INVESTIGATION OF THE IMPACT PROPERTIES OF THIN-PLY PREPREG AT ELEMENT LEVEL

Christian Buelow*, Norbert Heltsch, Dr. Yoshiyasu Hirano***, Dr. Yuichiro Aoki***, Dr. Kazumasa Kawabe **** [Christian Bülow]: christian.buelow@dlr.de**

*** German Aerospace Center, DLR, ** Airbus Operations GmbH, *** Japan Aerospace Exploration Agency, **** Industrial Technology Center of Fukui Prefecture, ITCF**

Keywords: *CAI, crippling panel, thin-ply, coupon level, element level, automation*

Abstract

This paper describes the cooperation between ITCF, JAXA, DLR and Airbus for the research on thin-ply laminates. For the first time the manufacturing and preparation of thin-ply specimens at element level is described. The test campaign is not yet finished, but the first results are quite promising.

In the focus of the test campaign are two types of specimens: omega-stringer stiffened crippling panels and CAI coupons. For both specimen types, thin and standard ply are compared. The manufacturing, specimen preparation and the first results of the impact tests are presented in this paper.

1 Cooperation between ITCF, JAXA and DLR

In August 2016 three organizations – the Industrial Technology Center of Fukui Prefecture (ITCF), the Japan Aerospace Exploration Agency (JAXA) and the German Aerospace Center (DLR) – signed a cooperation agreement to examine thin-ply prepreg and their automated layup. At that time, ITCF had already gained about 10 years of experience in production of high quality thin-ply prepreg down to 20 gsm.

ITCF and DLR started their cooperation before the agreement in 2015 with the delivery of the first rolls of thin-ply prepreg from Fukui to Stade. With this material, DLR examined the feasibility of automated layup and presented the first results at the SAMPE 2015 symposium in Kanazawa [1]. At that time, some problems occurred in automated layup. This paper presents some strategies to overcome these problems.

In 2016 JAXA joined the cooperation to add their expertise in composite design, simulation and testing. Around this time, Airbus Hamburg also joined these research activities. The agreed main objective was to benchmark the technology in a representative use case. Therefore an omega-stringer stiffened panel was chosen to test thin ply prepreg at element level.

2 The advantages of thin-ply prepreg

The application of thin-ply prepreg has several advantages in comparison to standard (thick) prepreg. Firstly, it is possible to produce very thin laminates even if stacking rules need to met. An example from Amacher et al. [2] shows that the production of a 0.6 mm laminate with 160 gsm plies is only possible with a [0°/90°]s stacking sequence with four layers; however, with 20 gsm plies it is possible to build up 32 layers with a sequence such as [+45°/90°/-45°/0°]4s. Furthermore, it would also be possible to introduce other orientations or even neglect symmetry requirements [2]. Thin-plies thus introduce a new degree of freedom in the design of thin laminates.

Another significant advantage of thin plies is their suppression of microcracks and delamination. This characteristic permits higher strain allowances in thin-ply designs [3] and allows higher knock-down factors of 0.8 in comparison to typical material factors of about 0.5 [2]. Knock-down factor increase is also related to the suppression of delamination and microcracks if thin-ply composites are loaded. The onset of damage thus begins at higher stresses if the plies are made thinner [4]. Additionally, tests show a 10% increase in compressive strength for thin-ply materials compared to standard materials [4, 5].

The same advantages that thin-ply prepregs show are also valid for thin-ply non-crimp fabrics [6].

3 Test specimen

Despite the variety of literature detailing tests of thin plies on coupon level, there have been no tests of thin-ply structures at element level. Therefore, a plan to test a typical aerospace structure is developed. An omega-stringer-stiffened panel (crippling stringer) is selected as the test structure (see Fig. 1). The idea is to impact the stringer in the middle and test the residual strength.

