# LESSONS LEARNED IN FULL COMPOSITE AERO-STRUCTURES DEVELOPMENT IN JAPAN

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## Abstract

*The research work accomplished by the author, the recipient of ICAS Award for Innovation in Aeronautics, Dr. Takashi Ishikawa, is briefly reviewed. His early research work was inspired mainly by the development of the full composites horizontal empennage model for the experimental STOL aircraft, named "Asuka" and developed in Japan in early 80's. From those days, the most widely applied composites were carbon fiber reinforced plastics: CFRP. His later research accomplishments related to the most serious drawback of CFRP, the mechanism of degradation in compression after impact (CAI) strengths is also reviewed. His final achievement is the one of the recent topics: research related to the low cost manufacturing technology, so-called vacuum assisted resin transfer molding: VaRTM. Typical examples of his recent work will be shown in ICAS 2012 presentations.*

## 1 Introduction

National Aerospace Laboratory (NAL: Currently one part of Japan Aerospace Exploration Agency: JAXA) decided to develop a full composite empennage of the NAL experimental STOL aircraft in 1977. This tail plane by full carbon/epoxy composites was one of the earliest challenges in the world to composite aero-structures. In order to carry out this program, the author joined NAL in 1978. During his contribution work to the development of the structures, he came across the problem of serious warping of a composite plate using "8 harness satin" weave carbon fiber fabric, which was deformed during a curing process. He discovered the reason of warping, the anti-symmetric nature of a satin weave fabric. Inspired by this discovery, he started the systematic research of the mechanics of textile composites to connect the most basic plain weave and the two-layered anti-symmetric cross ply laminate as an extreme case. This theory appears many composite textbooks and it is familiar with composite researchers and students all over the world. A brief essence of the theory will be shown.

Another contributing topic to the development was the clarification of the true reason of immature failure of the developed full composite wing model. According to his analysis, this failure was caused by the geometry of the corrugated web in sine wave. By integrating his contributions, and by transferred technologies from NAL, Mitsubishi Heavy Industries Co. Ltd (MHI) developed Japan's F-2 fighter aircraft with full composite main wings. Based on this achievement, MHI was nominated as the manufacturer of Boeing B-787 composite main wing.

He also tackled the essential problem of composite structure governing a weight reduction ratio, "strength reduction in compression after impact (CAI)". After performing many experiments and numerical calculations he is now identified one of the world level authorities in this important problem.

In recent years, he devoted himself to develop low cost manufacturing technologies of composite structures, such as vacuum resin transfer molding (VaRTM). JAXA started the early R & D program in late nineties and obtained a great success to improve the quality of VaRTM structure to an aircraft level. He played a key role in this R & D project. The recent typical examples of this work will be presented at ICAS 2012 award lecture.

## 2 Basic Mechanics of 2-Dimensional Textile Composites

### 2.1 Background Empennage Model

As stated in Introduction, the author's early work was inspired by the development of the empennage model for "Asuka" aircraft. Pictures of the model and its spar bending test are shown in Fig. 1. As seen, the spar web shape was corrugated in sine wave in order to prevent shear buckling in the web. For achieving drapability to sine-shaped mold, an adoption of 8 harness satin weave fabric was indispensible as reinforcement. At that time being, behavior of fabric reinforced composites, even 8H satin reinforcement itself, was not known to entire composite communities worldwide. One day, an engineer of the manufacturing company of the model (Mitsubishi Heavy Industries Co. Ltd.: MHI) came to the author for asking the reason of serious thermal warping during curing of one ply 8H satin CFRP plate. When checked the section of the plate, he could immediately speculate the true reason of warping. This event was the starting point of a historical birth of mechanics of 2-dimensional textile composites.

