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POST-IMPACT FATIGUE BEHAVIOR OF HIGH TEMPERATURE POLYMER MATRIX COMPOSITES

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ABSTRACT

Recently, the feasibility studies have been done as a part of evaluating and predicting long-term durability performance of candidate composite and structures in Japan Supersonic Research Program for 2nd Generation Supersonic Civil Transport in order to achieve through long-term and short-term tests under conditions simulating SST flight, development of associated predictive and accelerated test methods, and assessment of durability performances for design. This paper discussed in details the long-term durability, especially post-impact fatigue performance of the interesting and candidate high temperature polymer matrix composites and summarized the effects of low-velocity impact damage on fatigue behavior in a comparison with the open-hole fatigue behavior.

KEYWORDS: Post-impact Fatigue, High Temperature Polymer Matrix Composites, Fully Reversed Tension-compression Fatigue, Low-velocity Impact Damage, Residual Compressive Strength

INTRODUCTION

Recently, the feasibility studies have been done as a part of evaluating and predicting long-term durability performance of candidate polymer matrix composite materials and structures in Japan Supersonic Research Program for 2nd Generation Supersonic Civil Transport [1] in order to achieve through long-term and short-term tests under conditions simulating SST flight, development of associated predictive and accelerated test methods, and assessment of durability performances for design.

It is very important for a wide practical use of polymer matrix composites how to ensure the impact damage tolerance for long-term structural integrity. Generally, static compressive strength of laminated composites can be significantly reduced by delamination. Delamination can develop at a free edge, particularly at a hole, where inter-laminar stresses are very high. Delamination can also develop from low-velocity impact. Impact damages have strong influences on not only static strength characteristics but also fatigue behavior. Relatively little information is available on the post-impact fatigue behavior of advanced high temperature thermosetting and thermoplastic polymer matrix composites as compared with conventional epoxy matrix composites.

The objective of this paper is to investigate the post-impact fatigue behavior between the interesting high temperature polymer matrix composites. The low-velocity impact damage was introduced into a narrow coupon type laminated specimen and then performed the fully reversed tension-compression fatigue tests. The effects of low-velocity impact damages on fatigue lives were summarized for both the screening of new composite materials and the determination of a baseline fatigue design allowable for ensuring the long-term structural integrity of primary structural components.

MATERIALS AND EXPERIMENTAL PROCEDURE

Materials

The materials chosen in this study are carbon fiber reinforced, toughened bismaleimide (BMI), G40-800 /5260, thermoplastic polyimide, IM600/PIXA-M and thermosetting polyimide, MR50K/PETI-5. They are laid up into a 32-ply quasi-isotropic laminate with a $[+45^{\circ}/0^{\circ}/-45^{\circ}/90^{\circ}]_{4s}$ stacking sequence. Room temperature mechanical and chemical properties [2] are summarized in Table 1.

TABLE 1 Summary of mechanical and chemical properties

	G40-800/5260	IM600/PIXA-M	MR50K/PETI-5
OHT MPa	569	461	426
Tensile modulus GPa	NA	58.2	55.1
OHC MPa	385	309	317
Compressive modulus GPa	57.2	60	53.8
CAI (1500 in.·lb/in.)	358	383	298
Tg ˚C	274	235	250

Test Specimens

Post-impact fatigue specimens

A narrow coupon type specimen with same configuration and dimensions to open-hole (6.35 mm-dia.) fatigue specimen was used for the post-impact fatigue test. After machining from the as-fabricated panels, the impact damage was introduced at the center of specimen. Figure 1 shows the configuration and dimensions of the post-impact fatigue specimen. All specimens were nondestructively inspected before testing to document machining defects. There was no biasing of damage development due to initial defects.