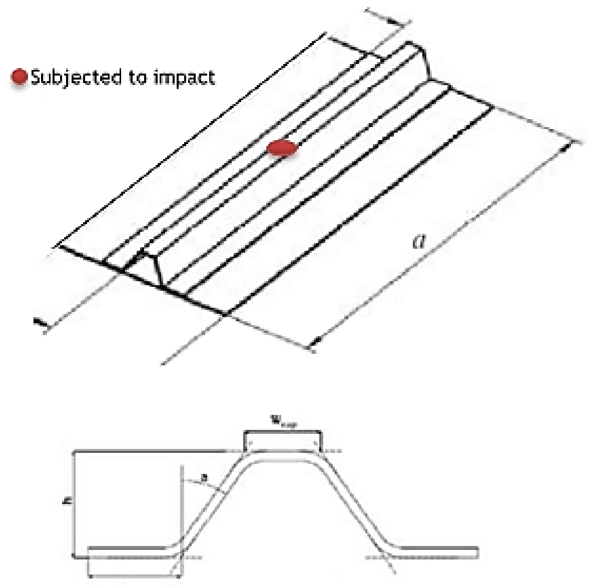


Fig. 1 Drawing of the omega-stringer with impact position

For reference purposes, compression after impact (CAI) coupons were also built. The CAI tests increase understanding of the fracture mechanisms and allow comparison between gained data for the used material and other CAI examinations.

All used prepreg material – thin and standard ply – is provided by ITCF comprising an epoxy resin system with a curing temperature of 180° C. Thin and standard ply prepreg use the same Toray T800 SC fibers. The thin-ply prepreg’s 40 µm thickness is about three times thinner than the 135 µm standard prepreg.

3.1 Manufacturing of the crippling panel specimen

The omega-stringers in the crippling panel specimen were built with thin-ply prepregs to compare with other panels where the omega-stringers are built with standard prepreg. For the panels it is not necessary to build the skin laminate with thin-ply prepreg as only the stringer head is impacted. The thin-ply omega-stringers were made of 27 plies [(45/-45/0/0/90/0/0/-45/45)$_3$], leading to a thickness of about 1.1 mm for the final part. To fabricate the panels, two stringers were laid up manually with a length of about 2.8 m (see Fig. 2). The laid-up stringers were then cured in an autoclave at Airbus Stade.

Because the standard prepreg is about three times thicker than the thin-ply prepreg, the number of layers for the standard stringer is one-third (or nine layers) at the whole [45/-45/0/0/90/0/0/-45/45]. The resulting thickness of the stringer with standard prepreg is similar to that with thin-ply prepreg. For both the thin and standard ply, two stringers were manually laid up and cured at Airbus Stade.

Fig. 2 Omega-stringer with a length of about 2.8 m

In total, two panels with an approximate size of 1.4 x 0.7 m were created. For the manufacture of the panel, the stringers had to be cut in half; for every panel three stringers with a length of 1.4 m were used. The skin or base laminates of the panels consist of 13 layers of standard prepreg and were laid up manually [45/-45/-45/45/90/0/90/0/90/45/ -45/-45/45]. After layup of the skin, the cured stringers and wet skin were joined in a co-bonding process in the research autoclave at DLR Stade (see Fig. 3).

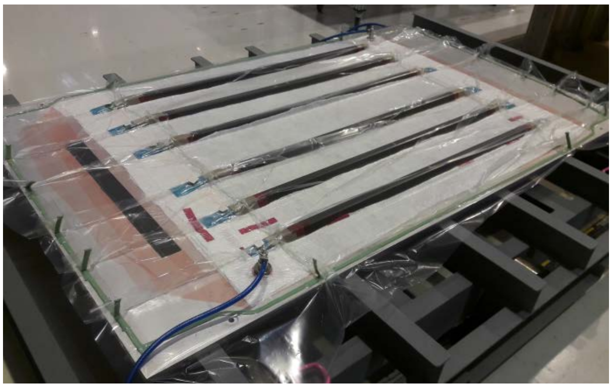


Fig. 3 Vacuum bagging of two omega-stringer stiffened panels with a size of about 1.4 x 0.7 m