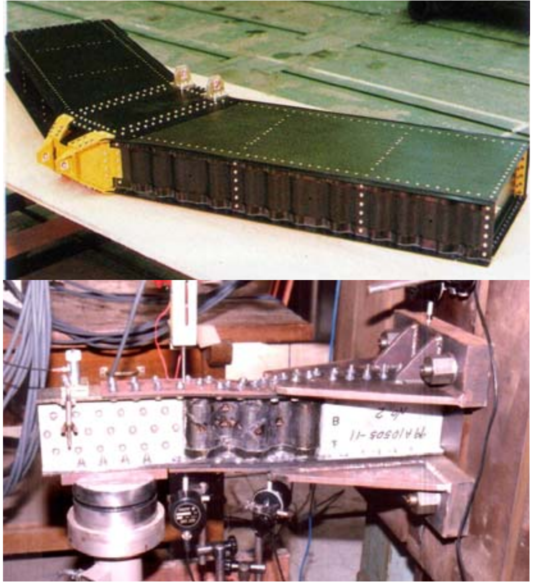

Fig. 1 All CFRP Empennage Model developed For "Asuka" STOL Aircraft and Its Spar Bending Test (1978)

### 2.2 Identification of Fabric Pattern and Development of Mechanical Theories

Later on, he summarized the pattern of 2-D weaves and a simple explanation chart is shown in Fig.2. It is basically classified by the geometrical number for interlacing region appearance, $n_g$. The case of $n_g = 2$ is the basis of the textile, so called the plain weave. Satin weave can appear for larger $n_g$ than 4. Typical satin weaves correspond to $n_g = 5, 8$, etc..

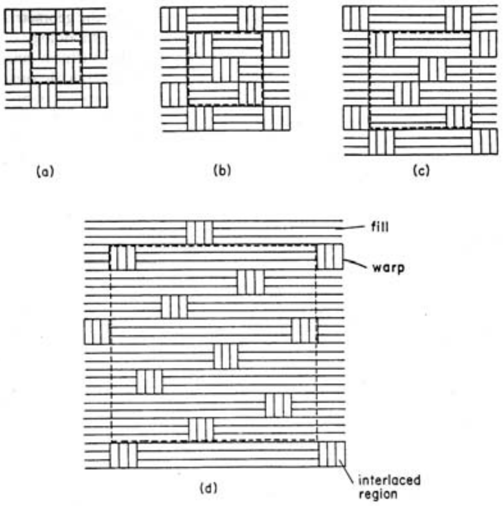

Fig.2 Typical Weaving Patterns of 2-D Fabric
(a) Plain: $n_g = 2$, (b) Twill: $n_g = 3$,
(c) (Claw Foot) Satin: $n_g = 4$,
(d) 8 Harness Satin: $n_g = 8$

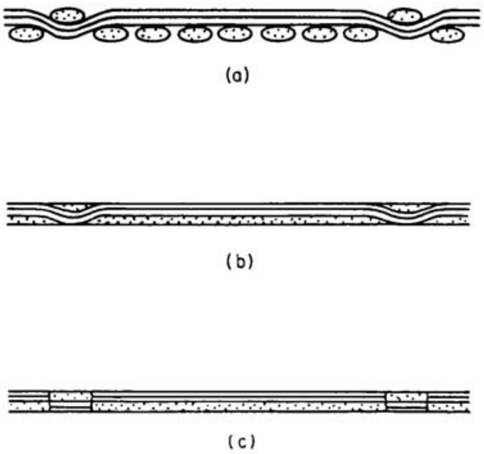

Fig. 3 Idealization Process to the Mosaic Model Invented by the Author

He invented so called the Mosaic Model and improved it to the “Fiber Crimp Model”. An idealization process from the section of the real 8H satin weave (a), after consolidation (b), to Mosaic Model (c) is shown in Fig.3. Based on this Mosaic Model, the author derived very simple upper and lower bound theories of the elastic moduli of fabric composites.

As the next step, he introduced the effect of fiber crimp which of course appears in the true fabric. The concept of the model is shown in Fig.4 where a sinusoidal undulation is assumed.

