972 may be called the 'year of the hybrid' because many papers on hybrid composites were published in this year. Among them, however, Hayashi's paper [9] was the only one that survived the next 20 years, if some exaggeration is allowed.

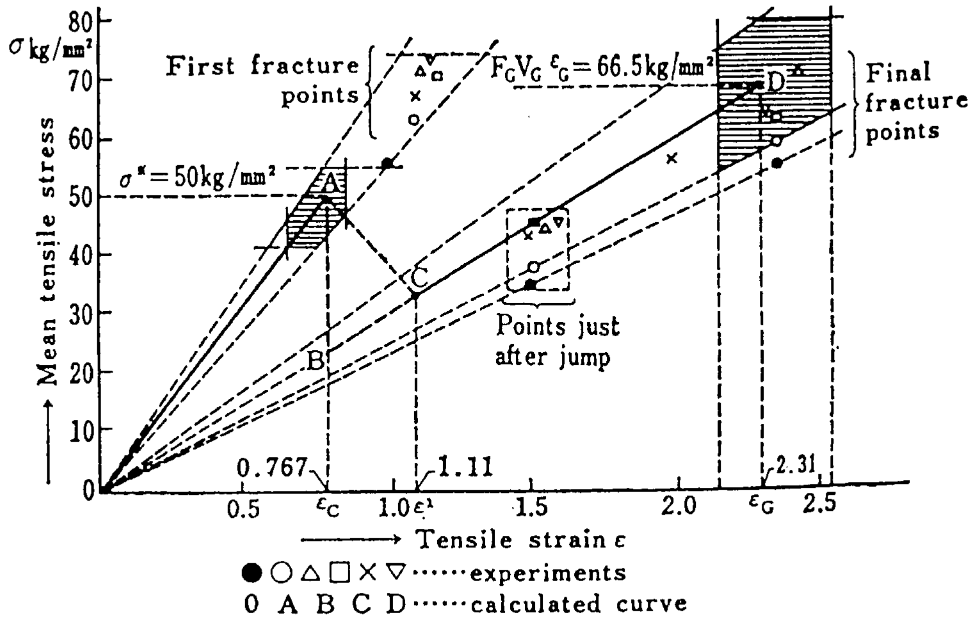

Figure 3. The hybrid effect (original figure, ref. [9]).

Carbon fibers manufactured at that time were more brittle than those of today. According to Hayashi's experiment, the failure strain of CFRP was 0.767%. So he tried to combine carbon fibers with glass fibers which have larger failure strain, of the order of 3%. This idea is neither novel nor surprising itself; everybody thought about the same.

However, Professor Hayashi's brilliant point is as follows: when CF prepregs and GF prepregs were interlaminated, the failure strain of CF parts increased from 0.767% to 1.1% (see Fig. 3). Surprisingly, a synergistic effect occurred! Professor Hayashi called it the 'hybrid effect'.

More interestingly, this discovery caused an instant sensation that provoked heated debates. The first debate seems to have taken place at the ICCM-1 [10], although the session atmosphere was calm and moderate. But Phillips' report [11] is still vivid and interesting, more exciting than a top-level 'action movie'.

Intense discussion of the hybrid effect continued. After Phillips' report [11], Bunsell [12] immediately presented his opinion based on his original work [13]; the essence of Bunsell's explanation on the hybrid effect is the thermal stress induced during the fabrication. Because the thermal stress was able to explain only one third of the hybrid effect, Zweben [14] tried to understand the hybrid effect by a statistical approach, later modified by the present author [15].

Although the author cannot judge this intense discussion by himself, it provides an example of the way science and engineering advances through these kinds of debates. At any rate, Professor Hayashi should be congratulated for his having played such an important role in this matter.

5. OTHER ACTIVITIES

The following are some short comments on other activities of Professor Hayashi.

5.1. Interlaminar shearing stress

The work of Professor Byron Pipes [16] is famous concerning the ILSS; but Professor Hayashi was also involved in this subject almost in the same time period. Unfortunately, the work of Hayashi–Sando [17] was presented at a conference only, and hence has secured less widespread distribution.