3.2 Manufacturing of the CAI specimen

Besides comparing standard and thin-ply prepreg, another aim of the CAI specimen was to compare manual and automatic layup. For this comparison, three 400 x 400 mm laminates were built: one in manual layup with thin-ply, one in manual layup with standard ply and one in automated layup with thin-ply. The thin-ply laminates consist of 80 layers in quasi-isotropic design $[45/0/-45/90]_{10s}$, whereas the standard laminate consists of 24 layers $[45/0/-45/90]_{3s}$. Like the first trials described at SAMPE 2015 [1], the automated layup was made by a robot with a tape laying head at the GroFi facility of DLR Stade. All three laminates were cured in the research autoclave at DLR Stade (see Fig. 4).

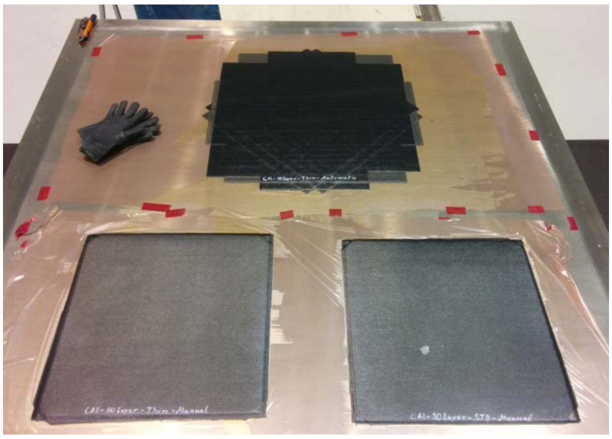


Fig. 4 CAI laminates after curing

4 Specimen preparation

4.1 Crippling panel

Before the specimens were cut out, the stringers were impacted with a gas gun. (see Fig. 5). A wooden fixture was used to support the panel comparable to an aircraft environment. (see Fig. 6). The impacts began with a calibration of the necessary impact energy (for more details see chap. 5.1). Six impacts were used for the calibration, and afterwards six more impacts were used as final impacts for the later crippling panels. The panels were cut afterwards to a size of 160 x 315 mm by waterjet trimming at Airbus Hamburg.

Fig. 5 Impacting of the crippling panel at Airbus Bremen

The impacted and cut specimens (see Fig. 7) were sent to JAXA where they were prepared for the test of the ultimate crippling load. Part of the preparation involved machining massive aluminum blocks to absorb the compression force. Into these aluminum blocks the crippling panel is potted with resin, a drawing of which is shown in Fig. 7.

Fig. 6 Crippling panel fixture

Fig. 7 Impacted and cut crippling specimen

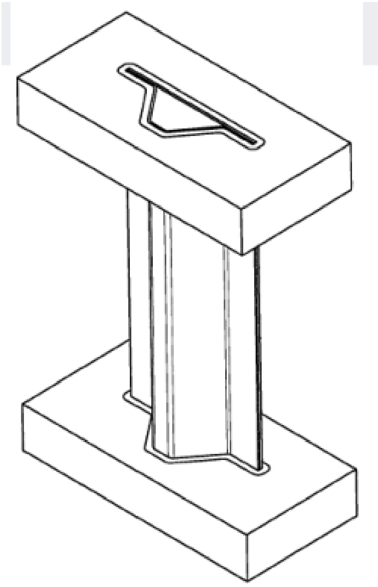


Fig. 8 Drawing of the potted crippling panel

4.2 CAI specimen

For the impact and compression tests, the CAI laminates were also sent to JAXA. Once there, the laminates were examined by ultrasonic (US) scanning, and then the areas for cutting the specimen were selected. The cut specimens were impacted by an Instron drop-weight test machine. The impacts started with a calibration of the necessary energy level (see chap. 5.3).

Fig. 9 Drop weight impact testing machine

5 Results

The tests are still ongoing, and the presented results are not complete.