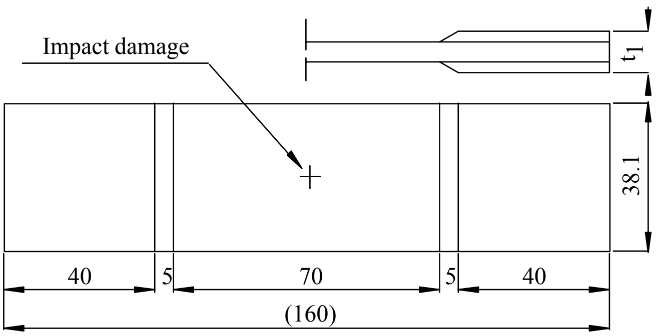


Figure 1: Post-impact fatigue test specimen dimensions

Test Equipment and Procedure

Impact test

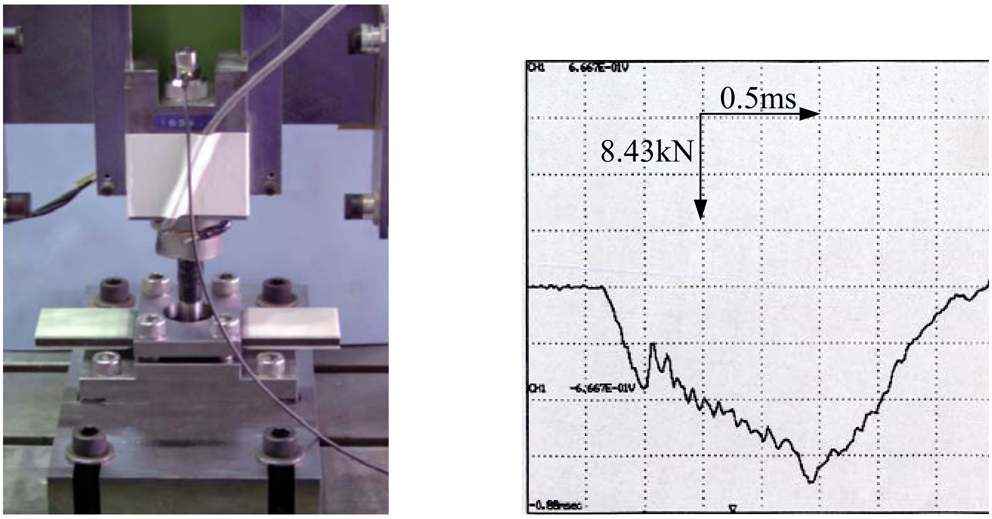
Impact load was directly applied on a coupon type specimen by using an instrumented drop-weight impact tester. The test fixture used for the impact portion of this study contained a 30 mm-diameter opening. A free-falling mass impacted at the center of the specimen. The impactor set-up and test fixture are shown in Fig. 2. The total weight of the impactor with a 12.7 mm diameter steel spherical tup was approximately 1.9 kg. The impact acceleration and impact force were measured using a piezoelectric accelerometer and two strain gages mounted on the impactor. The impact acceleration and impact force were recorded with a digital data acquisition system.

The coupon-type specimens were mounted in the holder (see Fig. 2), and the bolts were torqued to 49 J. The instrumented impactor was centered above the coupon-type specimen at the required height to impact the desired impact energy per unit thickness. After the impactor struck the specimen, a piece of thick GFRP was quickly moved between the fixture and specimen to prevent the impactor from repeatedly hitting the specimen. Three series of impact energy per unit thickness of 1668, 3336 and 6672 J/m (equal to 1500 in.·lb/in.), which are very low as compared with an industry standard for evaluating thick, quasi-isotropic laminates, were chosen.

Open-hole and post-impact fatigue tests

The open-hole fatigue and post-impact fatigue tests were performed with load controlled-mode, sinusoidal wave-form, at a constant cyclic frequency of 5 Hz using the personal computer-controlled MTS materials testing system with a environmental chamber kept temperature at 23 ± 1°C and relative humidity at 50 ± 2%. All specimens were loaded in fully reversed tension-compression fatigue with R= -1. Cyclic stress versus strain curves were continuously measured by using extensometer (gauge length 25.4 mm) mounted on the specimen side edge, and monitored stiffness changes as a means of evaluating damage accumulation during fatigue loading.