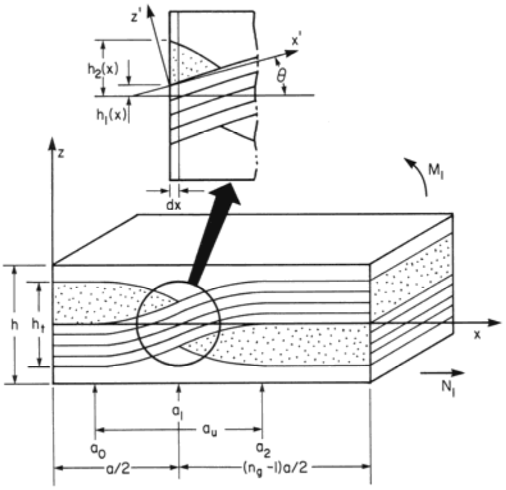

Fig. 4 Concept of Fiber Crimp Model

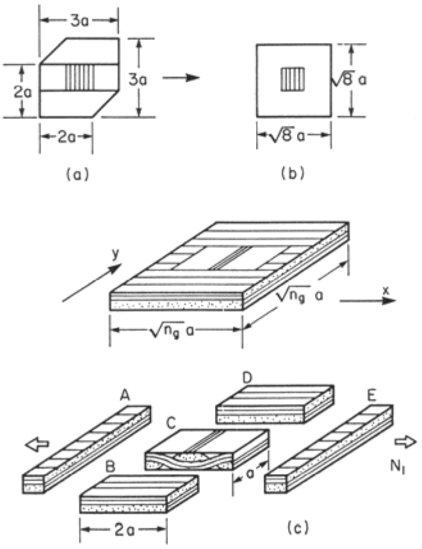

Fig. 5 Introduction of Bridging Model for
Satin Weave Reinforced Composites

By using this model, the author made a success in deriving semi-analytical results of elastic moduli of textile composites based on rather one dimensional arrangement of the representative volume element (RVE).

As the final improvement of the mechanical model, he developed the “Bridging Model” particularly for the prediction of the elastic behavior of satin composites. Its concept is indicated in Fig.5. The key point of the model is as follows: A low modulus portion where fiber crimp is observed with the length of 2a is surrounded by the straight fiber portion which is the feature of the satin weave.

Numerical results of non-dimensional in-plane stiffness are shown in Fig.6 where the focus is placed on a comparison between numerical results for the Bridging Model and a experimental result of 8H satin indicated by a solid circle. A correlation of numerical and experimental results looks very good. With number of other supporting comparisons and proofs in many published papers by him, developed mechanical theory for 2-D textile composites with his advisor, Dr. Tsu-Wei Chou became one of the world standard textbook contents. His name is now known to the worldwide composite communities

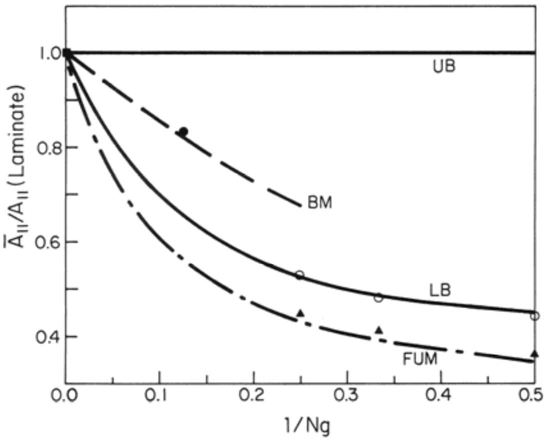

Fig. 6 Comparison of Numerical results with
Experimental one for 8H Satin in the
Case of Non-Dimensional In-Plane
Stiffness

## 3 Post-buckling Compressive Failure Behavior of CFRP T-Stiffeners

### 3.1 Background :Immature Failure of Empennage Model in Bending Test

The second important topic related to the developed empennage model is an immature failure of the model at the ultimate strength test that was conducted in 1983. The model failed at 74% of the estimated symmetric bending (downward) load as shown in photos in Fig. 7.

