Tow spreading technology and mechanical properties of thin ply laminates

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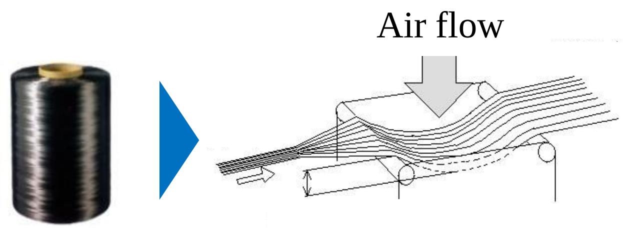
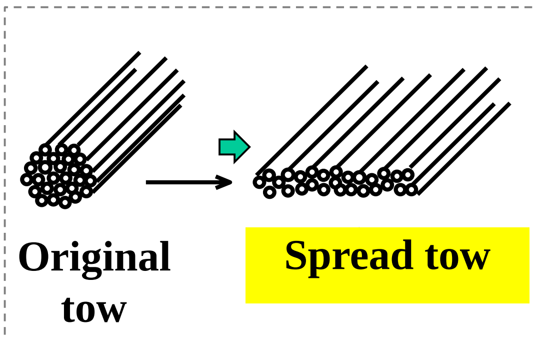
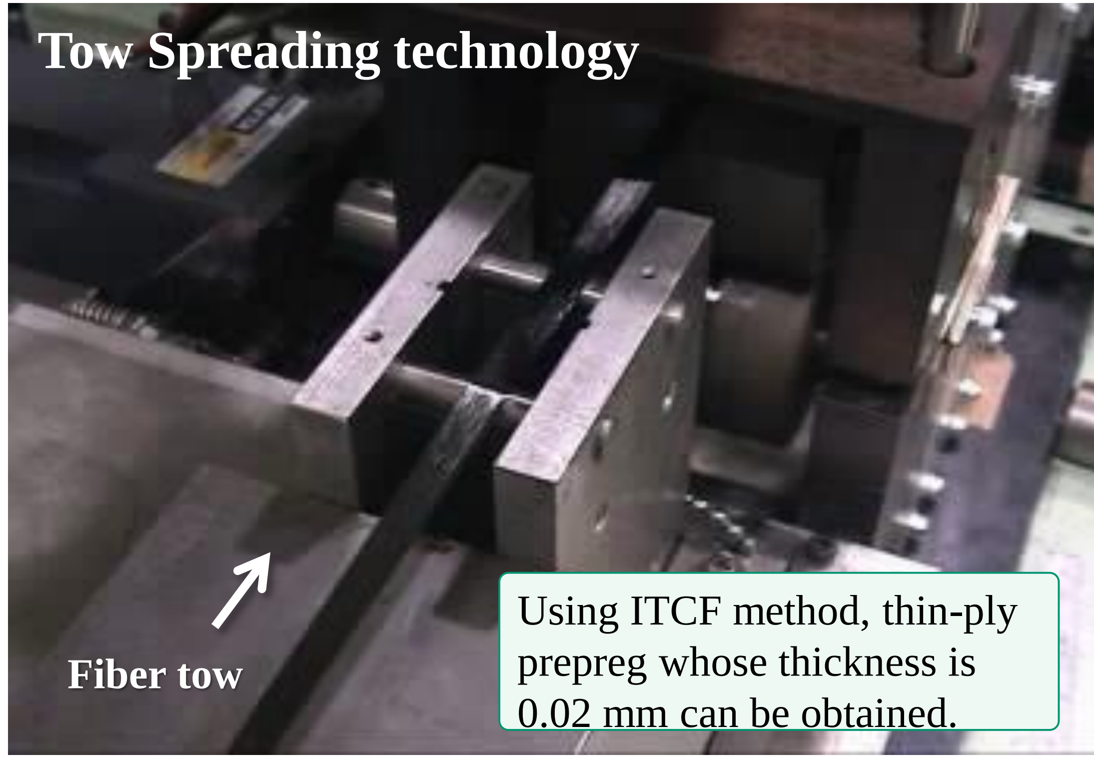
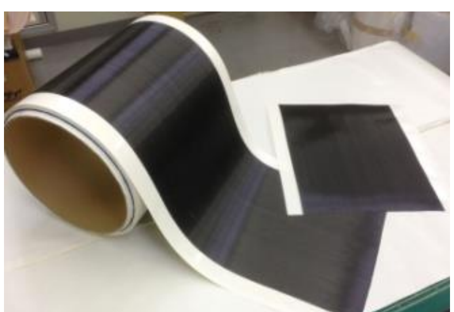
Tow spreading technology (ITCF method)



Fiber tow **Spreading technology**







Thin-ply prepreg

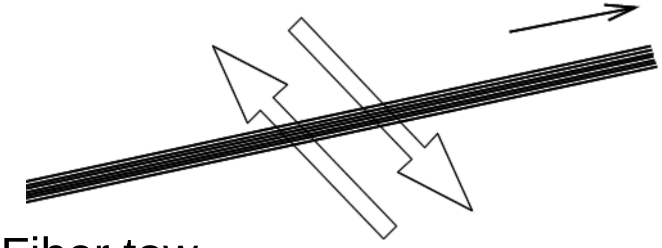
By use of Tow spreading technology,

- **Thin-ply prepreg (thickness: 0.02～0.1mm) can be produced.**
- **Thin-ply prepreg using both of thermoset and thermoplastic resin can be produced.**

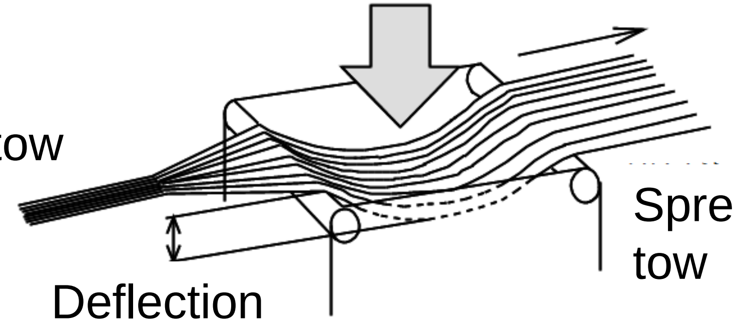
Tow spreading technology (ITCF method)

In conventional method,
Fiber tow should be contact with a roll under the tension.

It is difficult to spread the fiber tow.
Furthermore, the damages of fiber tow easily occur.



In our original method,
Tension along the fiber tow is kept low.
Fiber tow can be spread easily without any damage by use of the air flow.



Features of Tow spreading technology (ITCF method)

☑ **Force and tension to the fiber tow are not necessary.**

→ Damage of the fiber tow does not occur.

☑ **Fiber tow can be spread in a moment by airflow.**

→ High speed production process can be realized.

☑ **Spreading width of the fiber tow can be arbitrarily determined.**

→ Thickness and fiber volume fraction can be designed freely.

→ Large tow such as 50K with a low cost can be used.

☑ **Spread fiber tow can be easily impregnated with the resin.**

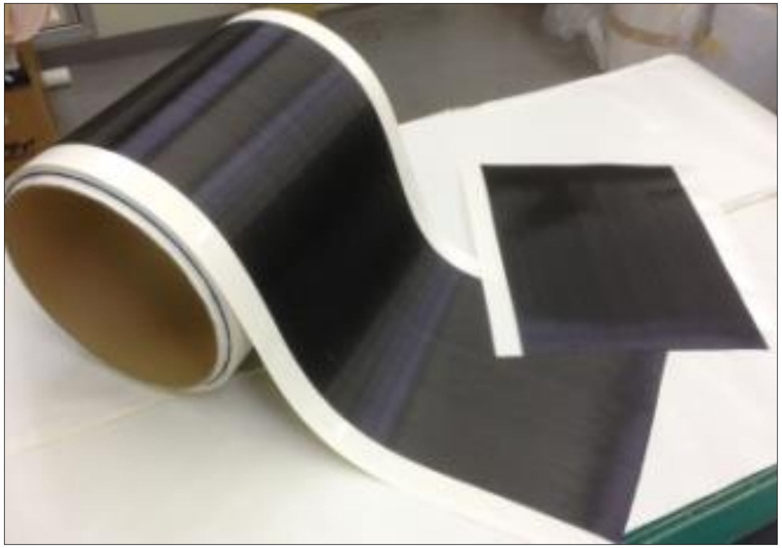
→ Even in the case of thermoplastic resin which has a high viscosity, no void in the laminates can be realized.

Our original tow spreading technology leads CFRP products with the high performances.

【Video】The manufacturing process of the thermoset thin ply prepreg

Carbon fiber: TR50S15K (Mitsubishi Chemical), Fiber areal weight: 22 g/m^2, Thickness of the prepreg: 0.02 mm, Vf: 60%

Specifications of the thermoset thin ply prepreg



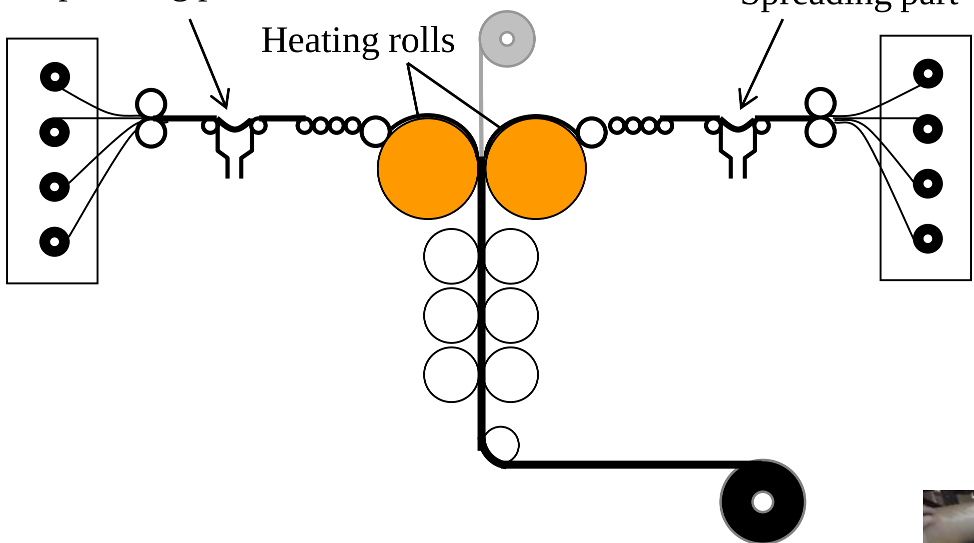
CF/ Epoxy

Glass fiber/ Epoxy,
Aramid fiber/ Epoxy

Fiber volume fraction:30-70%
The maximum sheet width:320 mm
Thickness:20-120μm（can be designed freely）
Production speed > 10m/m
Glass fiber, Aramid fiber etc. are also available.

High speed production with a low cost

Thermoplastic thin-ply prepreg



Schematic drawing and picture of thermoplastic prepreg machine

Thermoplastic prepreg machine

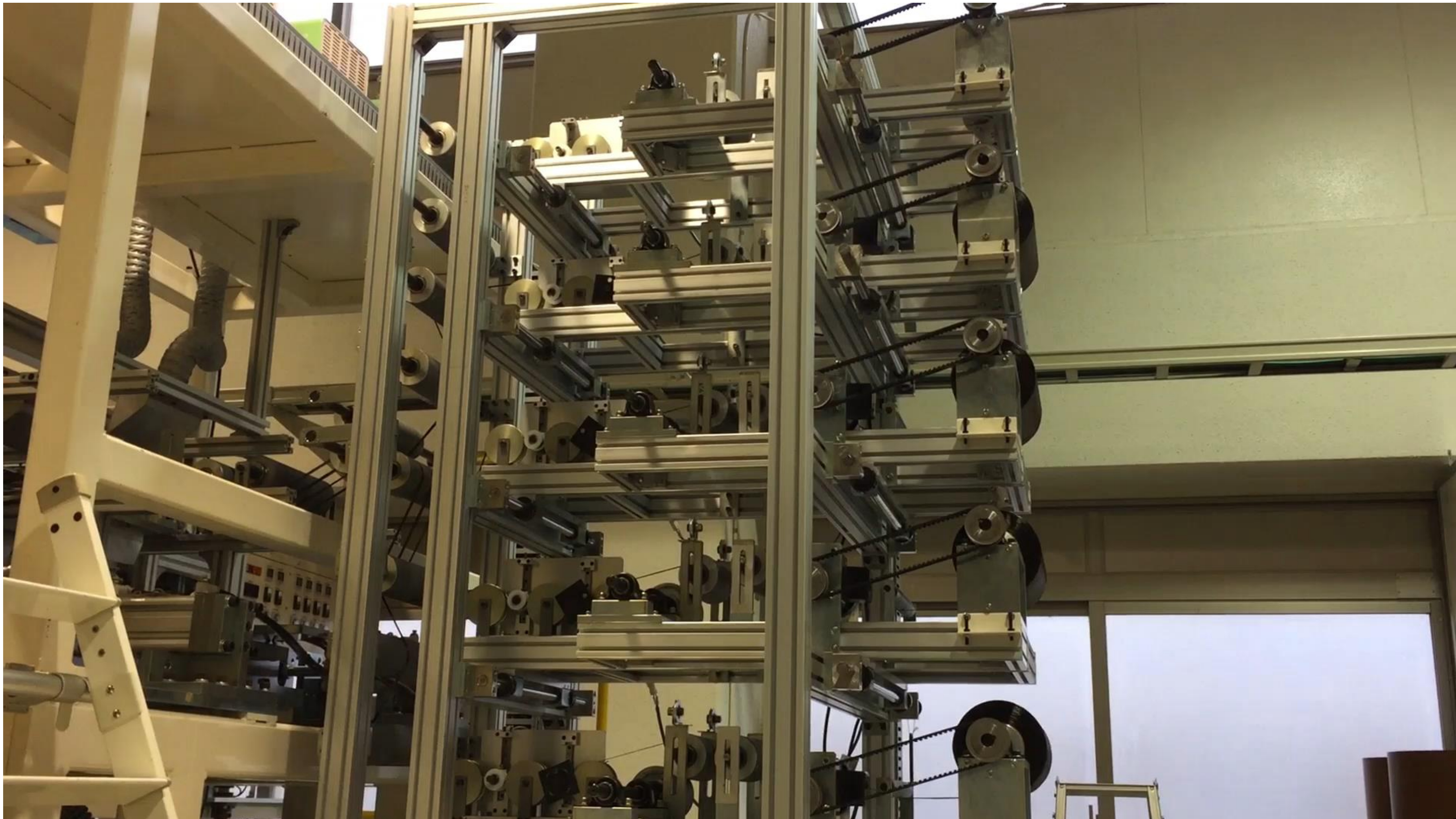
- Thickness: 0.04 mm (40μm)～
- Fiber weight: 40 g/m^2 ～
- Vf: 30～60%
- Production speed: ＞20 m/min

Picture and cross sectional image of thin ply thermoplastic prepreg

Thermoplastic prepreg using super-engineering plastic, such as PEEK, PPS also can be produced by the same manufacturing process.