5.1 Impacts at the crippling panels

The first trial began with an impact energy of about 20 J. The delamination area was then analyzed with a mobile US scanning device, revealing a large area of about 90 mm (see Fig. 9). A subsequent repeat trial produced an even larger delamination area. Consequently, the impact energy was decreased to 15 J and then to 10 J (see Tab. 1). Following calibration, the impact energy for the six crippling panel specimens was set to 10 J (see Tab. 2 and Fig. 10).

Tab. 1 Impact calibration results

#	Energy (J)	Length (mm)
1	20	90
1 b	21	140
2	15	n/a
3	10	80
4	10	95
5	10	85

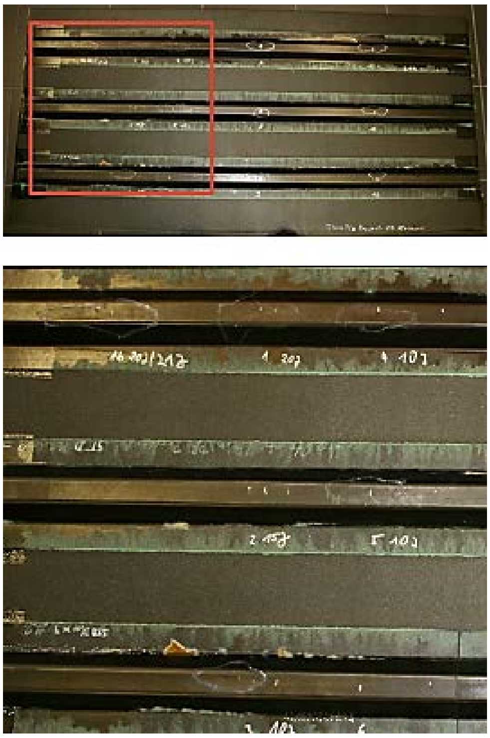


Fig. 10 Panel with impacts

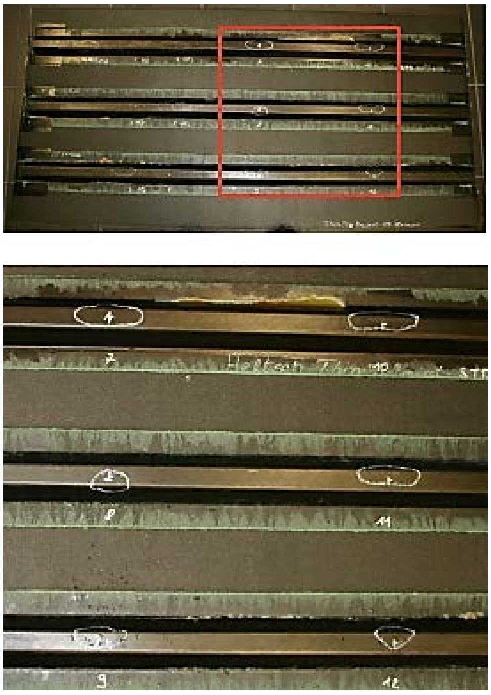


Fig. 11 Impacts for crippling test

Tab. 2 Impacts for crippling tests, standard ply

#	Energy (J)	Length (mm)
7	10	90
8	10	50
9	10	70
10	10	100
11	10	90
12	10	55

The calibration of the impact energy for the thin-ply panels started with 10 J. With a length of just 20 mm, the resultant delamination area was considerably smaller in contrast to the standard-ply stringers. The energy level was therefore increased to 14 J, and then further to 20 J (see Tab. 3). Even at 20 J the delamination area was still comparably small (see Fig. 12). Notable is that the area is limited to the stringer head with no delamination into the flanges unlike the standard-ply stringers. The impacts for the crippling test specimen were done with 20 J (see Tab. 4).