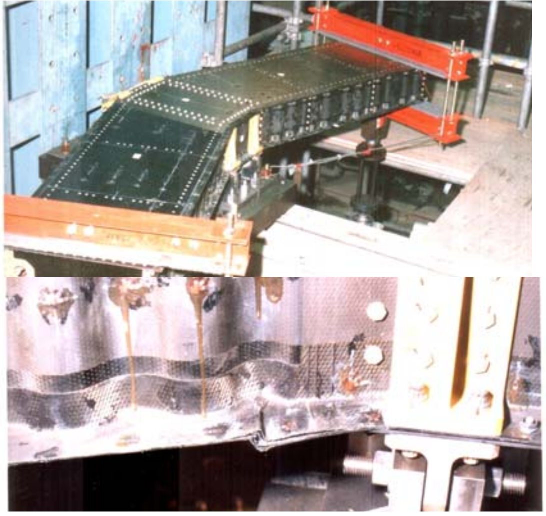

Fig. 7 Photos of the Ultimate Bending Test of the Developed Empennage Model
Upper: Model and Loading Devices
Lower: Trigger of the Failure
= Lower Rear Spar Flange, Crippling

The author supposed the reason why the model failed at such a low level of loading. His presumption is as follows: The buckling load estimation was not conducted for the real sine-shaped web model but done for a hypothetical flat web model due to small computer resource at that era. In other words, estimated failure load was wrong. However, the detailed research was not conducted immediately after the test.

### 3.2 Post-Buckling and Final Failure Tests for CF/Epoxy and CF/PEEK composites

A chance of the research was given to the author almost ten years later when NAL decided to develop thermoplastic (TP) composite aero-structures and appointed him as the project leader. So, this project had double fold purposes to develop TP components, actually Poly-Ether-Ether-Ketone (PEEK) was chosen as matrix, and to prove the reason why the model failed so low load induced by spar buckling.

As the first component, T-shaped stiffeners were chosen to develop, where this shape was the best choice to idealize the behavior of spar flange. Of course, CF/PEEK stiffeners were the target of the development, while CF/Epoxy stiffeners were also important baseline components to compare the post-buckling behavior. Figure 8 describes actual geometry of the specimens where two types are adopted, N (narrow) and W (wide). This figure also indicates the buckling mode shape observed in all the compression tests.

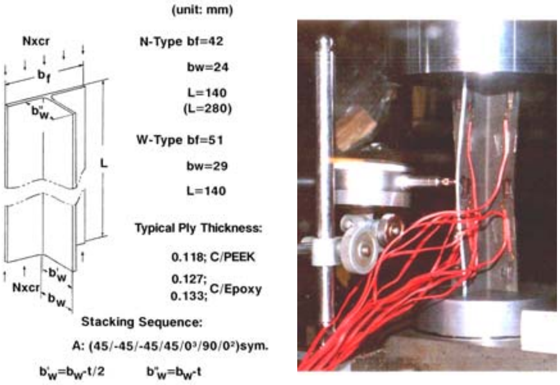

Fig. 8 Geometry of the Test Specimen of T-Shaped Stiffener and the Actual Buckling Mode in the Test

Rayleigh-Ritz and Finite Element Analyses (FEA) were performed for these T stiffeners. Only FEA results are shown and discussed in this text.

The first goal is to estimate initial buckling loads of these stiffeners. The left portion of Fig. 9 shows the buckling mode and comparison with the experimental mode in Fig.8 looks very good. The right portion of Fig.9 indicates a