【Video】The manufacturing process of the thermoplastic thin ply prepreg

Carbon fiber: TR50S15K (Mitsubishi Chemical), Fiber areal weight: 22 g/m^2,
Matrix resin: PA6, Thickness of the prepreg: 0.05 mm, Vf: 55%,
Production speed: 20 m/min



Laminates using thermoplastic thin ply prepreg

Tow spreading technology

Spread fiber tow (CF) +resin film (PA6)

Thickness : 0.04 mm

Conventional prepreg

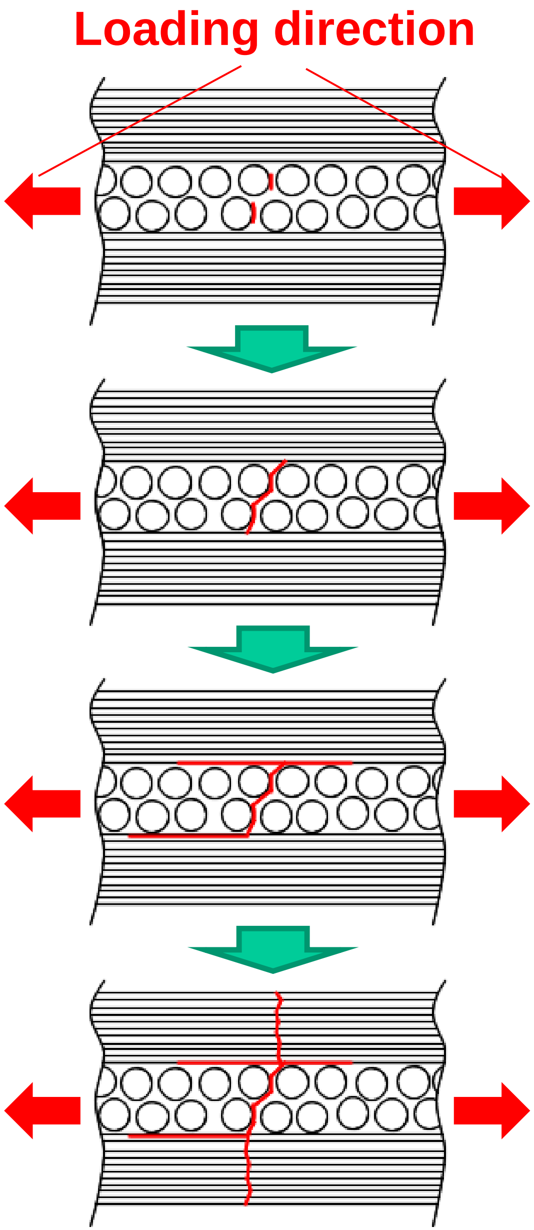
Non spread fiber tow(CF)＋resin (PA6)

Thickness : 0.14 mm

Laminated in the same direction and Molded by hot press

Impregnation of resin to fiber tow and dispersion of fiber can be improved.

Typical failure mode of CFRP laminates



Micro crack (Debonding between fiber and resin)

Interfacial debonding between fiber and resin occurs

Transverse crack

Micro crack propagates and associate with other one. Then, matrix crack penetrates the ply.

Delamination

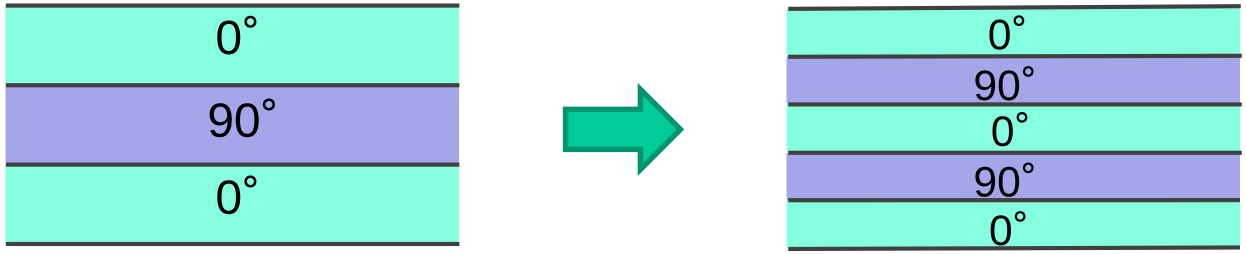
Transverse crack propagates through the interlayer region leading to the delamination. This failure reduces the stiffness of the laminates remarkably.

Fiber breakage

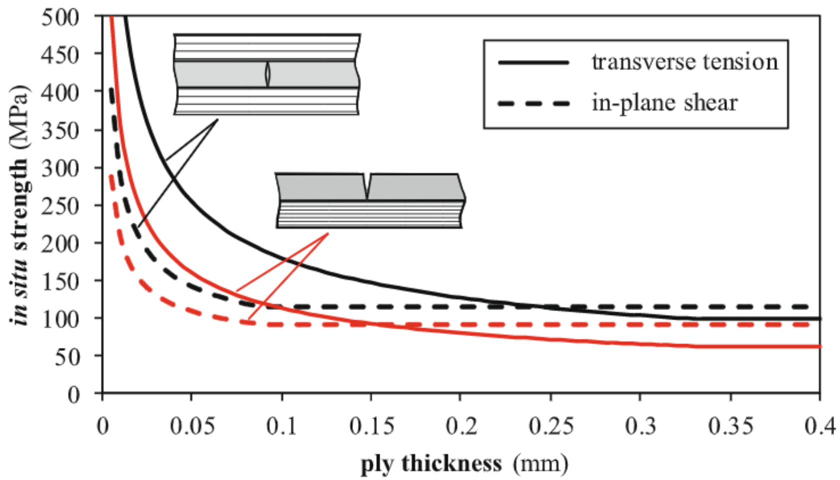
Fiber breakage along the loading direction occurs. Laminates cannot bear the load, leading to the final failure.

Suppressing effect of ply failure in thin ply laminates

Thin ply effect (Constraining effect)



Propagation of the transverse crack is suppressed by constraining effect by neighboring layers.



Relationship between in-situ strength and ply thickness [1]

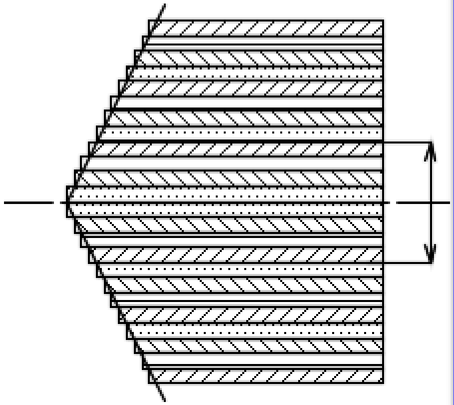
Constraining strength by neighboring layer become stronger as the ply thickness is deceased.

First ply failure such as transverse crack is delayed or suppressed by decreasing the ply thickness.

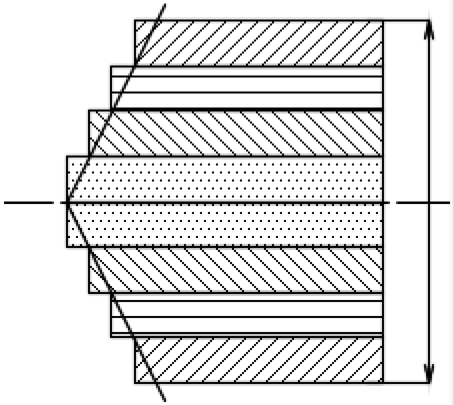
[1] A. Arteiro et al., “Thin-ply polymer composite materials: A review”, Composites A 132, 2020.

Merits of using thin ply prepreg

Ply drop off



Thin ply laminates



Thick ply laminates

◎***Thickness of the minimum ply become also thin.***
ex) Minimum ply [45/0/-45/90]$_{sym.}$➔ 0.16 mm
➔Thinning the thickness of structural material can be realized.

◎***The pattern of configuration of the laminates can be increased.***
ex) Laminates with a thickness of 1 mm
Thin ply : 1 mm / 0.02 mm = 50 plies
Thick ply : 1mm / 0.2 mm = 5 plies
➔ The freedom of the design of structural material can be expanded.

◎***Accuracy of the formability can be enhanced.***
ex) Ply drop off : The smooth curvature can be realized.

◎***Potential strength of carbon fiber can be utilized.***
Mechanical properties of the laminates is improved by decreasing the ply thickness.
➔ The thinner structure with a light weight can be realized.

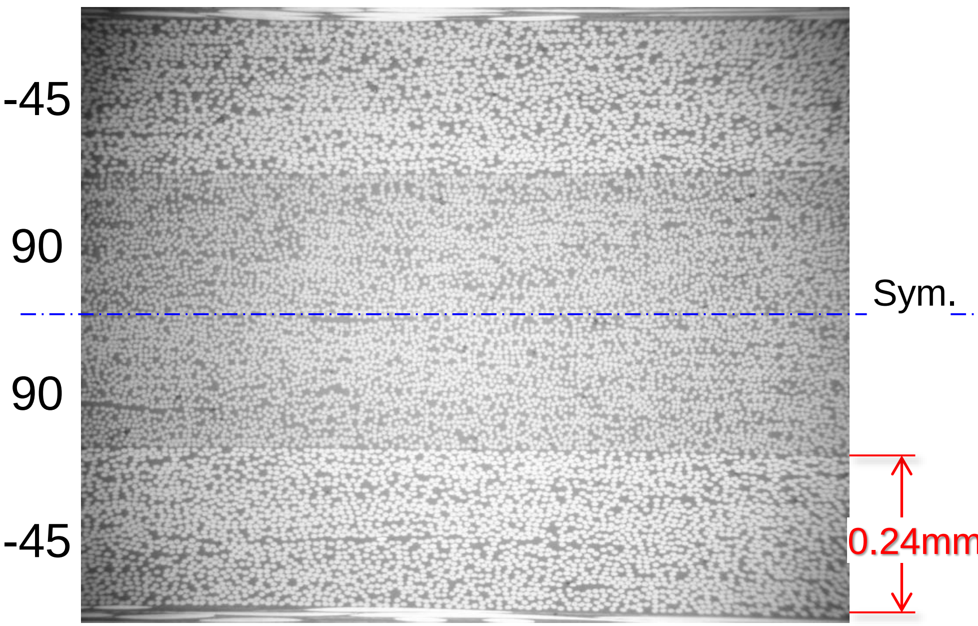
Comparison of mechanical properties between thin and thick ply laminates

Thick-ply | **Thin-ply**

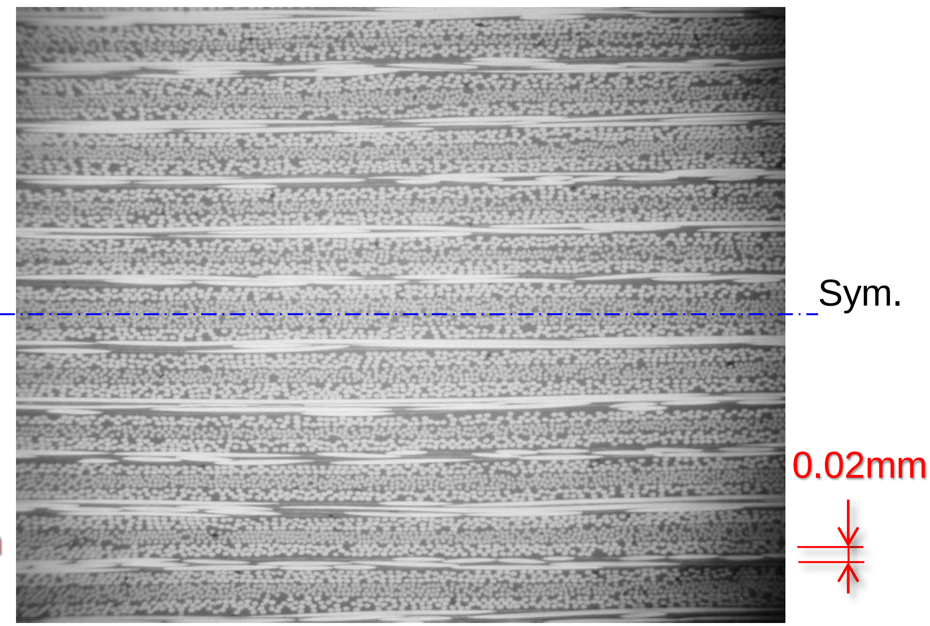
Cross-sectional images of quasi-isotropic laminates