Laser optical microscope, SEM and soft X-ray radiograph examinations were also conducted at various fatigue cycles in order to examine fatigue damages initiated and propagated from both impact damaged area and a root of initial circular hole.



(a) Impactor set-up and test fixture (b) G40-800/5260 (3336 J/m)

Figure 2: An instrumented drop-weight impact tester and impact force versus time record

RESULTS AND DISCUSSION

Impact Damage

An example of typical impact force versus time record is shown for G40-800/5260 in Fig. 2(b). The peak impact force in a case of impact energy per unit thickness of 3336 J/m was approximately 14.75 kN. The force-time signals for all the impact tests were almost consistent for every material. The impactor rebounded on the first collision and was out of the way before the test specimen rebounded. The high-frequency oscillations throughout the load-time histories are mostly ringing of the impactor and vibrations of the specimens.

Before and after impact, each specimen was nondestructively evaluated to examine the extent of impact damage by laser optical microscope, soft X-ray and C-scanned ultrasonic examinations. The plastically deformed area at the impact surface was measured with the use of the laser optical microscope. The impact energy versus maximum depth of plastically deformed area relationships are shown in Fig. 3. At lower energy level, there is almost linear relationship regardless of materials. The G40-800/5260 composite had an even smaller plastically deformed area. The standard deviation was calculated for each of the impact area data sets. It showed a small variation especially within no fiber breakage damages for every material. This low standard deviation indicates that the impacts were consistent and repeatable.
Typical internal damage patterns observed by soft X-ray examinations are shown in Figs. 4(a), (b) and (c) for impact energy per unit thickness of 6672 J/m. The IM600/PIXA-M had a larger impact damaged area.

They had many transverse cracks in every 0˚, ±45˚ and 90˚ laminate layers and delaminations especially at -45˚/90˚ interlayer. There are much differences in extents of un-symmetric internal impact damages fundamentally depending on both toughness of matrix resin and inter-lamellar properties. Figure 4 also shows that these impact damaged area doesn't spread to whole specimen width within the limits of this experiment.

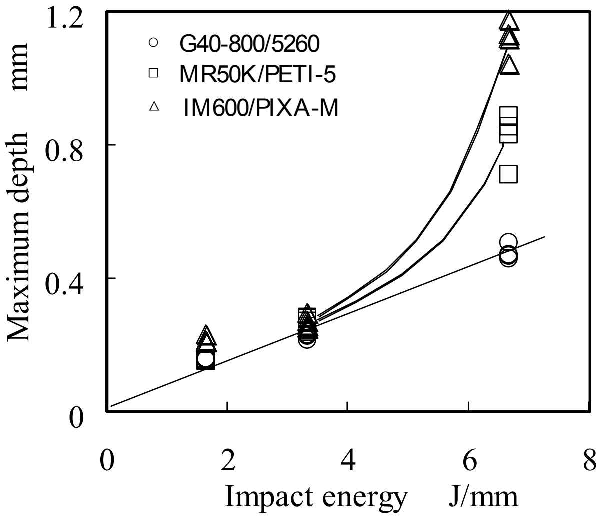
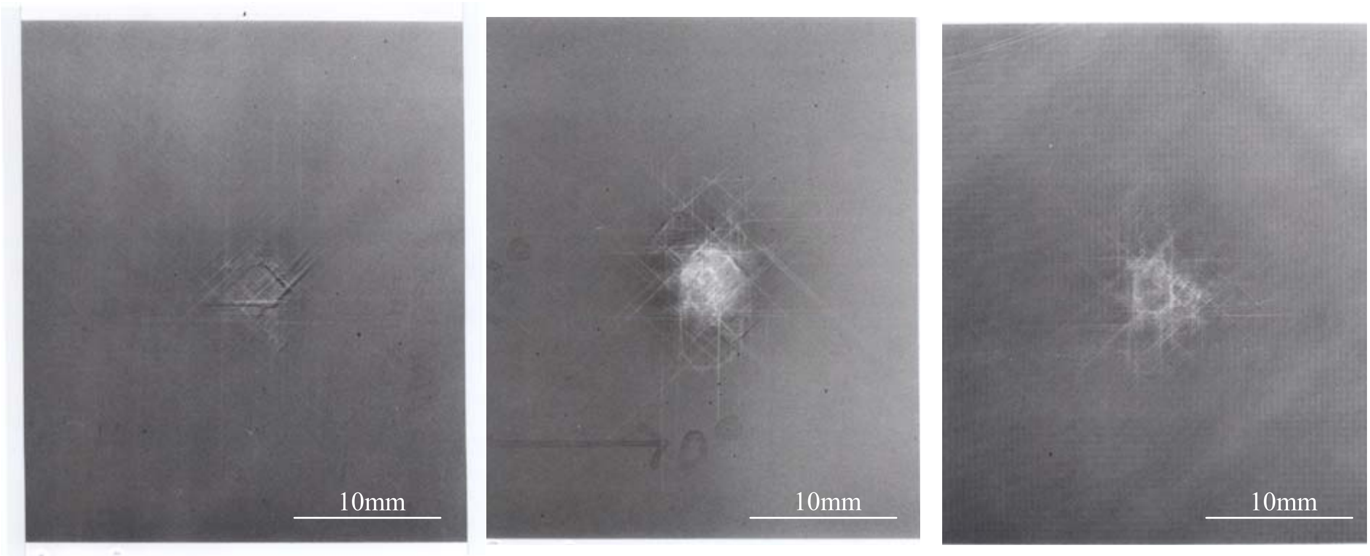