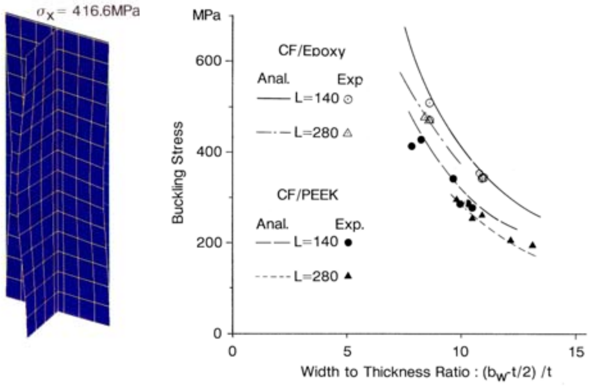

Fig. 9 Numerical Buckling Mode by FEA and Comparison of Experiments and FEA

comparison between experimental and numerical buckling loads for both composite systems. The horizontal axis of Fig. 9 right is the key parameter which governs this kind of T-stiffeners, a ratio of the web width to web thickness. In order to adjust the web width considering the true center of rotation, a parameter of $(b_w - t/2)/t$ was actually chosen. As shown in this figure, the buckling load was seriously affected by this ratio. It means that the buckling loads decrease rapidly if web becomes thinner, or wider. Experimental results of CF/Epoxy and CF/PEEK are plotted by open and filled legends. An agreement between experimental and numerical buckling loads looks fairly goods. Up to this step, research phase is not so difficult if experiments were properly conducted.

From here on, the handling of the problem went into the nonlinear stage, i.e., post-buckling analysis. At early nineties, due to the lack of supporting knowledge, it was not an easy task to perform accurate post-buckling analysis. After many trials, the author could make a great success in post-buckling behavior predictions of T-stiffeners. Figure 10 describes the first numerical product related to the post buckling analysis, an iso-value contour chart of web out-of-plane deflection after buckling. It can be seen that the largest deflection occurs at the center of the web in terms of the loading direction. If compared with the picture of the experiment in Fig. 8, a good agreement between numerical and experimental results of deflection is verified well. A proper assumption of the initial imperfection in the stiffener is essential to obtain such a good correlation.

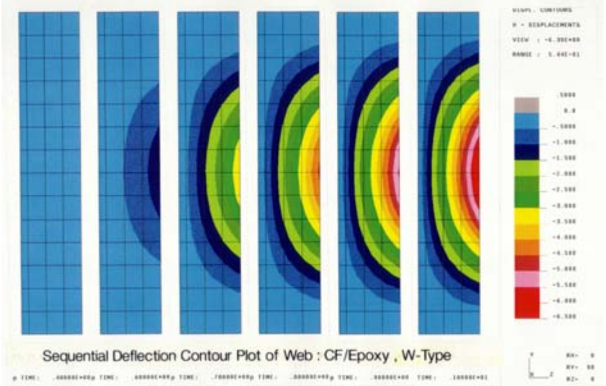

Fig.10 Iso-Value Contour of Web Out-of-Plane Deflection after Buckling

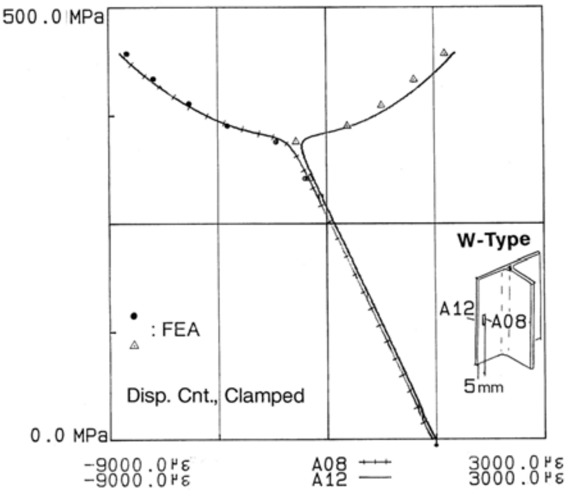

Fig.11 Comparison of Experimental and Numerical Strain Values at the Center of Stiffener Flange

Because it was confirmed that numerical deflection predictions coincide well with experiments in almost all cases, a comparison went into more sensitive results, strain data, which show basically derivative nature. Figure 11 compares experimental plot (continuous curves at back to back gages on the flange center) and numerical strain outputs at the corresponding nodes to the gage location before and after buckling. Again, a correlation of both results looks perfect. By inspired these good agreements, the author tried a prediction of post-buckling compressive strengths of these T-stiffeners. For doing that, he adopted a simple