Quasi-isotropic laminates : [45/ 0/ -45/ 90]$_s$

Ply thickness: 0.24mm

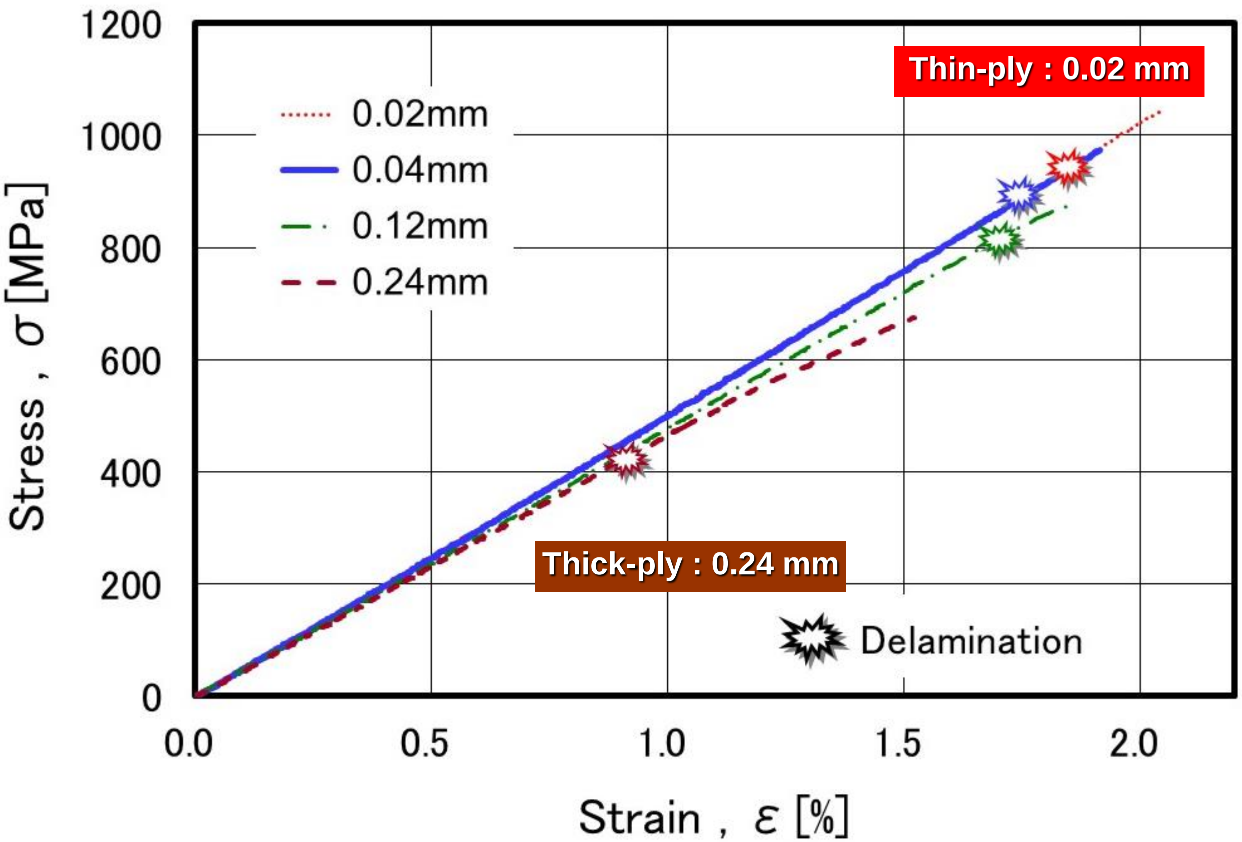


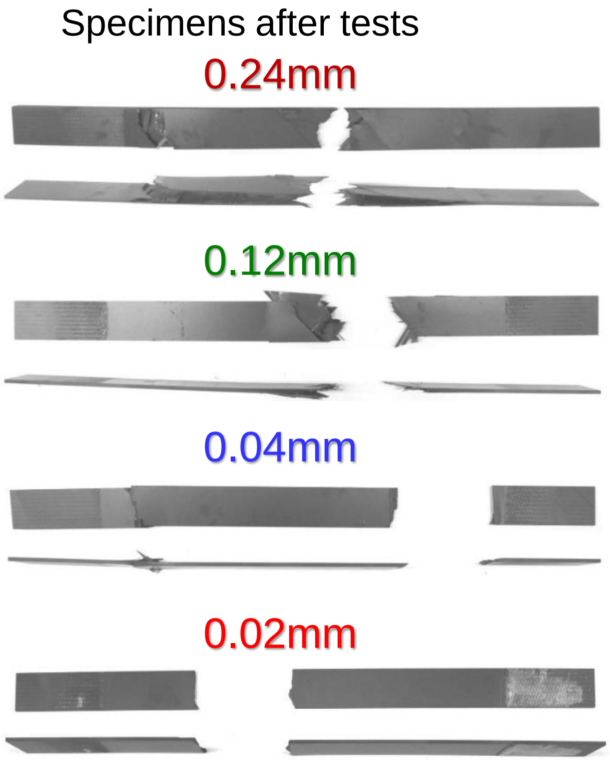
Ply thickness: 0.02mm



The more ply can be inserted in case of thin ply laminates.

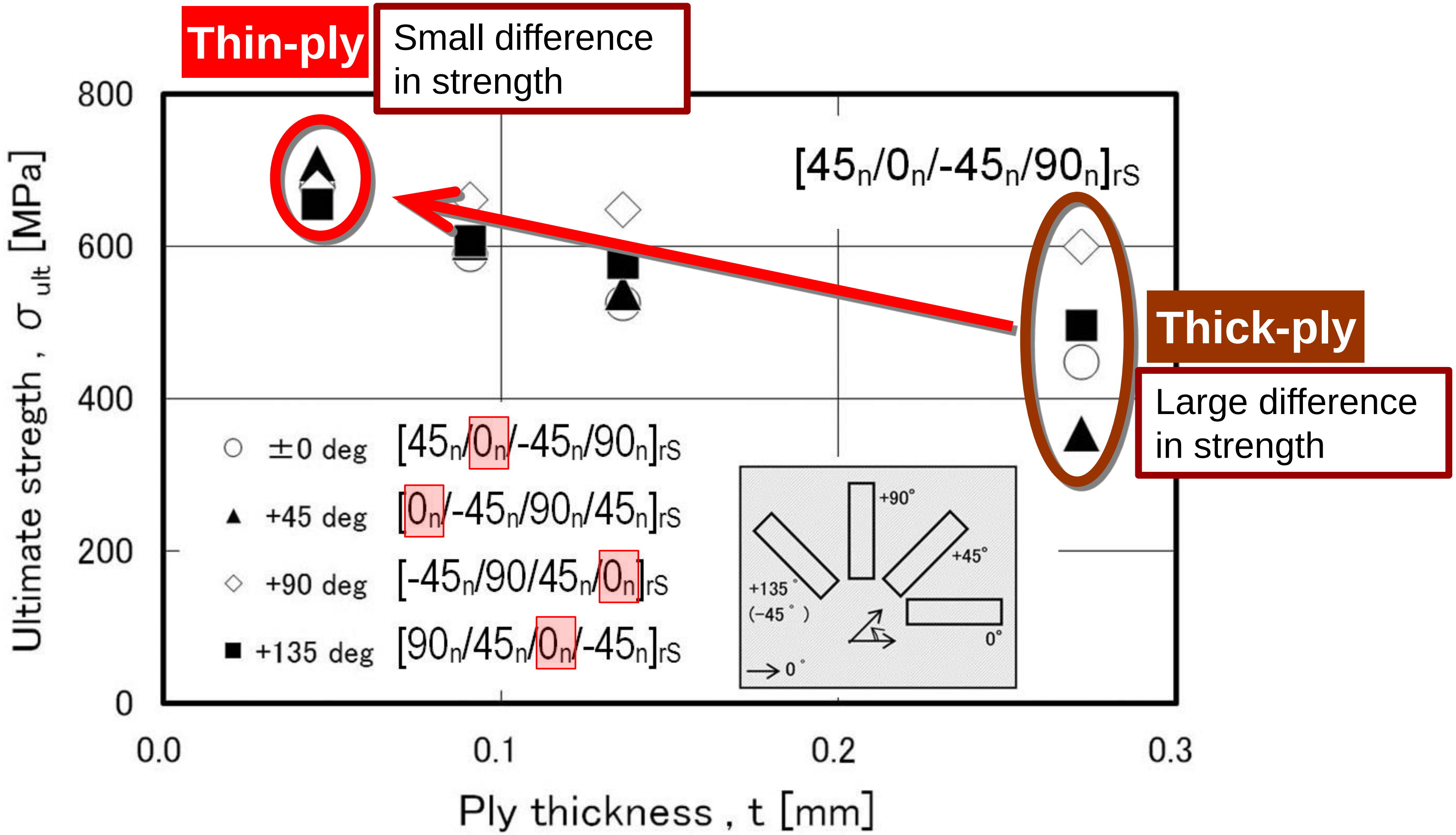
Tensile properties





Delamination was suppressed until the final failure, thus tensile property was improved by decreasing ply thickness.

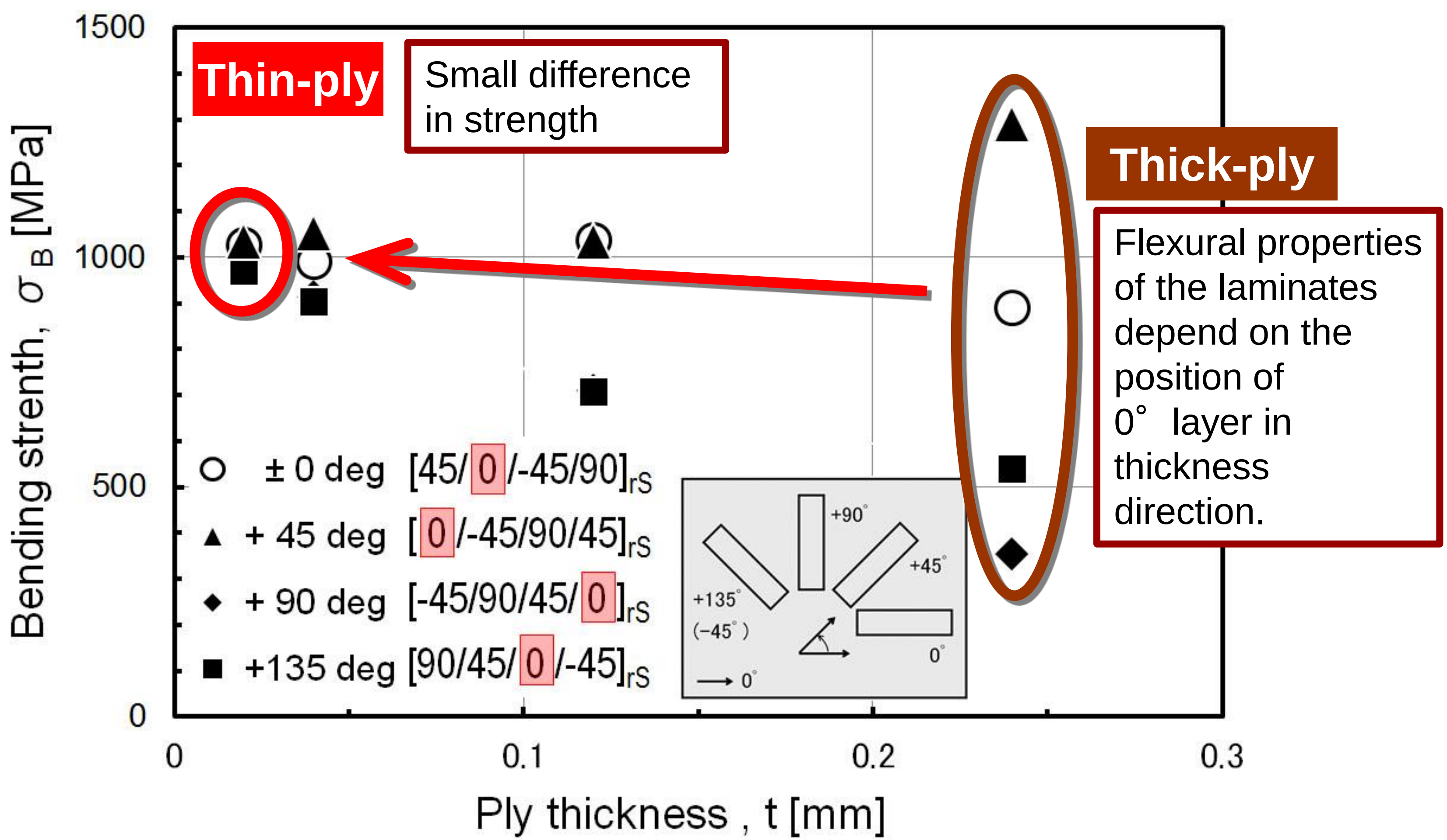
Compressive properties



Compressive properties were also improved. Differences in strength between different directions were decreased.