Tab. 3 Impact calibration results for thin ply

#	Energy (J)	Length (mm)
1	10	20
2	14	20
3	20	40
4	20	60
5	15	25
6	18	30

Tab. 4 Impacts for crippling tests, thin-ply

#	Energy (J)	Length (mm)
7	20	40
8	20	40
9	20	40
10	20	45
11	20	45
12	20	45

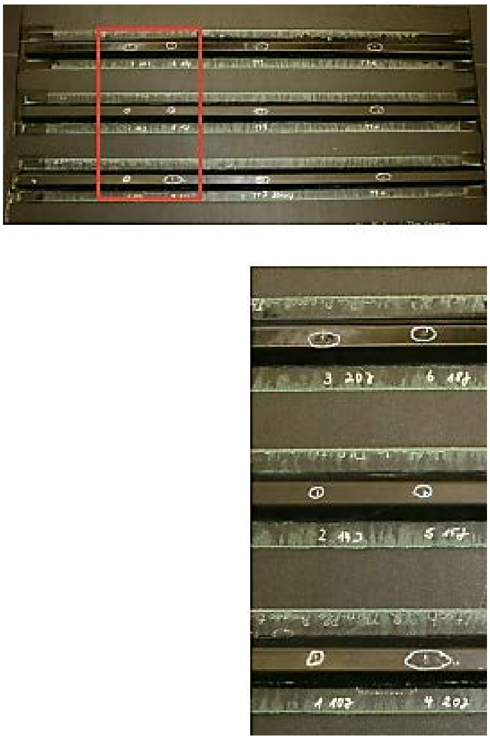
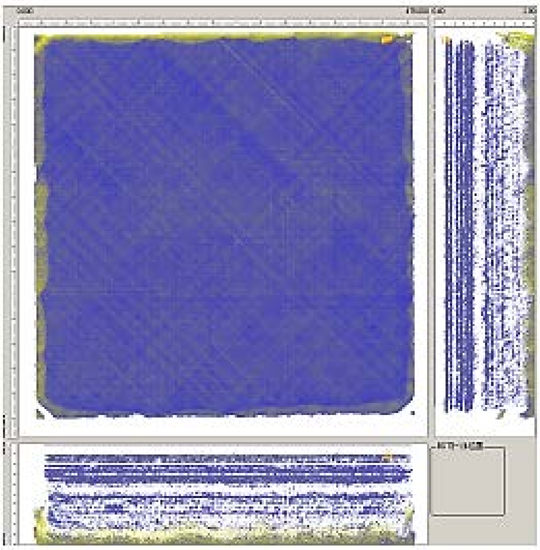


Fig. 12 Calibration impacts at thin-ply

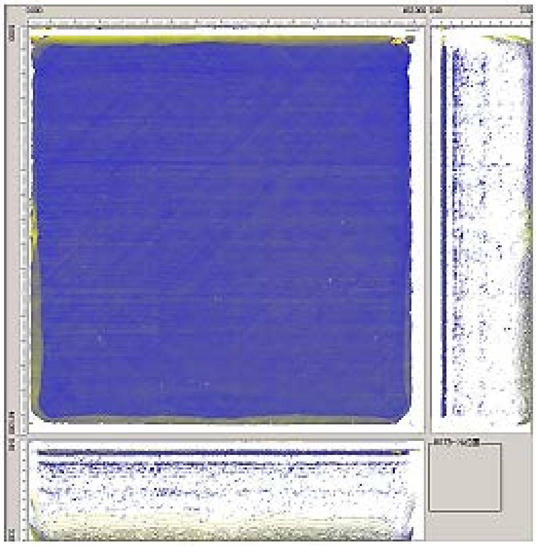
5.2 US scans of the CAI laminates

The laminates are scanned by US before cutting out the CAI specimens. While the US scan shows good quality for the manual layups (see Fig 13 and Fig. 14), the quality of the automatic layup is worse (see Fig. 15). The bad quality of the automatic layup is also visible by a wavy surface, whereas the surface of the manual layups is smooth.