5.2. Compressive strength of unidirectional composites

No one can deny that Rosen's paper [18] presented a pioneering theory on the compressive strength of composites. In the shearing mode (Fig. 4), which occurs in most cases, the compressive strength is expressed as follows:

$$\sigma_c = G_m/(1 - V_f), \tag{5}$$

where σ_c is the compressive strength in the fiber direction of a unidirectional composite, G_m is the shear modulus of the matrix, and V_f is the volume fraction of fiber.

According to Hayashi [19], the compressive failure takes place due to the shear instability and his result is

$$\sigma_c = G_m. \tag{6}$$

5.3. Shape of aircraft

Professor Hayashi used to say that as airplane technology matured, the shape of aircraft would look similar to each other. For example, the planview and side view of the Boeing B747-200B are very similar to those of the Ilyusin I 1-86, although actually the size is different. Similarly, the same may be said for the Airbus A310 with respect to the B737 and the A330 to the B777. Figure 5 is one such example [20]. One day the author tried to debate with him saying, 'If the shape of

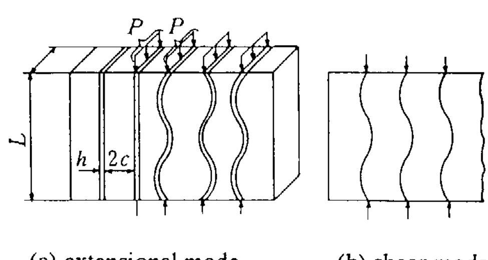

Figure 4. Microbuckling of fibers in a unidirectional model [18]. (a) Extensional mode; (b) shear mode.

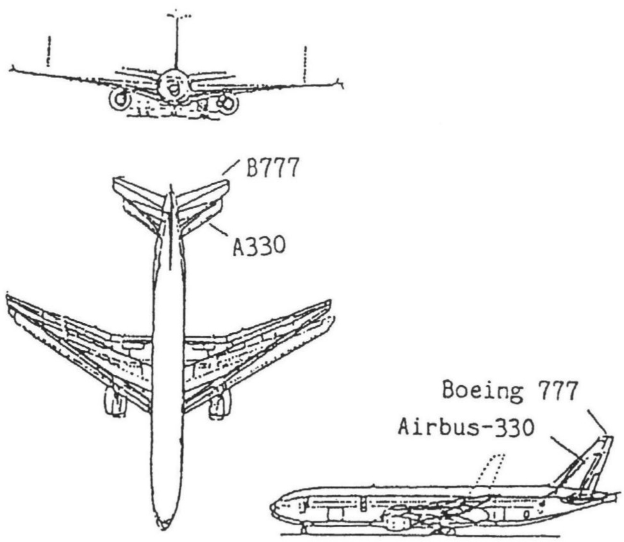

Figure 5. Matured airplanes resemble each other [20].