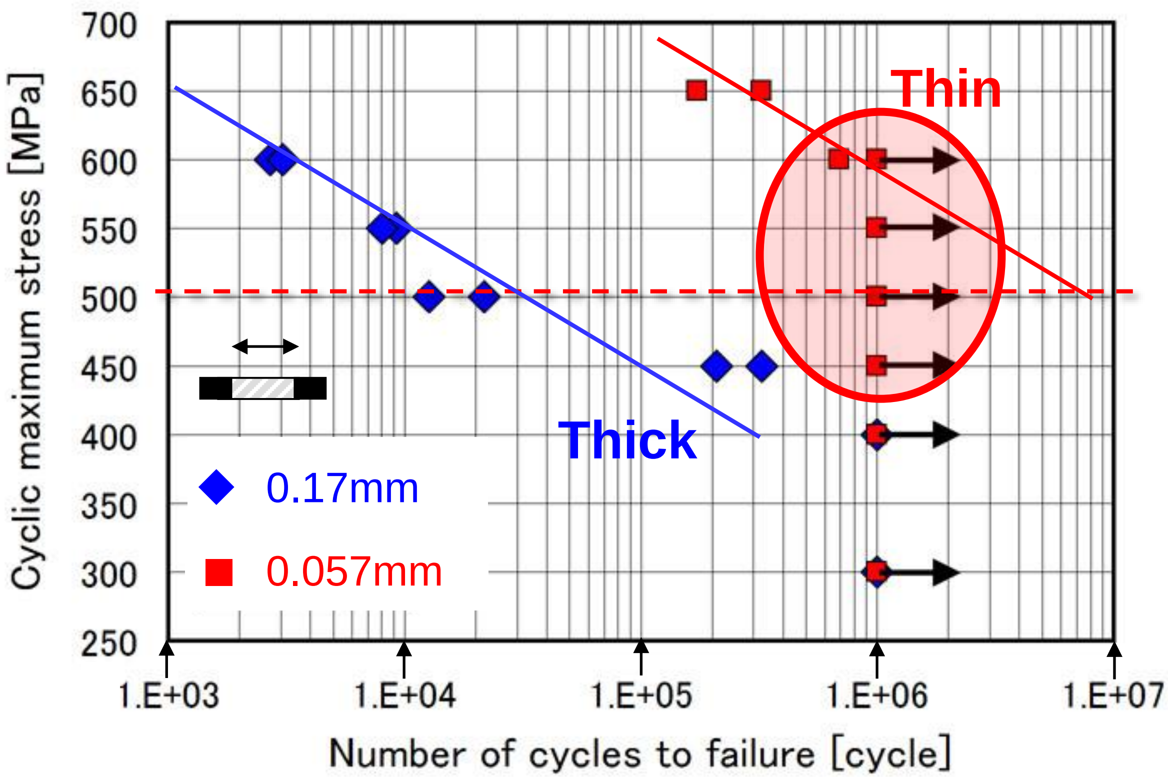
[2] K. Kawabe et al., "Effect of ply thickness on compressive properties in multidirectionally laminated composite", J Jpn Compos Mater. 34(5), 2008.

Flexural properties



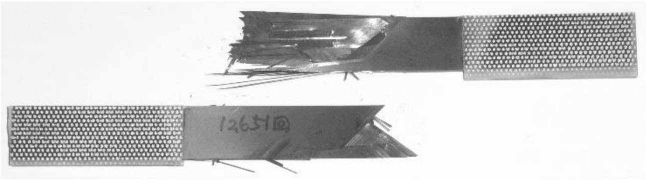
Differences in flexural properties between different directions were also decreased by decreasing ply thickness.

Fatigue properties

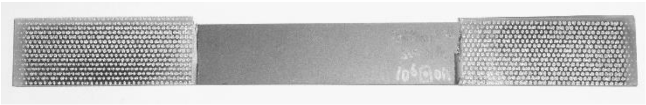


Images of specimens
Maximum stress: 500 [MPa]

【Ply thickness: 0.171 mm】



【Ply thickness: 0.057 mm】



Stress ratio: 1/10

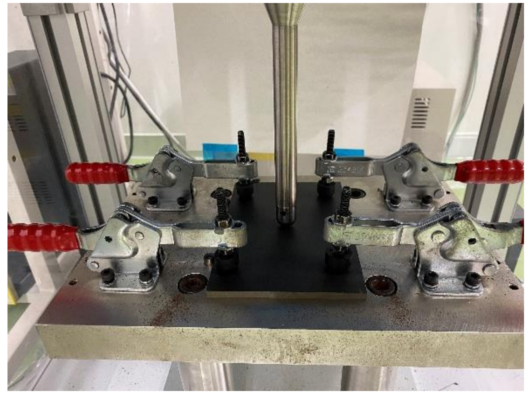
Frequency: 5Hz

Fatigue properties were improved, thus fatigue life was remarkably extended by thinning the ply thickness.

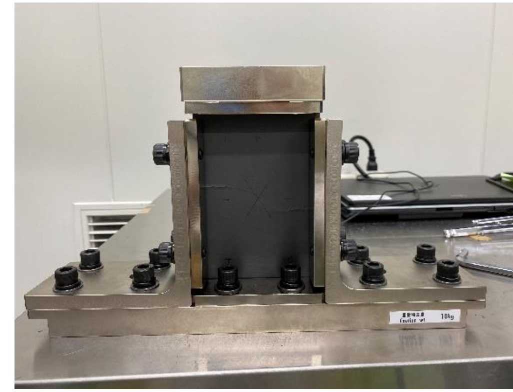
Impact and CAI tests

- Specimens

Quasi-isotropic laminates :
[45/ 0/ -45/ 90]s
Ply thickness:
・0.02 mm (Thin)
・0.24 mm (Thick)



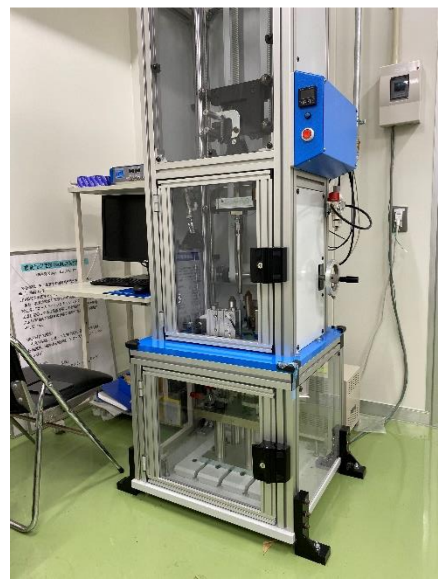
Specimen of impact test



Jig for CAI test

- Test methods:

・Impact tests: ASTM D 7136M
Impact energy：3, 5, 7 J/mm
Impactor mass: 5 kg
・CAI tests: ASTM D 7137M



Weight drop impactor

Ultrasonic scan

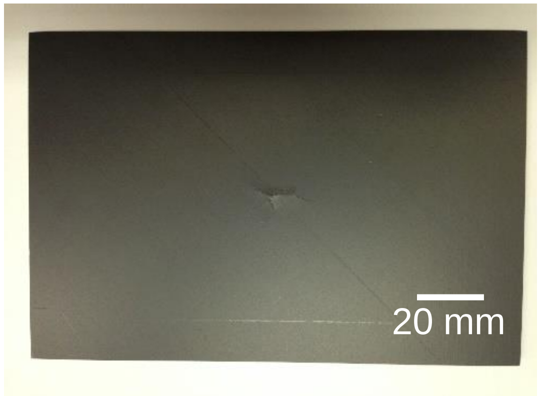
The effects of ply thickness and impact energy on the damage modes in impact tests and CAI strength were investigated.

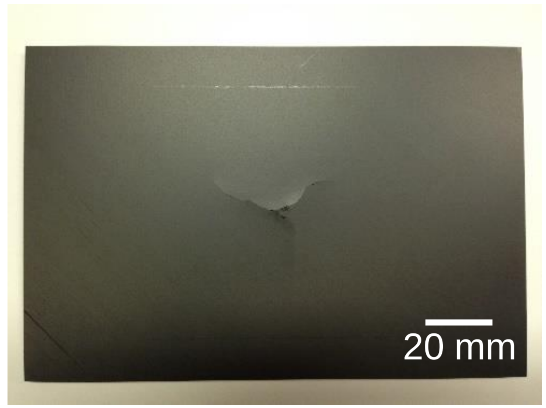
Failure mode after the impact loading

Thin ply laminates（Ply thickness: 0.02 mm）

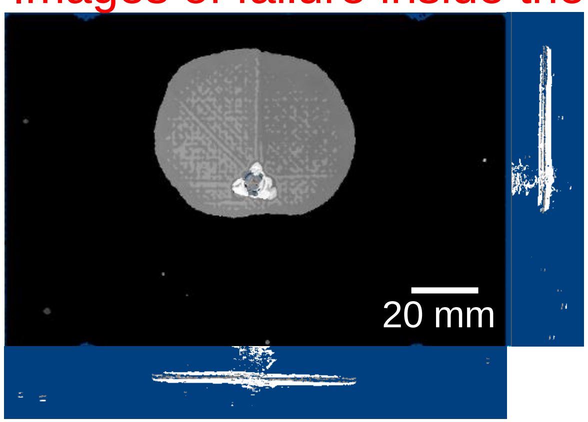
3 J/mm　　　5 J/mm　　　7 J/mm

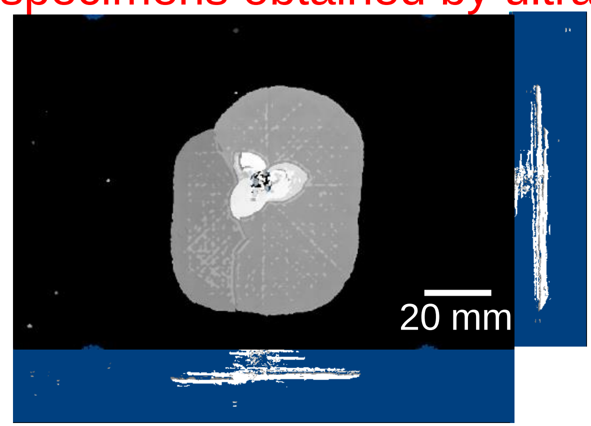
Images of the back faces

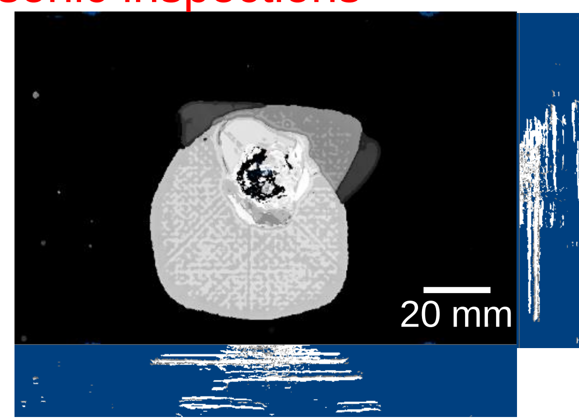




Images of failure inside the specimens obtained by ultrasonic inspections







An extremely large delamination occurred near the mid-plane and the size of delamination became larger with increase of the impact energies. In addition, fiber breakage at the back face which deteriorated residual compressive strength was observed.

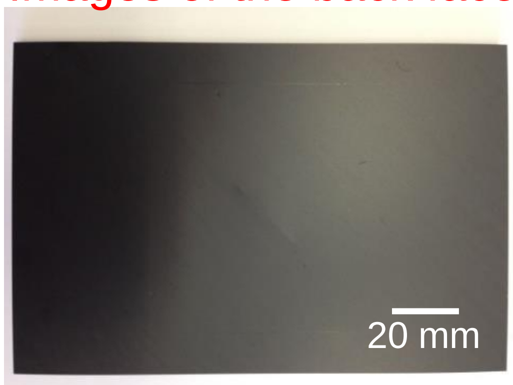
[3] K. Yamada et al., “Effect of ply thickness on impact damage modes of thin-ply CFRP laminates”, J Jpn Compos Mater. 46(1), 2020.