Figure 3: Relationships between impact energy and maximum depth of plastically deformed area



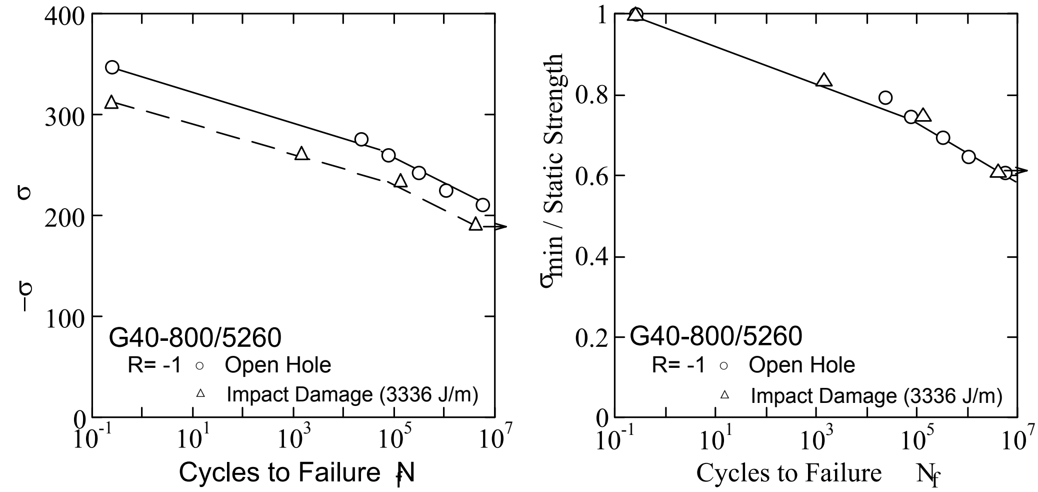
(a) G40-800/5260 (b) IM600/PIXA-M (c) MR50K/PETI-5

Figure 4: Soft X-ray examinations of impact damages (Impact energy per unit thickness: 6672 J/m)