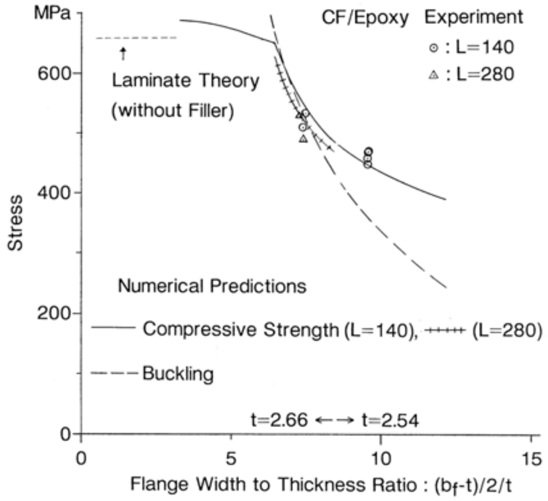

Fig. 12 Predicted Compression Strength after Buckling and Experimental Results

maximum stress theory to 0-degree lamina near the surfaces (5th and 16th lamina in Stacking Sequence A). Although description of examples of stress iso-value contour in 0-degree lamina is omitted here, the final predictions of compressive strengths are indicated in Fig.12. As experimental results, the data for CF/Epoxy only are plotted in this figure because CF/PEEK stiffeners exhibited highly progressive nature in compression failure. CF/Epoxy stiffeners exhibited almost explosive failure mode just after initial AE signals. A comparison of the experimental strengths with predicted strength curves is not as good as buckling stress or strain outputs. However, the prediction can work well in application in an engineering level. It is discovered that the employed value of $(b_f - t)/2/t \fallingdotseq 7.4$ is not the optimal but 6.5 may be the best to increase the compressive strength of the T-stiffener

### 3.3 Feedback of This Knowledge to Immature Failure of the Wing Box

The knowledge that a wider flange portion will show buckling earlier than a narrow portion suggests the true reason of the occurred immature failure of the developed full CF/Epoxy wing box model. FEA model was created and eigenvalue analysis was performed. Again, a full modeling of the whole wing was too cumbersome, the indicated model in Fig. 13 was employed for analysis. The buckling loads for a sine web spar and a flat web spar are shown in Fig.13 right. The sine web spar exhibits a lower buckling load and its mode implies the experimental failure in Fig.7.

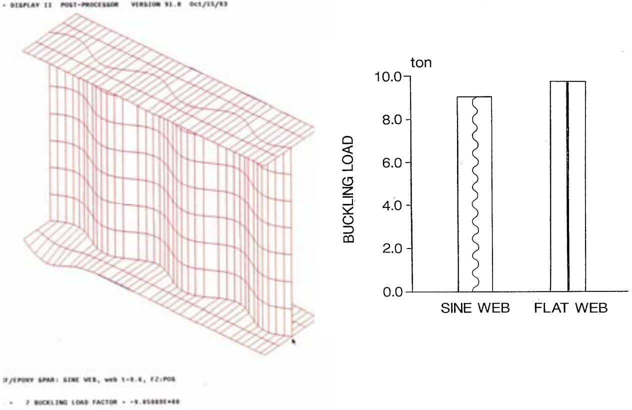

Fig. 13 Truncated Model of Sine Web Spar and Comparison of Buckling Loads

## 4 Research for Compression after Impact

### 4.1 Background

Reduction of compressive strength after impact delamination is well known to composite communities. However, the details of its phenomena and understanding of its mechanisms were not enough clarified in late eighties. The author tackled this problem with the assistance of Professor Hiroshi Suemasu of Sofia University Japan. The test standard (SACMA) for compression after impact (CAI) was already established and a key illustration of the test concept is shown in Fig. 14.

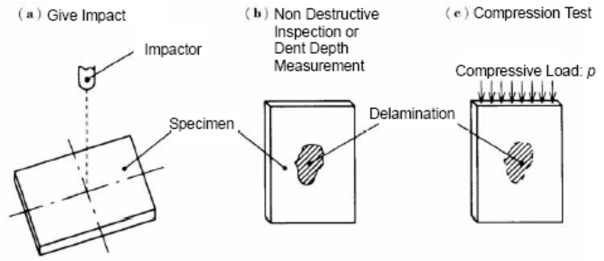

Fig.14 Test Concept of CAI

### 4.2 Understanding of CAI Behavior

The author conducted many CAI tests for variety of composite systems by some different tests methods. Here, some typical experimental findings clarified by his research will be shown. Figure 15 indicates a typical delamination geometry for the case of low toughness CF/Epoxy in NASA test method. Accumulated delaminations look like a hat and brim.