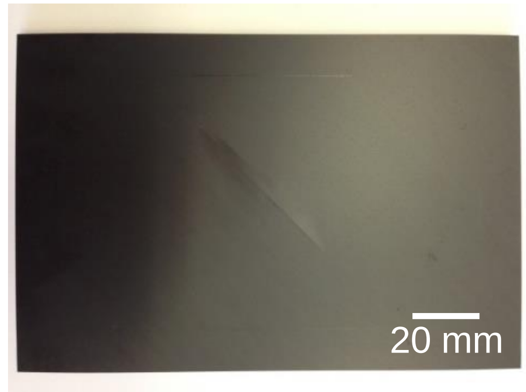
Failure mode after the impact loading

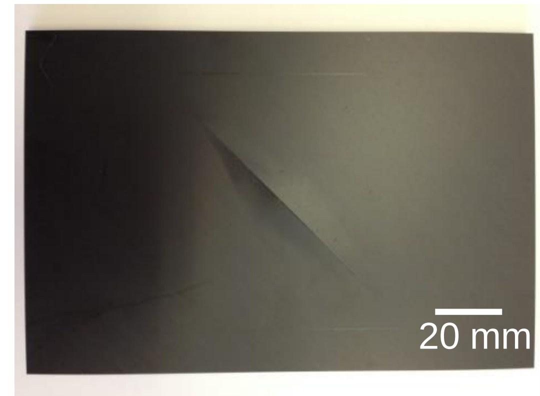
Thick laminates（Ply thickness: 0.24 mm）

3 J/mm 5 J/mm 7 J/mm

Images of the back faces







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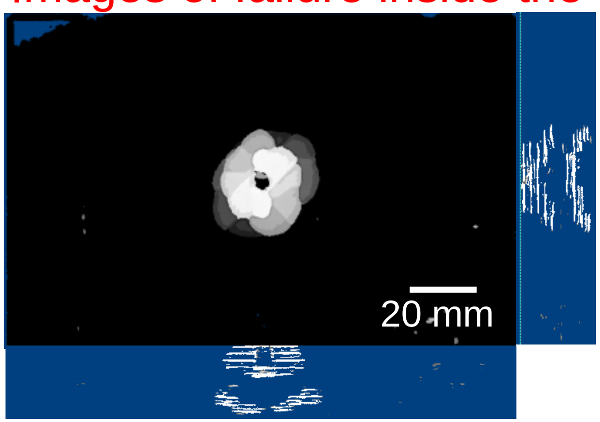
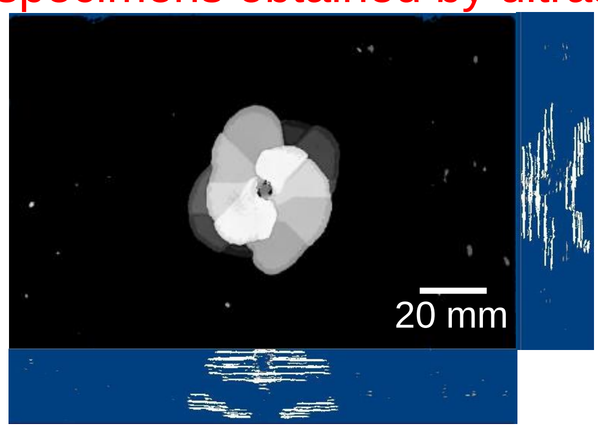
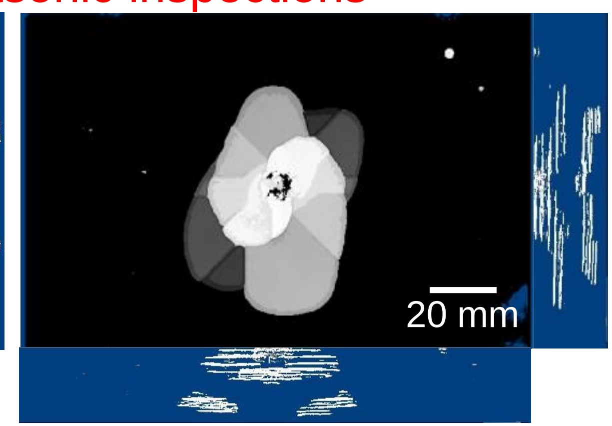


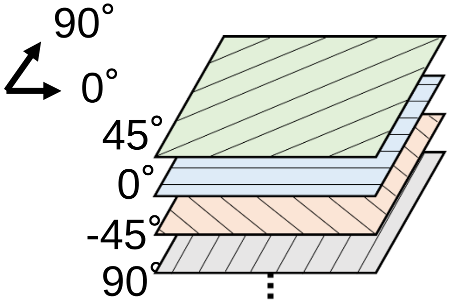


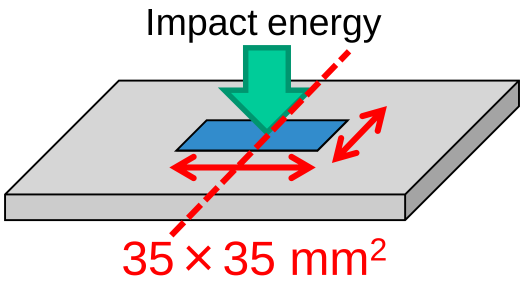


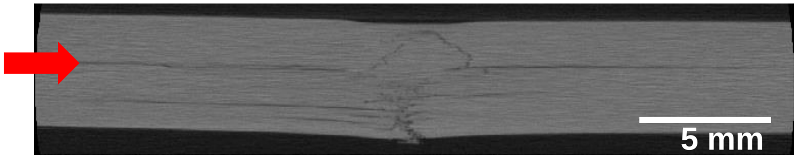
Distributed delaminations occurred in all interlaminar layers in thickness direction.

[3] K. Yamada et al., “Effect of ply thickness on impact damage modes of thin-ply CFRP laminates”, J Jpn Compos Mater. 46(1), 2020.

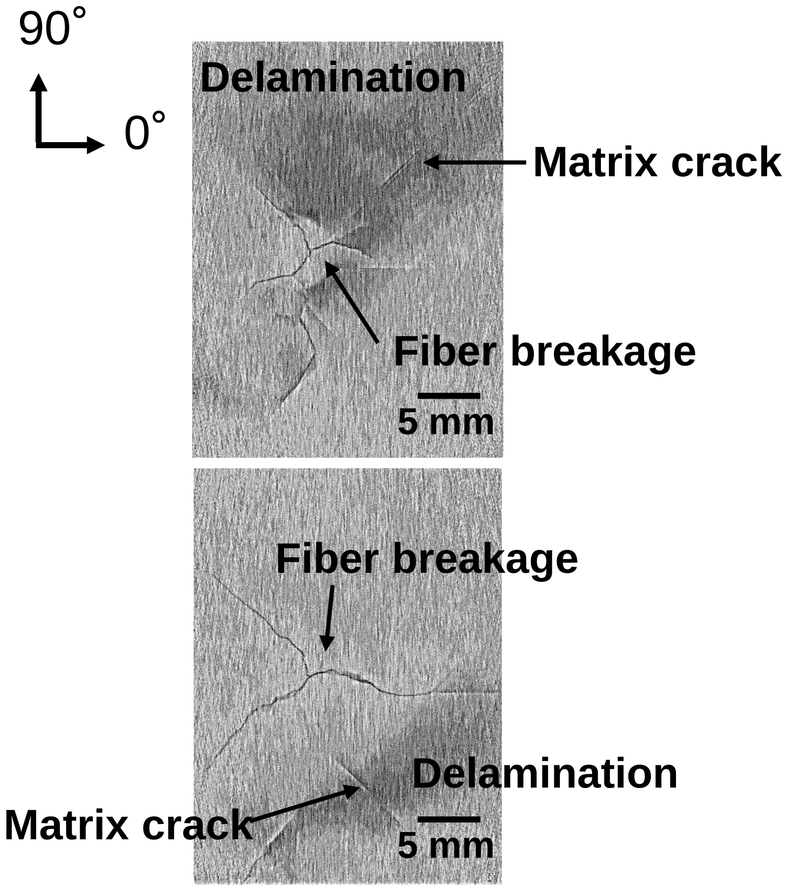
Observation by X-ray CT : Thin laminates (Ply thickness: 0.02 mm)

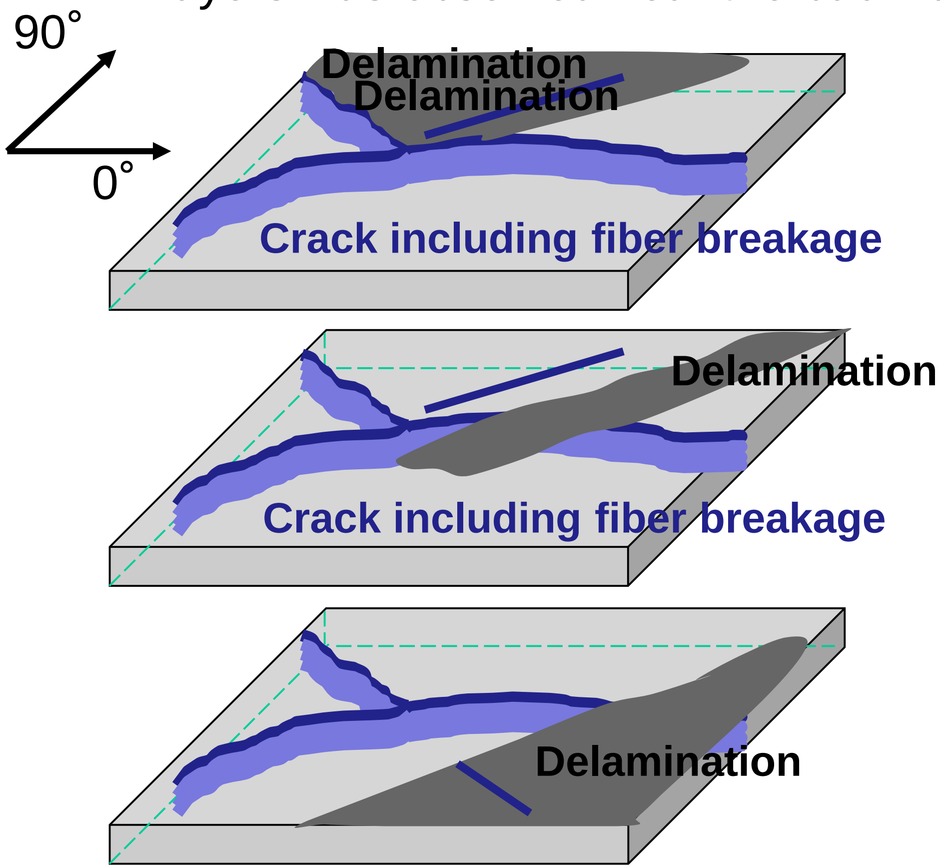






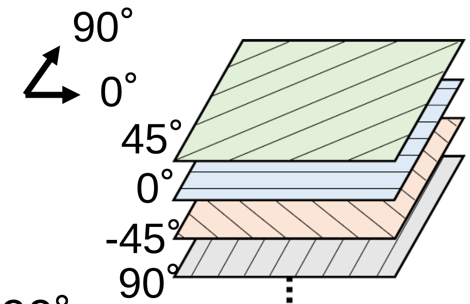
Fiber breakage perforating into various layers was observed near the back face

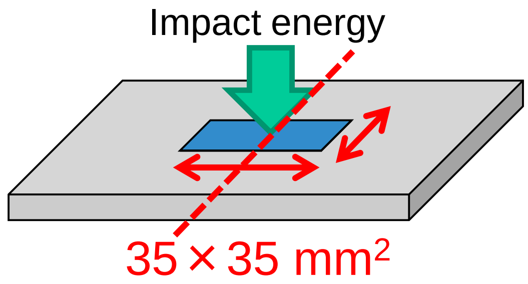


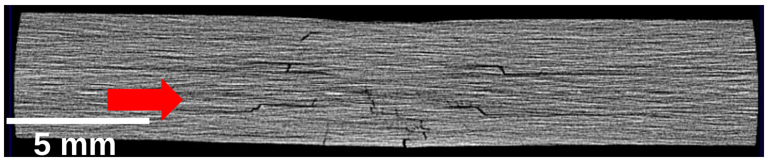


A large delamination near the mid-plane propagated with matrix cracks induced by fiber breakages.