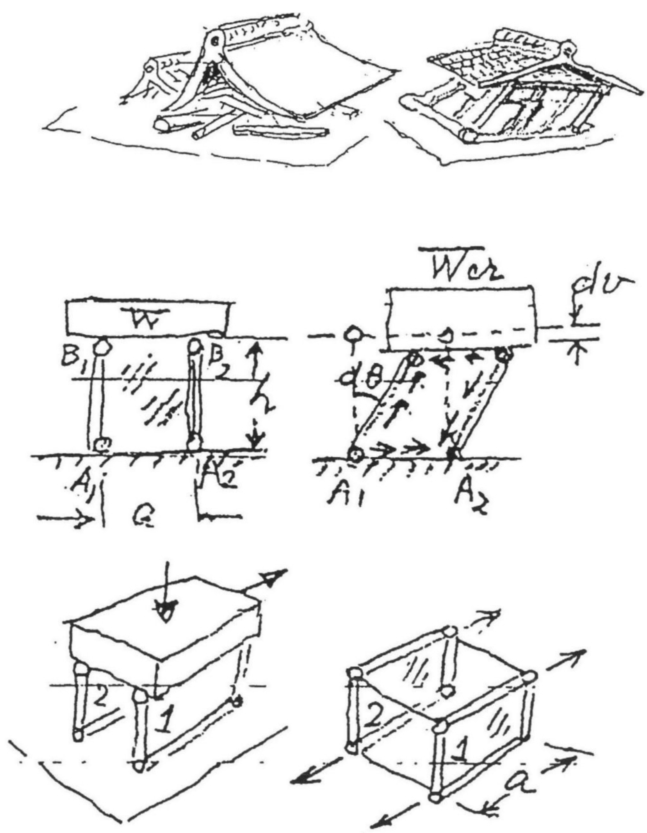

Figure 6. Shear buckling of a column-wall structure [21].

all aircraft is identical, then airplane engineers will have nothing to do'. Professor Hayashi went to another world without answering me.

5.4. Hanshin earthquake

In 1995, the terrible Hanshin Earthquake that took place in Kobe killed more than 6000 people. A tremendous number of buildings were destroyed. Professor Hayashi, in his mid-80's, discussed the collapse mechanism of buildings using his tiny hand-made model. His conclusion was: one major collapse mechanism might be shear instability due to axial compression, which was described in the preceding article of 'Compressive Strength of Unidirectional Composites'. Figure 6 is Professor Hayashi's hand-written figure to explain the case of the column and shear-wall model [21]. The author does not know whether Professor Hayashi's opinion is correct or not, but we must admire his never-ending activity.

In 1997, Dr. Philip Condit of the Boeing Company received his Doctor of Engineering degree from the Science University of Tokyo. Professor Hayashi arranged this ceremony and served as a committee member (see Fig. 7). This was his last official job.

Professor Hayashi is already in the heaven. However, his philosophy and soul remain strongly in the heart of many composite researchers. Let us pray for his soul.

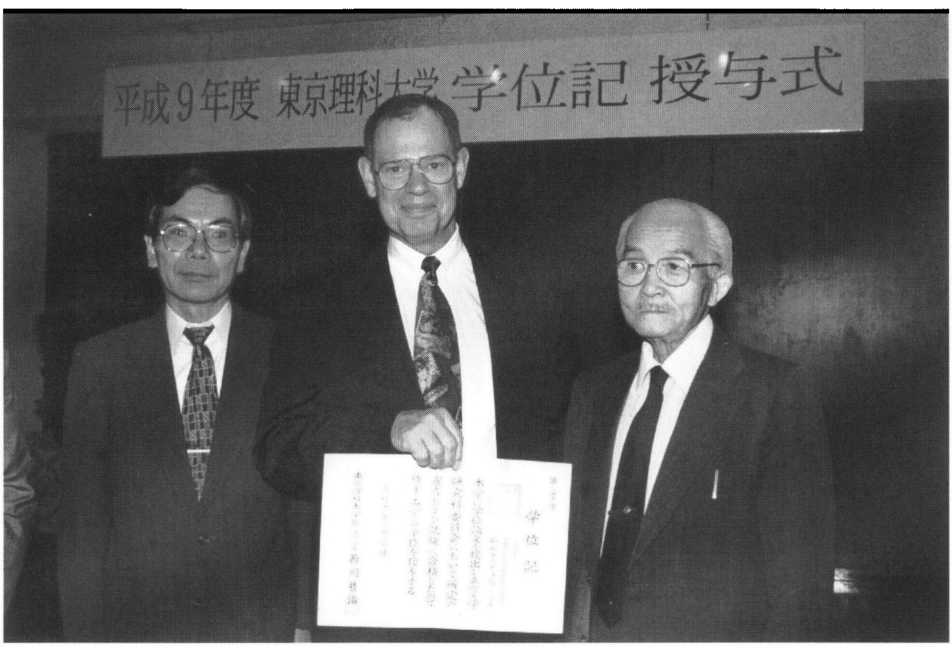

Figure 7. With Dr. Philip M. Condit (Sept. 1997).