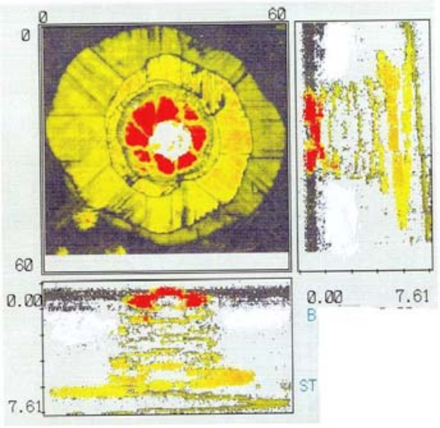

Fig. 15 Typical Delamination Shape by Impact "Hat and Brim" Case for Less Tough Carbon Epoxy

By changing the level of impact energy, delamination area variation was captured. Figure 16 shows such a variation for a less tough CF/Epoxy, the same system as Fig.15, where the horizontal axis is the normalized impact energy by a specimen thickness. One important point is an existence of a threshold in energy level for delamination creation. Leveling-off in delamination area at high energy is caused by reaching the delamination edge to a specimen support. It is also understood that experimental scatters in the results are fairly wide. Legends in Fig. 16 indicates test methods used. In compressive failure phase, a delamination growth to the transverse direction to the load was captured in several tests where a Moire- Topography photo device was used. Figure 17 compares growth behavior in CF/Epoxy and CF/PEEK. Percentage under each picture indicates a ratio to the final failure load. In case of CF/Epoxy, rather slow growth before the final failure was captured. It was found that delamination grows across the specimen in all over the tests without any exception. Reduced compression strengths after impact are plotted in Fig.18 for less tough CF/Epoxy, which means the core behavior of CAI. Impact energy lower than the threshold has no effect on strengths, while strengths become seriously low if energy level exceeds the threshold. This tendency is typical in less-tough CF/Epoxy CAI behavior. Strength level reaches almost one third of the pristine case.