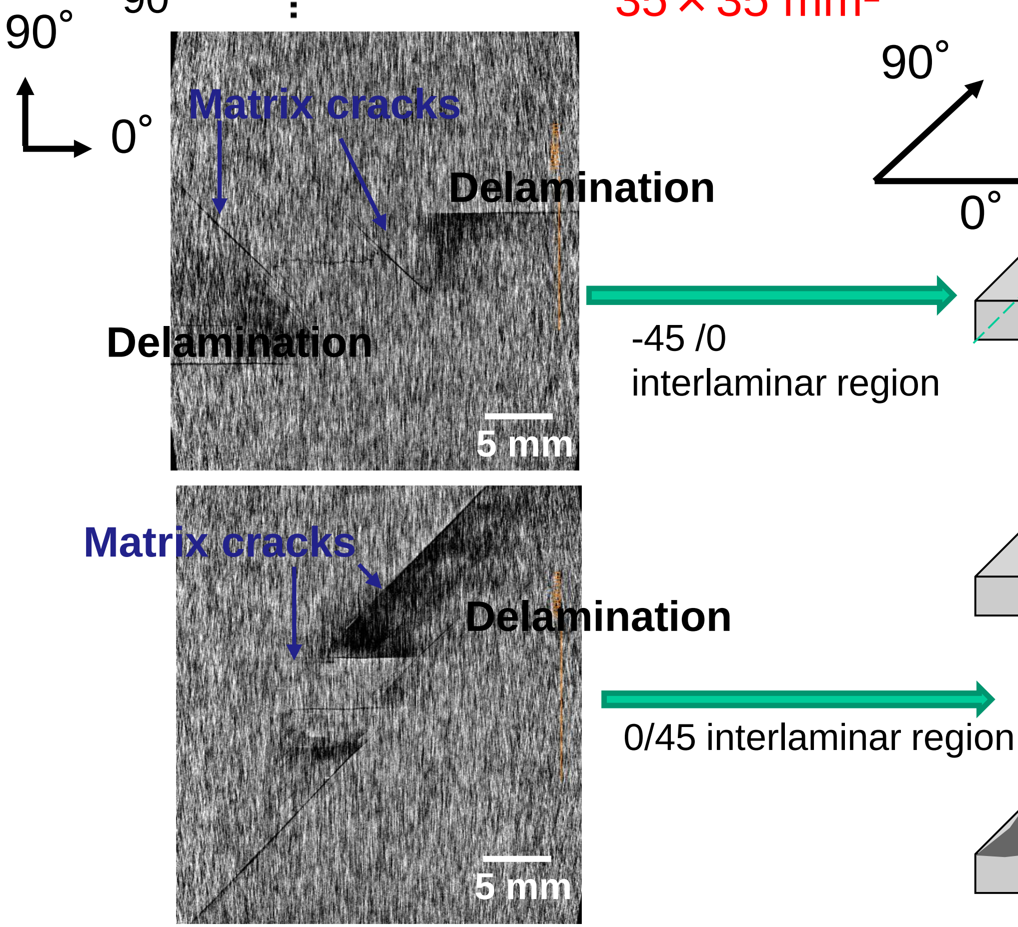
Observation by X-ray CT : Thick laminates (Ply thickness: 0.24 mm)

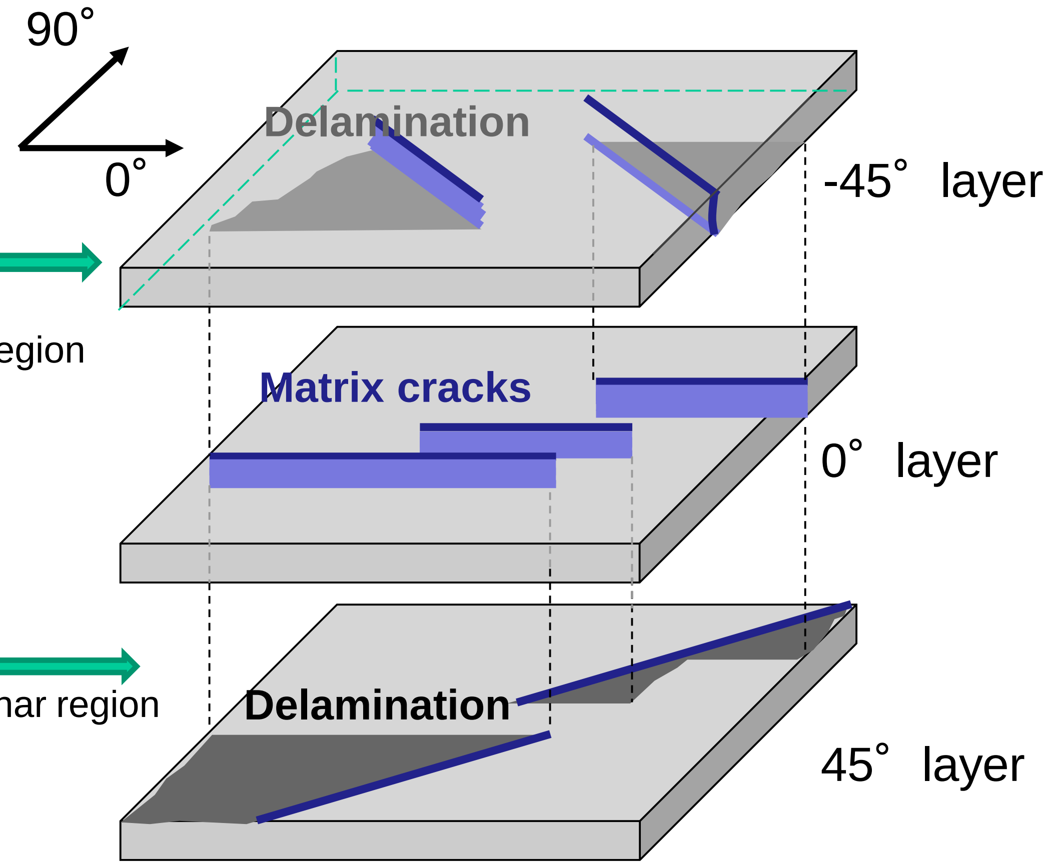






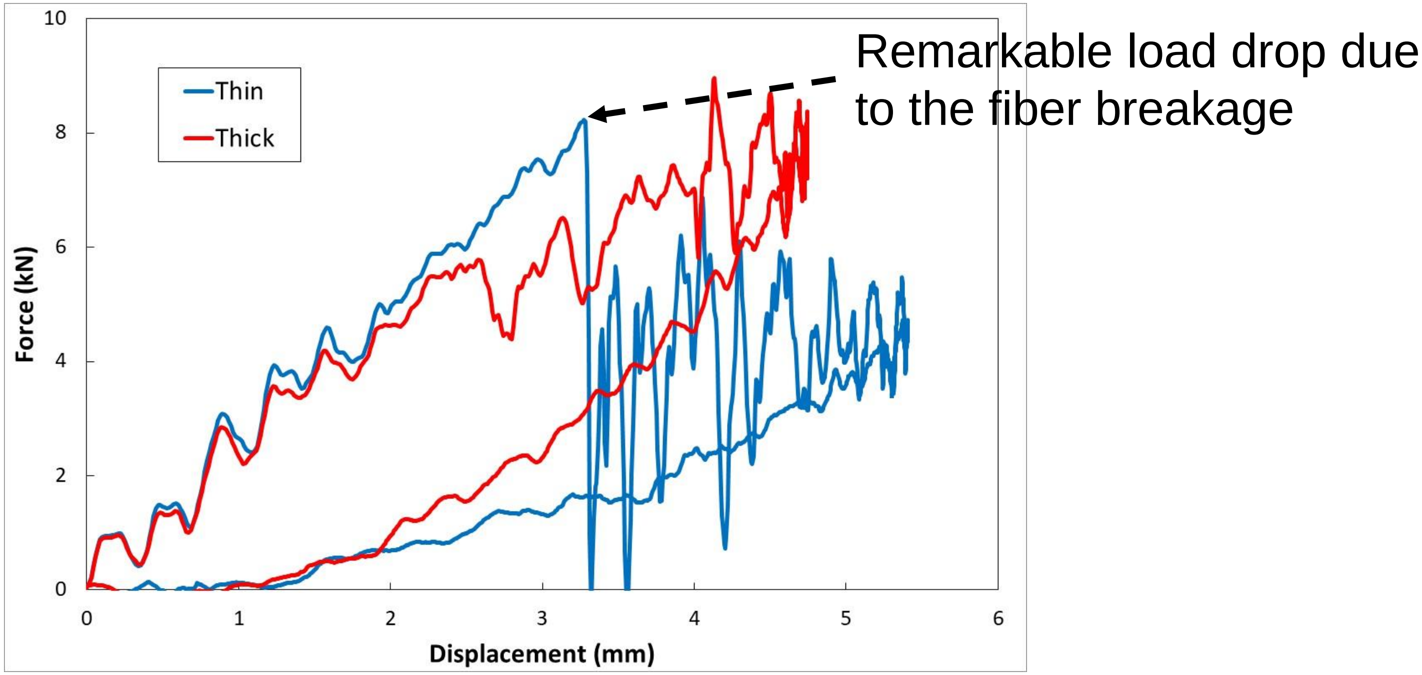
Delamination was induced by matrix crac





Matrix cracks occurred along the fiber direction in each layer and delamination occurred with connecting matrix cracks in neighbouring layers.

Dissipated energy during the impact events



Force – displacement curves of the impact tests

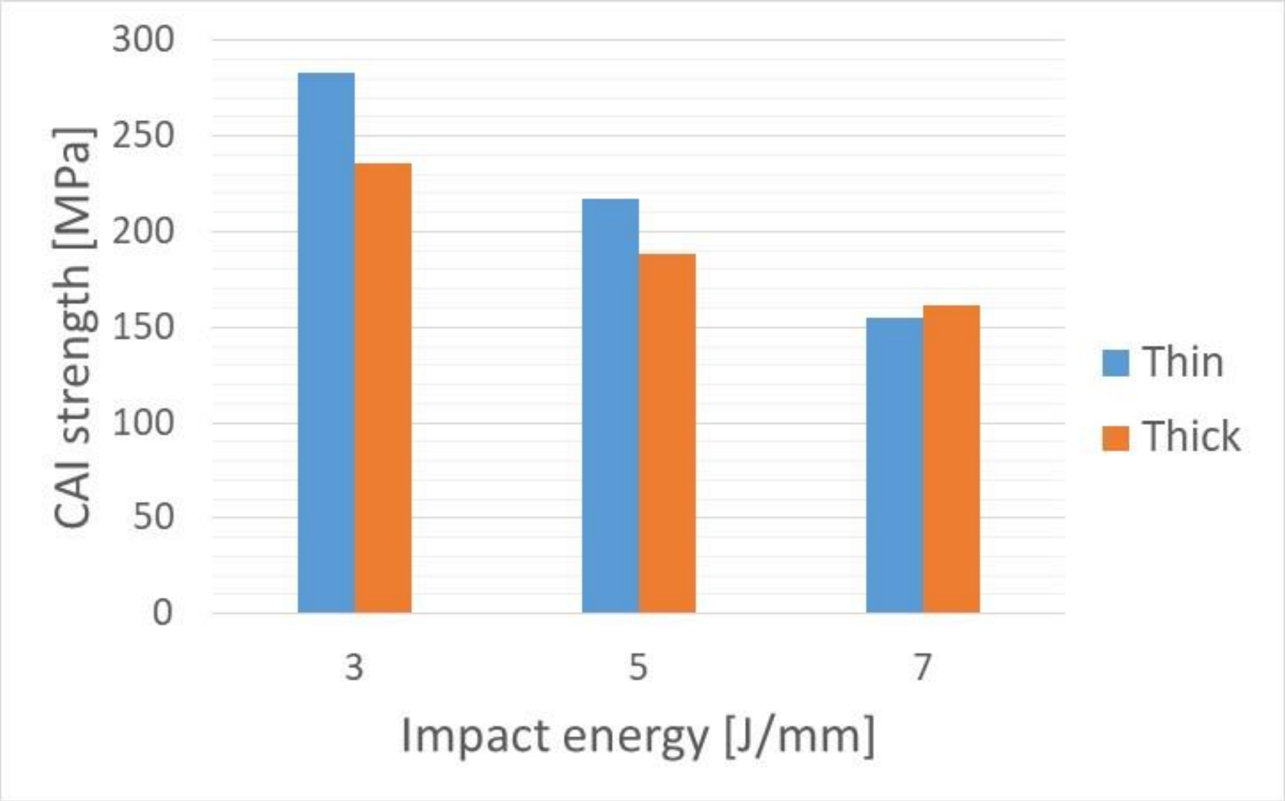
Dissipated energy during the impact events

Impact energy	3 J/mm	5 J/mm	7 J/mm
Thin	1.6 J/mm	3.5 J/mm	4.5 J/mm
Thick	1.4 J/mm	2.5 J/mm	3.5 J/mm

A remarkable load drop due to the fiber breakage was observed in Thin laminates. Thus, dissipated energy during an impact event was enhanced in thin ply laminates.

Residual compressive strength after the impact loading

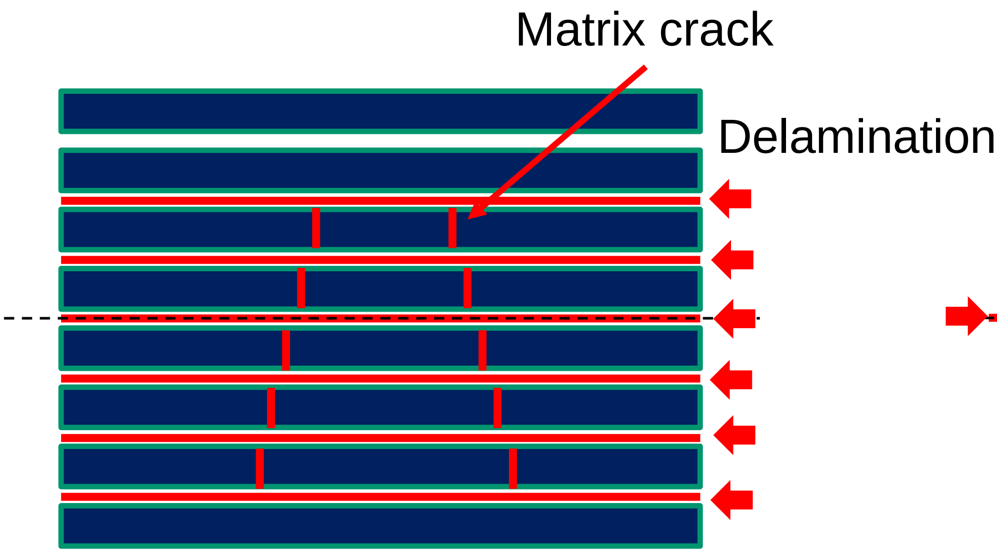
Compressive After Impact tests: ASTM D7137/D 7137M
Ply thickness: Thin (0.02 mm), Thick (0.24 mm)



CAI strength was improved by decreasing ply thickness when the impact energy was below 5 J/mm. In contrast, reduction of CAI strength in thin ply laminates was confirmed when the impact energy was 7 J/mm.