Post-impact Tension-compression Fatigue

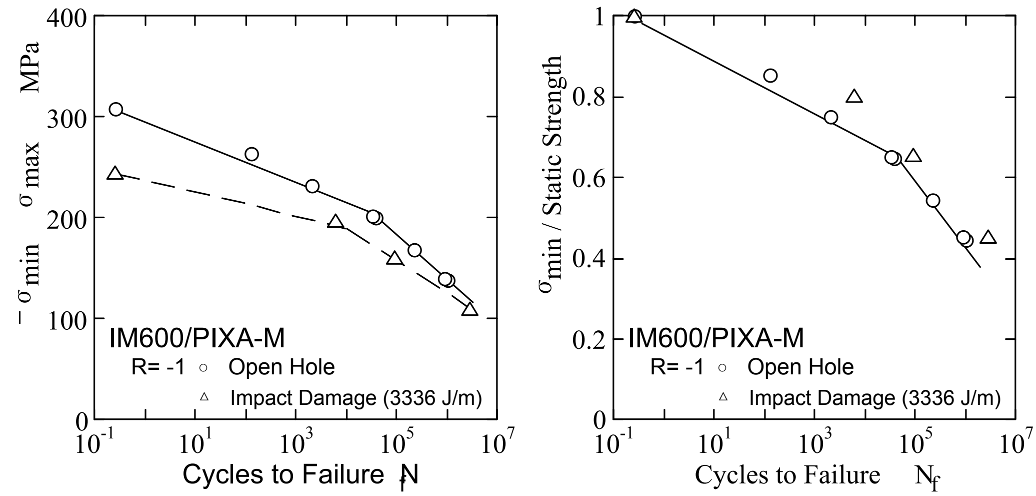
To assess the effects of impact damage on fully reversed tension-compression fatigue behavior, the S-N curves were compared with the smooth and open-hole specimens. Minimum gross compressive stresses are plotted against cycles to failure (log scale) in Figs. 5 to 7. Linear least squares regression fits to the data are also drown. These figures show that there is a remarkable influence of low-velocity impact damage and fatigue lives rapidly decreases with increasing of impact energy. There is much influence for IM600/PIXA-M with a larger impact damaged area and a lower residual compressive static strength after impact.

On the other hand, the normalized S-N curves in terms of static strength are consistent with those of open-hole specimens regardless of materials. It is concluded here that the decreases of fatigue lives fundamentally resulted from the reduction of static strength after impact damage. It is successfully predicted the fatigue lives of impact damaged specimen from normalized S-N curve and residual compressive static strength. It is very interesting that there is also a distinguishable knee point in the S-N curves of impact damaged specimen resulted from the transition in fatigue failure mode from compressive failure in the low cycles region to tensile failure in the high cycles region. There is no transition in fatigue failure mode in the whole cycles region for the MR50K/PETI-5.



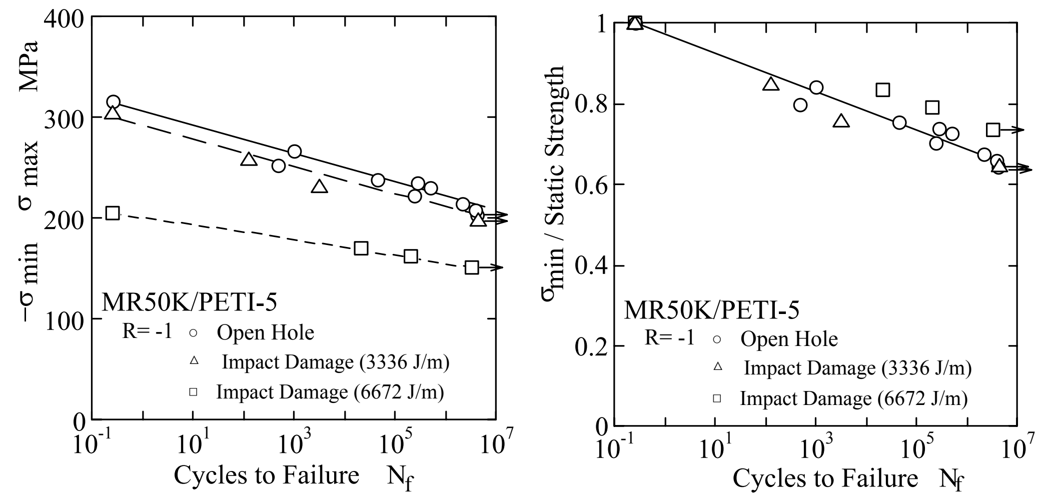
(a) S-N curves (b) Normalized S-N curves