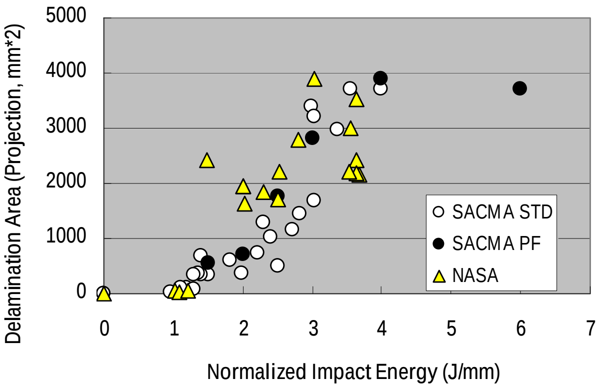

Fig. 16 Delamination Area Variation by Impact Energy Level Change

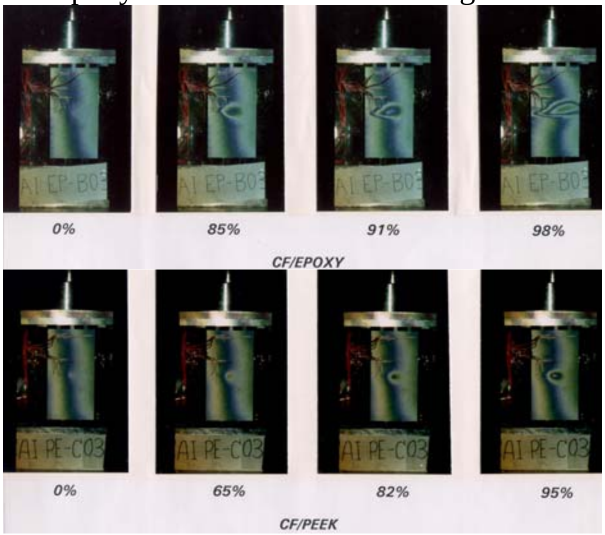

Fig.17 Transverse Delamination Growth to the Load: for CF/Epoxy and CF/PEEK

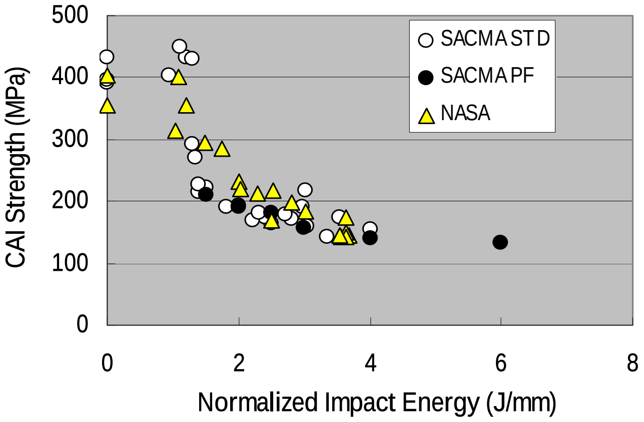

Fig. 18 Compression Strength Reduction after Impact (for less tough CF/Epoxy)

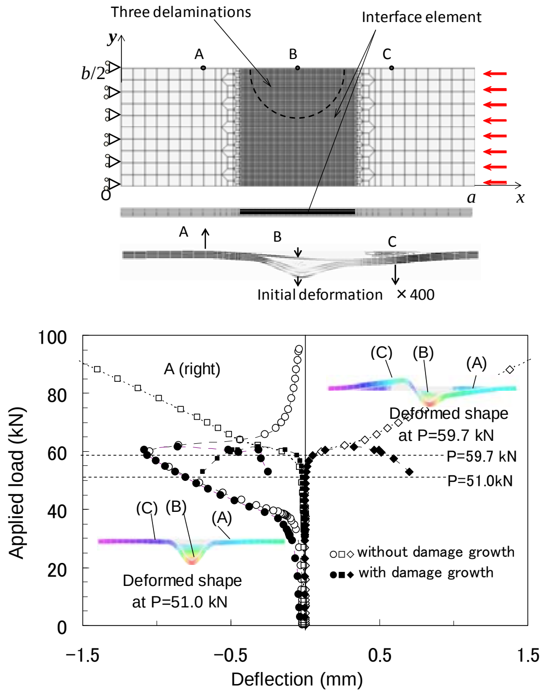

Fig. 19 Numerical Results of CAI Behavior Using Cohesive Element FEA

Numerical analysis was conducted with a co-ordination between the author and Prof. Suemasu. Figure 19 shows one of the most important recent results of FEA using a cohesive zone element. Mesh pattern is shown in Fig. 19 upper. The key finding is that applied load can drop if the delamination growth is taken into account as indicated by black circle plots in Fig.19 lower. It took a long time and enormous effort to obtain such a meaningful numerical result.

## 5 Conclusion

The author's recent accomplishments related to low cost fabrication technology seem to be also interesting, However, due to the lack of the space, they are omitted in this proceedings and will be shown in the ICAS 2012 presentations.

His early work topics inspired by the Japan's first full composite aero-structure development were reviewed here. Precious lessons learned like an immature failure of the developed wing model and attack efforts to find its true reason are also described. Advanced composites technology levels developed by him typified by such findings were gradually transferred to the Japan's airframe industries and his affections played a key role to strengthen their capability in design, manufacturing and testing of full composite aero-structures. A typical example is the production of Boeing 787 main wing done by MHI Co. Ltd. A stream from "Asuka's" empennage, to F-2 fighter main wing, and to B 787 main wing is an important passage for Japan's expansion in composite aero-structures technology. Finally, the author should deserve the honorable ICAS Award for Innovation in Aeronautics.

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