From top surface

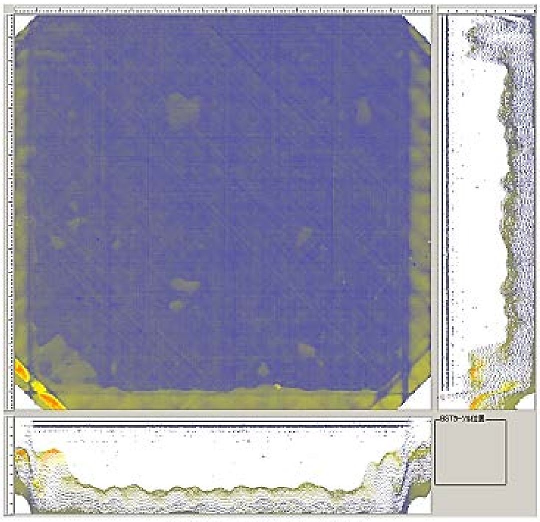
Fig. 13 US scan of standard-ply manual layup



From top surface

Fig. 14 US scan of thin-ply manual layup

The wavy surface is caused by some problems during automatic layup. No staggering of courses is used, causing plies of the next layer with the same direction to completely follow the same course. As the laminate builds up, so do the tolerances, thus producing a wavy surface. Furthermore, the tolerance for the gap between two tapes was set to zero inside the offline programming environment. This in combination with machine tolerances may cause slight tape overlay. As a consequence, the offline programming for the next automatic layup should include staggering and a gap tolerance greater than zero.



From back surface

Fig. 15 US scan of thin-ply automatic layup

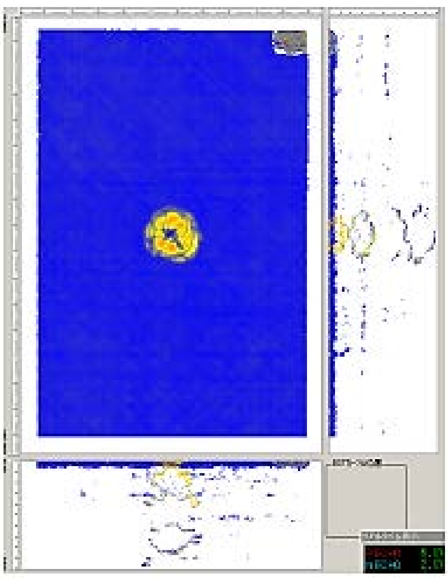
Beside the US scans, for each of the three plates a photomicrography is performed. This reveals that during manual layup of the thin-ply laminate some of the 80 layers are falsely oriented. Therefore, this laminate could not be used for the CAI tests and only two laminates – the automatic thin and the manual standard – are left for the examination of the CAI properties.

5.3 Impacting and failure load of the CAI specimen

As previously mentioned, the test campaign is still ongoing. Up to now, six specimens are tested (see Tab. 5) as part of the energy level calibration. Three impacts for the standard-ply manual layup and thin-ply automatic layup are made with 10 J, 20 J and 30 J.

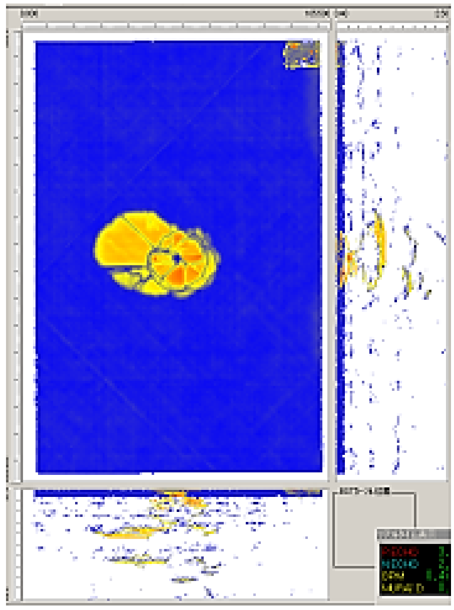
Tab. 5 Overview of impacted specimen and energy

Specimen #	01	02	03	04	05	06	07	08
Standard manual						10	20.85	30
Thin automatic			10		30	20.4		