Figure 5: Comparisons of post-impact fatigue lives with open-hole specimens for G40-800/5260



(a) S-N curves (b) Normalized S-N curves

Figure 6: Comparisons of post-impact fatigue lives with open-hole specimens for IM600/PIXA-M



(a) S-N curves (b) Normalized S-N curves

Figure 7: Comparisons of post-impact fatigue lives with open-hole specimens for MR50K/PETI-5

We have urgently done the following researches in order to achieve through long-term and short-term tests under conditions simulating SST flight, development of associated predictive and accelerated test methods, and assessment of durability performances for design.

- Failure mode transition in open-hole fully reversed, tension-compression fatigue behavior [3]
- High temperature open-hole compressive fatigue behavior [4]
- Moisture absorption effects on open-hole fatigue behavior [5]
- Thermo-mechanical response under the simulated SST flight cycles [6] and long-term durability analysis and database [7]

CONCLUSIONS

(1) There is a quite difference in the extent of low-velocity impact damages among the high temperature polymer matrix composites. For low-impact damage, compared on equal impact energy level, the residual compressive static strengths of the G40-800/5260 were slightly greater than those of the IM600/PIXA-M and MR50K/PETI-5.

(2) There is a remarkable influence of low-velocity impact damage on fatigue lives. The IM600/PIXA-M with a larger impact damaged area and a lower residual compressive static strength after impact has lower fatigue lives than those of the G40-800/5260 and MR50K/PETI-5.The G40-800/5260 composite was more resistant to initial impact damage, but the MR50K/PETI-5 composite was more tolerant to fatigue damage after impact.

(3) The normalized S-N curves in terms of static strength are consistent with those of open-hole specimens regardless of materials. The decreases of fatigue lives fundamentally resulted from the reduction of static strength after impact damage. It is successfully predicted the fatigue lives of low-velocity impact damaged specimen from normalized S-N curve and residual compressive static strength.

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REFERENCES

1. Hirano, K., Strategies for R&D on Construction and Preparation of Design Database for Advanced Composite Materials, *J. of the Japan Society for Composite Materials,* Vol.26, No.1 (2000), PP.3-8 (in Japanese)
2. NEDO Report, Studies on Establishment of Long-term Durability Testing and Methodologies for High Temperature Polymer Matrix Composites, March 31, 2000 (in Japanese)
3. Hirano, K., Long-term Durability Performance for Advanced High Temperature Polymer Matrix Composites, To be published in *ICCM-13*, June 25-29, 2001
4. Hirano, K., Miyake, S. and Yoshida, H., Moisture Absorption Effect on Open-hole Fatigue Behavior for High Temperature Polymer Matrix Composites, To be presented at *ICCE/8*, August 5-11, 2001
5. Hirano, K., Miyake, S. and Yoshida, H., Comparisons of Open-hole Fatigue Strength Characteristics for High Temperature Polymer Matrix Composites for the Next Generation Aircraft, To be published in Proc. of *APCFS&ATEM'01*, October 20-22, 2001
6. Hirano, K., Suzuki, T., Miyake, S., Noda, M. and Yamaguchi, Y., Thermo-mechanical Response under the Simulated SST Flight Profile and Residual Open-hole Tension/Compression Strength Characteristics for Advanced High Temperature Polymer Matrix Composites, To be presented at *5th International Conference on Durability Analysis of Composite Systems*, November 6-9, 2001
7. Hirano, K., Current Status and Future Prospects on Establishment of Design Database for Advanced Composites and Structures in Japan, To be presented at *7th Japan International SAMPE Symposium & Exhibition*, November 13-16, 2001