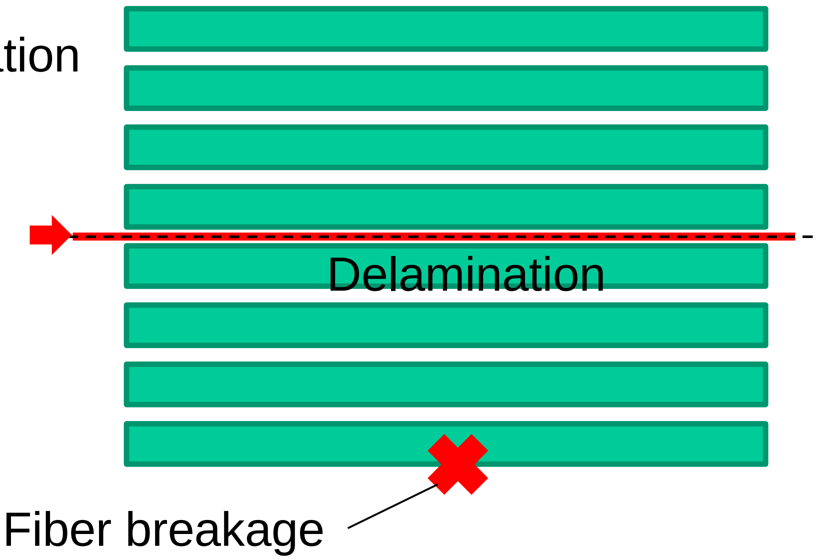
Failure mode after the impact loading

Thick ply laminates



Matrix crack in each layer induced delamination.

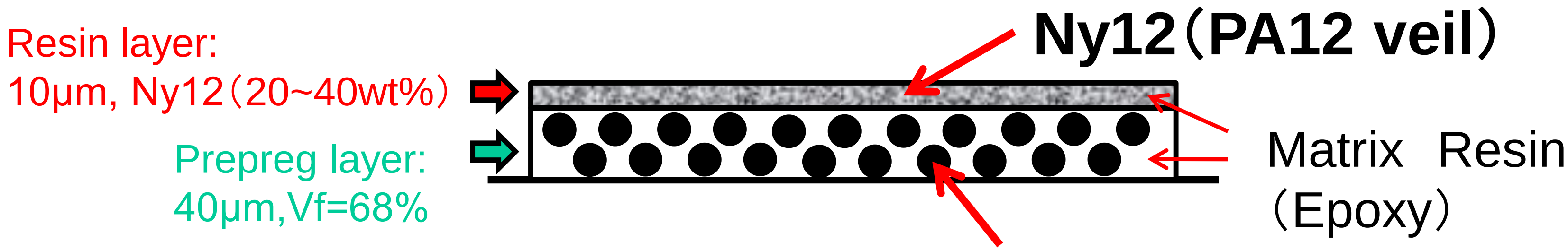
Thin ply laminates



Matrix cracks and delamination were suppressed due to the thin-ply effects. However, these caused a large delamination at mid-plane and fiber breakage which significantly deteriorated CAI strength.

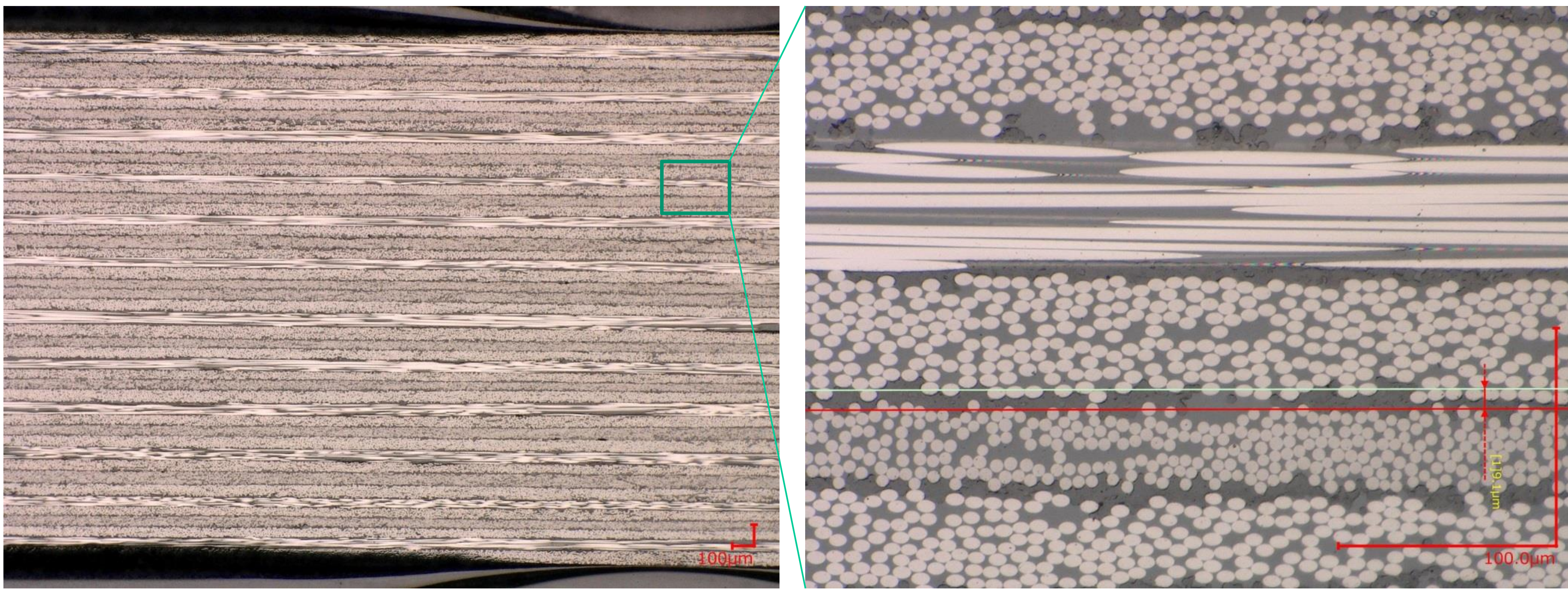
It was necessary to attenuate the fiber breakage and a delamination at mid plane to improve the CAI strength of thin ply laminates.

The thin ply prepreg with resin layer



CF: T800SC (Toray, intermediate modulus)

Prepreg: total fiber volume fraction = 55%

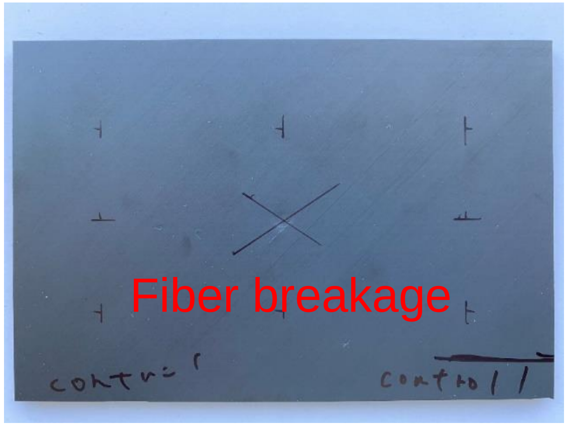


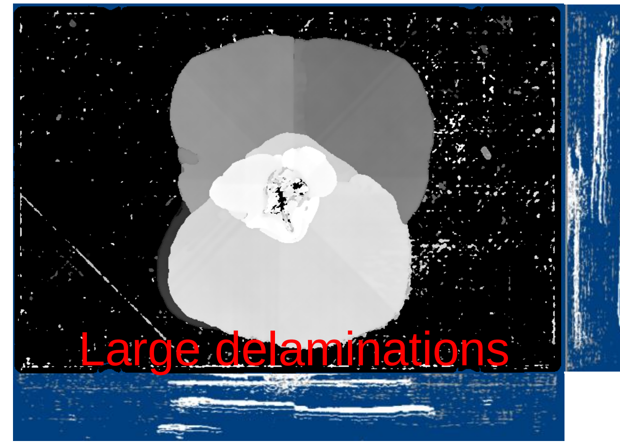
Cross-sectional images of the laminates

Failure mode after the impact loading

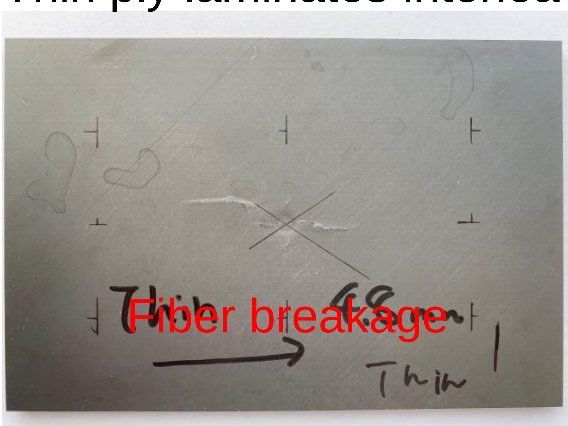
Impact energy：6.7 J/mm

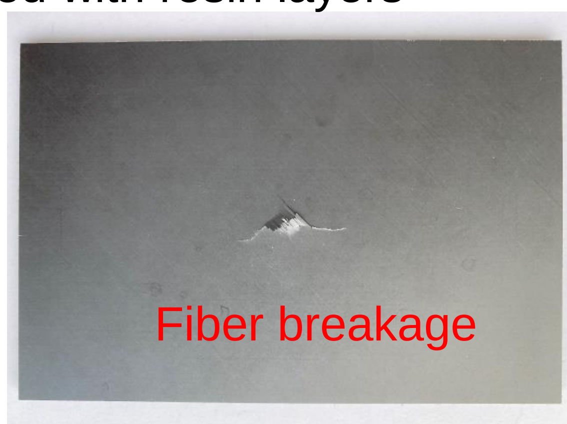
Thin ply laminates using carbon fiber with intermediate modulus (Normal)

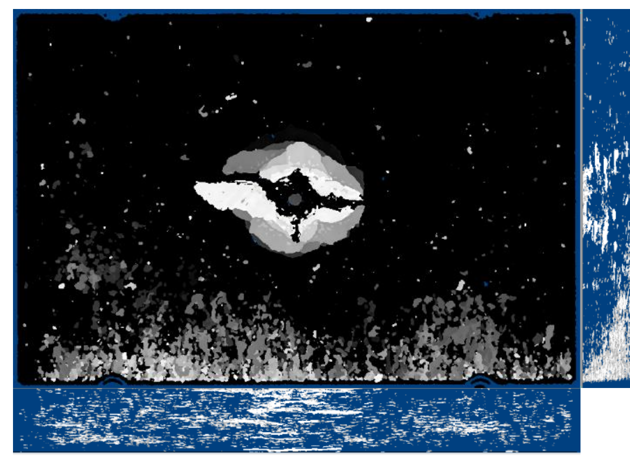




Thin ply laminates interleaved with resin layers

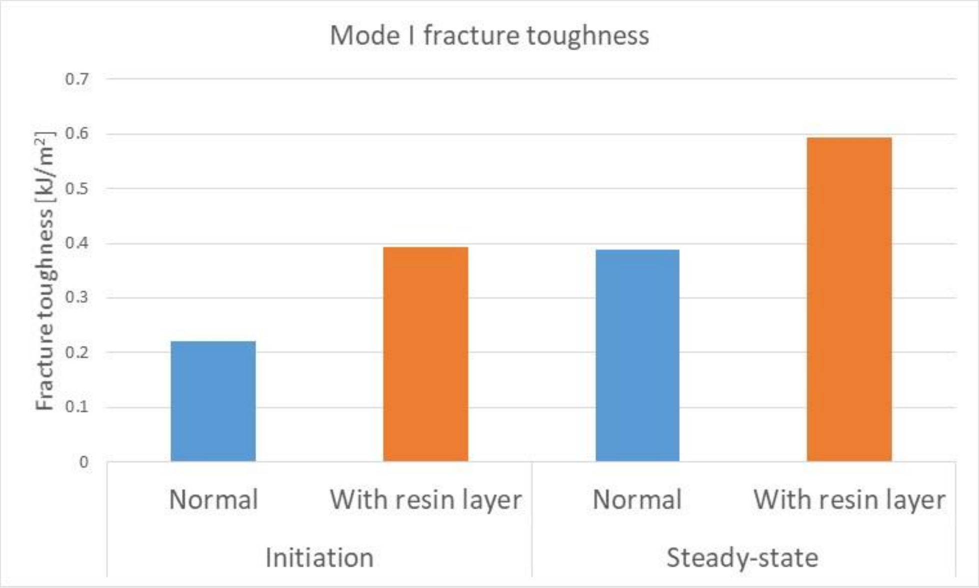




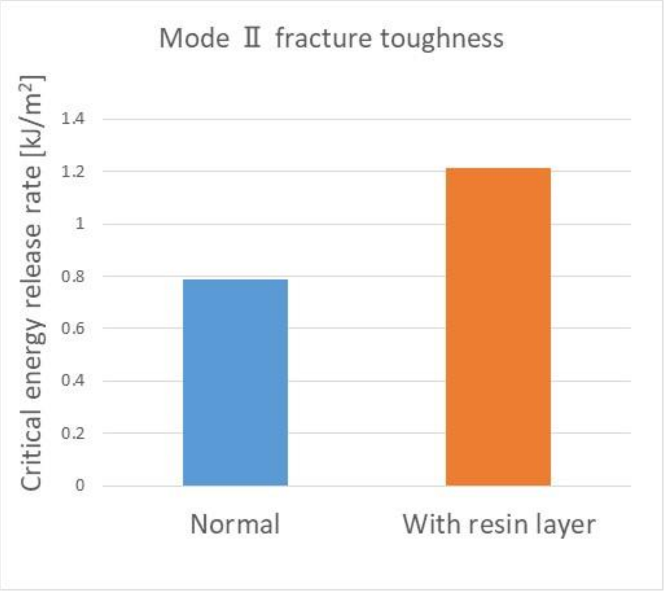


A large delamination at mid-plane that was typically seen in Thin ply laminates was suppressed by resin layer.