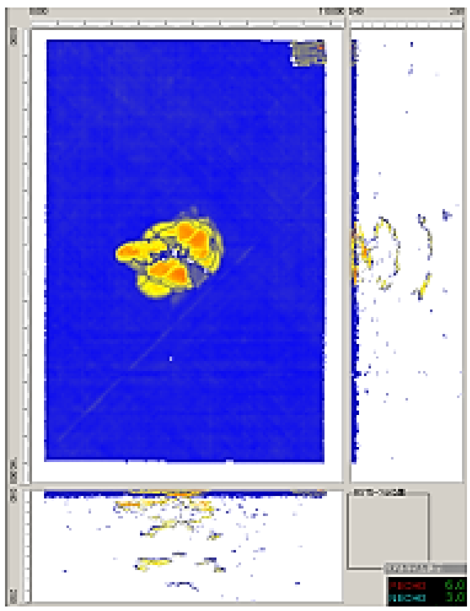
NDI from Impact side

Fig. 16 Standard manual at 10 J



NDI from Impact side

Fig. 17 Standard manual at 20.85 J

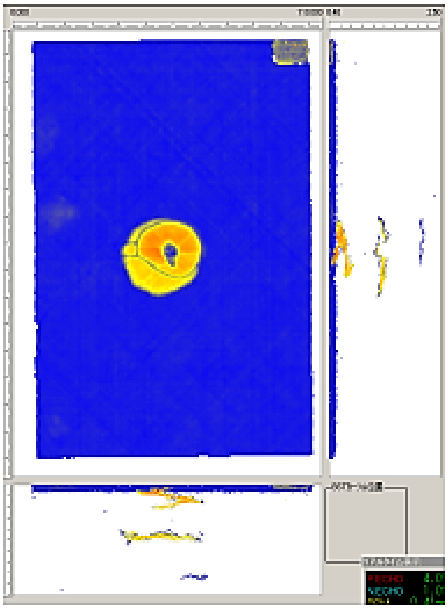


NDI from Impact side

Fig. 18 Standard manual at 30 J

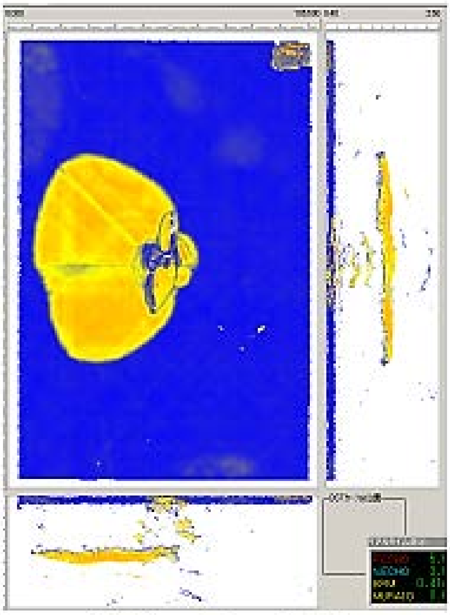
The impacts on the standard-ply specimens exhibit typical behavior. The delamination area increases from 10 to 20 J (see Fig. 17 and Fig. 18), and at 20 J the first slight flaking occurs. At 30 J the flaking increases (see Fig. 19).

The thin-ply specimens show a different behavior. At 10 J the delamination is slightly larger than the standard ply, and at 20 J the difference in delamination is substantially larger; however, at 30 J the delamination area is smaller than at 20 J. This may be explained by the large dent and broken fibers at the back side of the specimen. Additionally, flaking occurs at 10 J and 20 J.