REFERENCES

1. T. Hayashi, Anniversary Volume of Collected Papers of Tsuyoshi Hayashi (1973).
2. T. Hayashi, On the elasticity and stiffness of orthotropic plates, *J. Japan Soc. Aeronautics* **8** (79), 601–626 (1941) (in Japanese).
3. S. Lekhnitskii, *Theory of Elasticity of an Anisotropic Elastic Body.* English translation by P. Fern, Holden-Day (1963).
4. T. Hayashi, Photoelastische Untersuchungen der Spannungsverteilung in der durch Fasern Verstarkten Platte, in: *Proc. IUTAM Symp.*, Warsaw, pp. 501–511 (1958).
5. H. L. Cox, The elasticity and strength of paper and other fibrous materials, *Brit. J. Appl. Phys.* **3**, 72–79 (1952).
6. T. Hayashi, Reinforcement effect of fibers in fiber-reinforced plastics, in: *Proc. 5th Intl. Symp. on Space Tech. and Sci.*, Tokyo, pp. 683–694 (1963).
7. L. J. Cohen, Stress, strain and displacement fields in a composite material reinforced with discontinuous fibers, *J. Franklin Institute* **284**, 388–406 (1967).
8. B. Bürgel, A. J. Perry and W. R. Schneider, On the theory of fibre strengthening, *J. Mech. Phys. Solids* **18**, 101–114 (1970).
9. T. Hayashi, On the improvement of mechanical properties of composites by hybrid composition, in: *Proc. 8th Intl. Reinforced Plastics Conf.*, Brighton, UK, pp. 149–152 (1972); Also, T. Hayashi, Development of new material properties by hybrid composition (1st report), *Fukugo Zairyo (Composite Materials)* **1**, 18–20 (1972) (in English); T. Hayashi, K. Koyama, A. Yamazaki and M. Kihira, Development of new material properties by hybrid composition (2nd report), *Fukugo Zairyo (Composite Materials)* **1**, 21–25 (1972) (in English).
10. Discussion/Session 5A, in: *Proc. 1975 ICCM*, E. Scala, E. Anderson, I. Toth and B. R. Noton (Eds), Vol. 2, p. 442. Metall. Soc. AIME (1975).
11. L. N. Phillips, The hybrid effect — Does it exist? *Composites* **7**, 7–8 (1976).
12. A. R. Bunsell, Letter, *Composites* **7**, 158 (1976).
13. A. R. Bunsell and B. Harris, Hybrid carbon and glass fibre composites, *Composites* **5**, 157–164 (1974).
14. C. Zweben, Tensile strength of hybrid composites, *J. Mater. Sci.* **12**, 1325–1337 (1977).
15. H. Fukuda, An advanced theory of the strength of hybrid composites, *J. Mater. Sci.* **19** (3), 974–982 (1984).
16. R. B. Pipes and N. Pagano, Interlaminar stresses in composite laminates under uniform axial extension, *J. Compos. Mater.* **4**, 538–548 (1970).
17. T. Hayashi and S. Sando, Interlaminar shear stress distribution in a filament wound plate, in: *Proc. 8th Intl. Symp. on Space Sci. and Tech.*, pp. 291–302 (1969).
18. B. W. Rosen, in: *Fiber Composite Materials*, p. 37. ASM (1964).
19. T. Hayashi, On the shear instability of structures caused by compressive load, AIAA paper No. 65-750 (1965). Also, in: *Proc. 16th Japan National Congress for Appl. Mech.* I-20, pp. 149–159 (1966).
20. T. Hayashi, On the functional progress due to advanced composites and maturing of geometrical configurations in each epoch of developments in various structures with special reference to transport planes, in: *COMP '95*, Corfu, Greece (1995). (By mistake, this paper was not included in the Proceedings, *High Technology Composites in Modern Applications*, S. A. Paipetis and A. G. Youtsos (Eds). University of Patras. A copy is available separately from Prof. Paipetis).
21. T. Hayashi, On shear-instability buckling fractures — A discussion on the fracture modes of buildings at 'Hanshin Earthquake', *Advanced Materials and Harmonization* **4**, 1–7 (1996) (in Japanese).