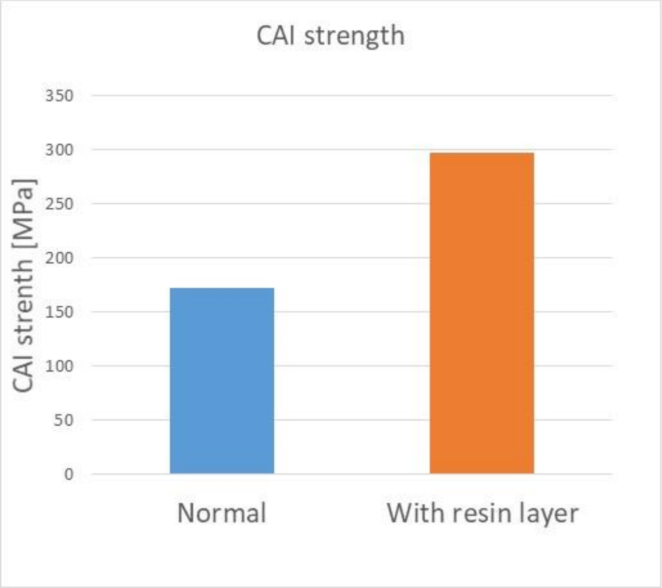
Mechanical properties of thin ply laminates with resin layers



Results of DCB tests



Results of ENF tests

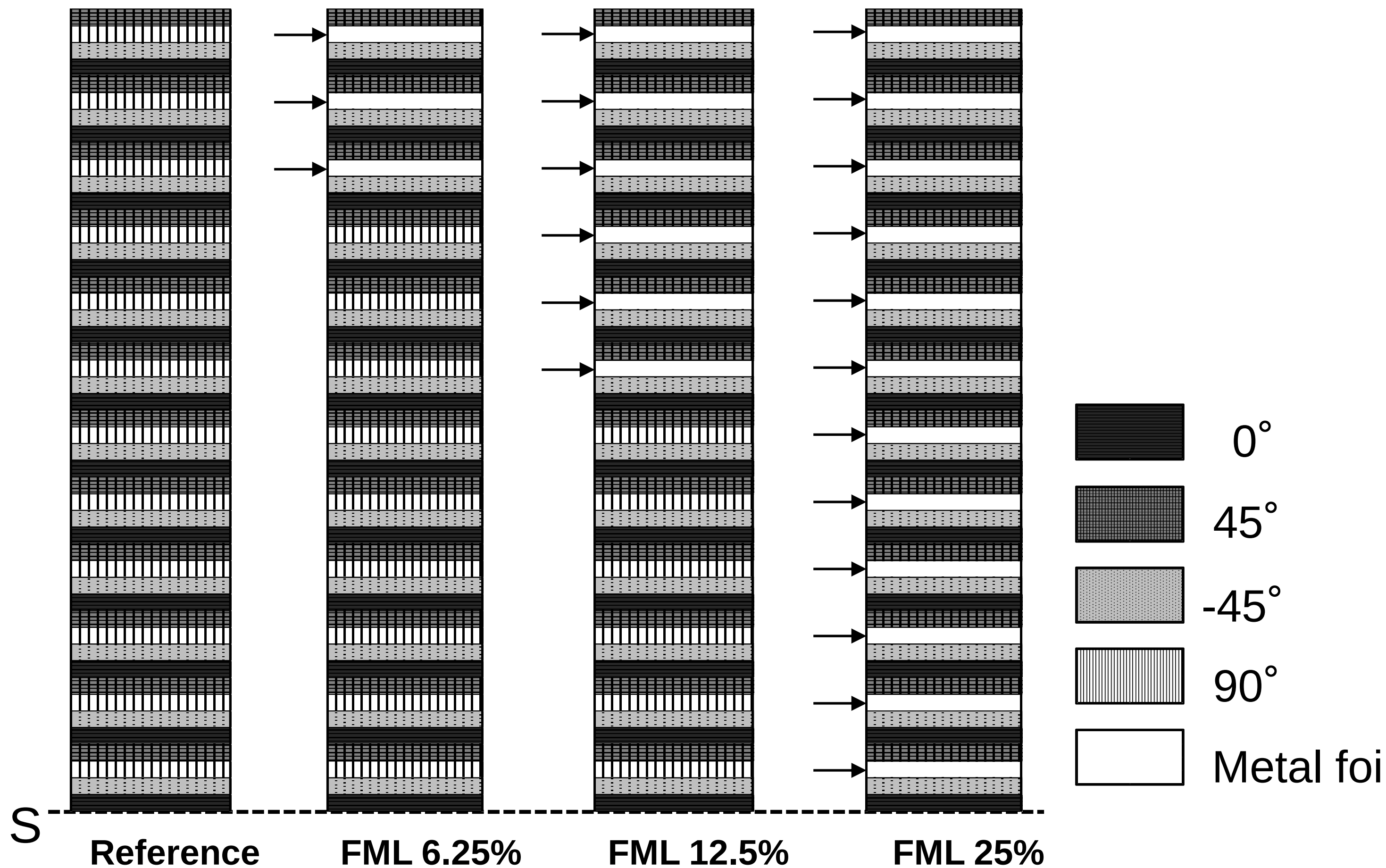


Results of CAI tests

Mechanical tests showed that fracture toughness and CAI strength of the thin ply laminates were improved due to the additional resin layer.

Thin ply fiber metal laminates

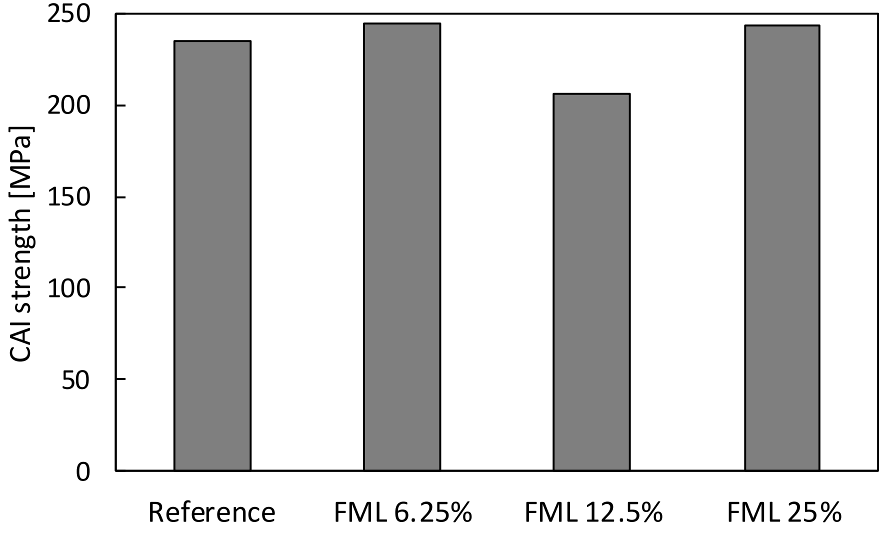
ex) FML 25%: $[45/90/-45/0]_{12s}$ ➔ $[45/M/-45/0]_{12s}$



90° layers that hardly can bear the load were replaced to the metal foil (SUS301).

[4] K. Yamada et al., "Mechanical properties and failure mode of thin-ply fiber metal laminates under out-of-plane loading", Composites A 143, 2021.

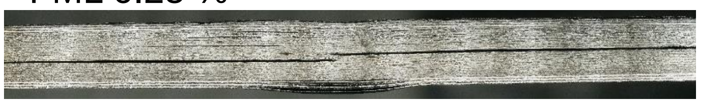
CAI strength of thin ply fiber metal laminates



Reference

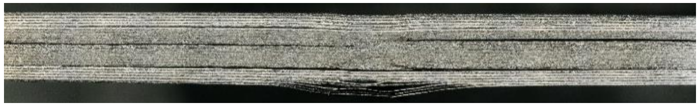
A large fiber breakage occurred at the back face.

FML 6.25 %



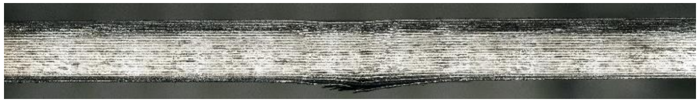
Fiber breakage at the back face and a large delamination near the mid-plane were observed.

FML 12.5 %



Fiber breakage at the back face and a large delamination near the mid-plane were observed.
In addition, delaminations between CFRP and FML layers were observed.

FML 25 %



Only a small fiber breakage was observed at the back face.

Mechanical property after the impact loading was also improved by combining with metal material.
Plastic deformation of metal foil relieved the brittle failure mode of the thin ply laminates.

[4] K. Yamada et al., "Mechanical properties and failure mode of thin-ply fiber metal laminates under out-of-plane loading", Composites A 143, 2021.

Conclusions

○Thin ply prepregs with a thickness blow 0.1 mm employing both of thermoset and thermoplastic resin can be manufactured by use of our original tow spreading technology.

○Using thin ply prepreg, various mechanical properties of structural materials can be improved.
➔ The thinner structure with a lighter weight than conventional one can be realized.
➔ Freedom of the design of the structural materials can be expanded.

○Mechanical properties after the impact loading were improved by modifying the configuration of the prepreg (adding the resin layer) or combining with metal materials.

Using our thin ply materials, the safer design with a lighter weight of the structural materials can be realized.

Future plans

○Another advantages of thin ply materials need to be verified.

ex) Mechanical properties and failure mode after a large impact loading assuming the crash should be studied.

○Adoption for the automatic lay up system should be studied.

In case of thin ply materials, more number of plies should be stacked. It is necessary to consider the combination of our material and this technology.

○The wider range of application of thin ply materials will be studied.

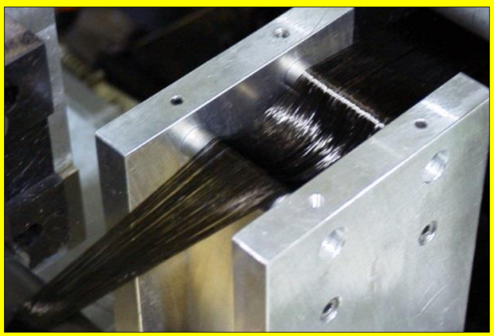
ex) Liquid hydrogen tank, Wind blade…etc.

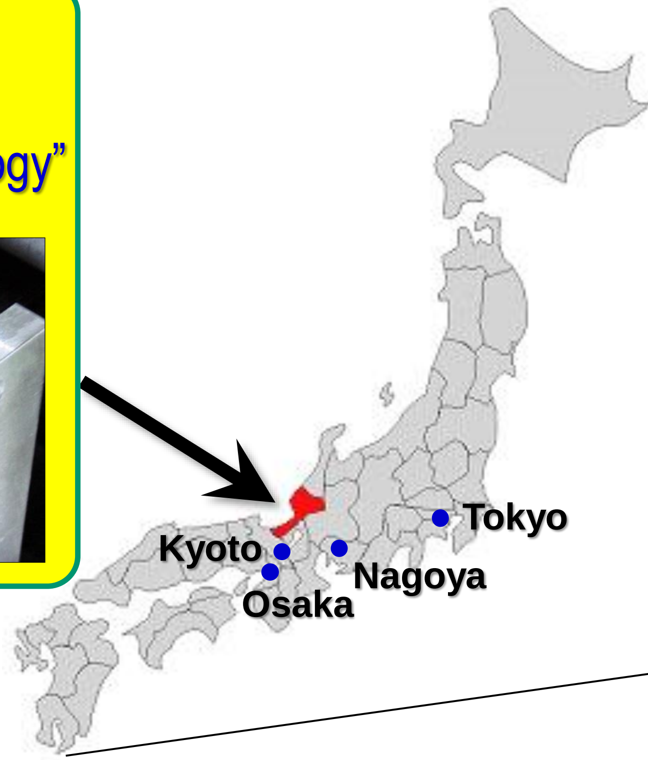
Thank you for your attention.

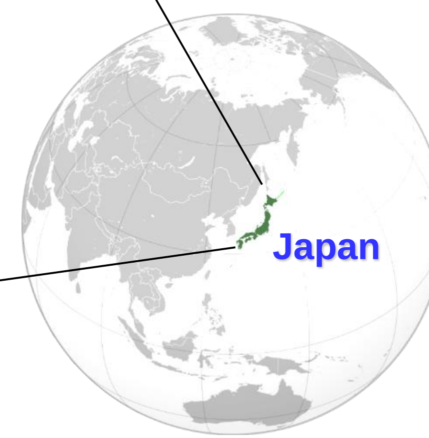
Fukui Prefecture

FUKUI Method

“Tow-spreading Technology”







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