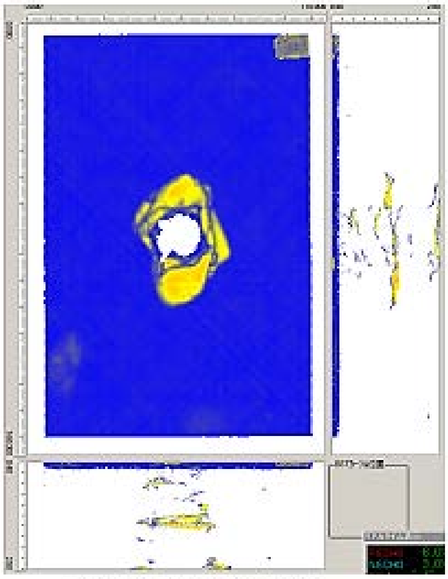
NDI from Impact side

Fig. 19 Thin automatic at 10 J



NDI from Impact side

Fig. 20 Thin automatic at 20.4 J



NDI from Impact side

Fig. 21 Thin automatic at 30 J

According to Saito [7], the large delamination in the 20 J thin automatic specimen (see Fig. 20) could be explained by the layup order. For the 80 ply symmetric layup, the symmetry plane is set at the middle so that there are twin plies of the same orientation right in the middle of the specimen. Saito explains that for plies with 40 µm thickness cracks are effectively suppressed – but for the resulting 80 µm ply thickness this is not the case. Therefore, tension accumulates in the middle plane and the plies delaminate.

6 Summary and outlook

This paper describes the cooperation between ITCF, JAXA, DLR and Airbus for the research on thin-ply laminates. For the first time the manufacturing and preparation of thin-ply specimen at element level is described. The test campaign is not yet finished, but the first results are quite interesting. The delamination area at the thin-ply crippling stringer is significantly smaller than for those with standard plies; however, the CAI specimens show the opposite behavior. Here the delamination in the thin-ply specimens is significantly larger. This could be explained by the double middle layer and the resulting missing crack suppression effect.

As a result of the failure in the layup order, the plan is to refabricate the manual-layup thin-ply laminate. For the new layup, Fukui delivered a slightly different material with a thickness of 50 µm.

This prepreg still consists of 40 µm thin-ply prepreg, but has an additional 10 µm toughening layer.

Along with the additional manual layup, a second automatic layup will be manufactured. This layup will use some of the approaches to overcome the described problems which caused poor quality. Hence, it will use an offline-programmed path including staggering, a gap tolerance greater than zero and the 50 µm material.

Finally, the results for the failure load of the crippling stringers and of the CAI specimens will soon be presented.

References

[1] Nguyen C., Bülow C., Krombholz C., Kruse F., Kawabe K. , Hirano Y. and Linde P. "Experiments for automatic layup of thin-ply prepreg and investigation of their parameters", SAMPE Japan 2015, Kanazawa

[2] Amacher R., Smith W., Botsisz J., Dransfeld C. and Cugnoniz J. "New design opportunities using thin-ply composites". JEC Composites Magazine, No 96, pp 33-35, 2015.

[3] Sihn S., Kim R., Kawabe K. and Tsai S. "Experimental studies of thin-ply laminated composites". *Composites Science and Technology*, Vol. 67, Issue 6, pp 996-1008, 2007.

[4] Amacher R., Cugnoni J., Botsis J., Sorensen L., Smith W., Dransfeld C. "Thin ply composites: Experimental characterization and modeling of size-effects", *Composites Science and Technology*, Vol. 101, pp. 121-132, 2014

[5] Yokozeki T., Aoki Y., Ogasawara T., "Experimental characterization of strength and damage resistance properties of thin-ply carbon fiber/toughened epoxy laminates", *Composite Structures*, Vol. 82, Issue 3, pp. 382-389, 2008

[6] Arteiro A., Catalanotti G., Xavier J., Camanho P.P., "Notched response of non-crimp fabric thin-ply laminates", *Composites Science and Technology*, Vol. 79, pp 97-114, 2013

[7] Saito H., Morita M., Kawabe K., Kanesaki M., Takeuchi H., Tanaka M. and Kimpara I. "Effect of ply-thickness on impact damage morphology in CFRP laminates". *Journal of Reinforced Plastics and Composites*, Vol.30, issue: 13, 2011