A study of decrease burst strength on Compressed-hydrogen containers by drop test

〇Masuda Shunsuke, Tomioka Jun-ichi,
Tamura Hiroaki, Tamura Yohsuke

Japan Automobile research Institute
E-mobility Research Division

Agenda

- 1.Back ground
- 2.Objective
- 3.Research method
- 4.Test Result
  - 4-1 ： Ultrasonic Flaw Inspection
  - 4-2 ： X-ray CT Imaging
  - 4-3 ： Carbon Fiber Damage Inspection
  - 4-4 ： Influence of the Pressure Cycling Test on the Drop Test Damage
  - 4-5 ： Discussion
- 5.Conclusions

Agenda

- 1.Back ground
- 2.Objective
- 3.Research method
- 4.Test Result
  - 4-1 : Ultrasonic Flaw Inspection
  - 4-2 : X-ray CT Imaging
  - 4-3 : Carbon Fiber Damage Inspection
  - 4-4 : Influence of the Pressure Cycling Test on the Drop Test Damage
  - 4-5 : Discussion
- 5.Conclusions

Back ground：GTR13

GTR13：The global technical regulations for fuel cell vehicles（HFCV GTR）

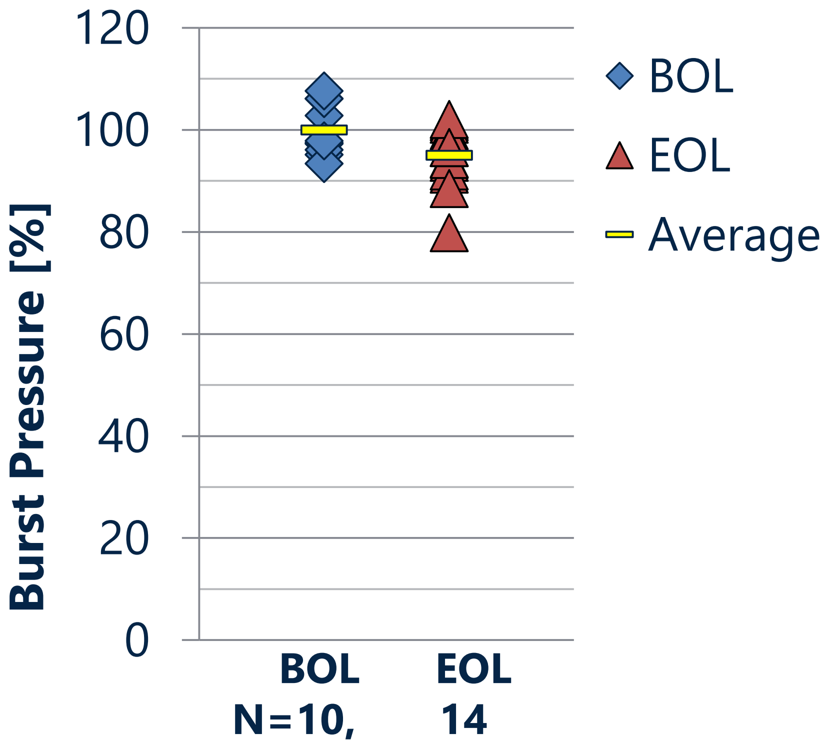
- Key Concept：An assurance of sufficient strength of compressed hydrogen container throughout its service life by requiring the container to retain a minimum residual burst strength of at least 180% of its nominal working pressure(NWP) at the End-of Life(EOL).

- Deliberation task：

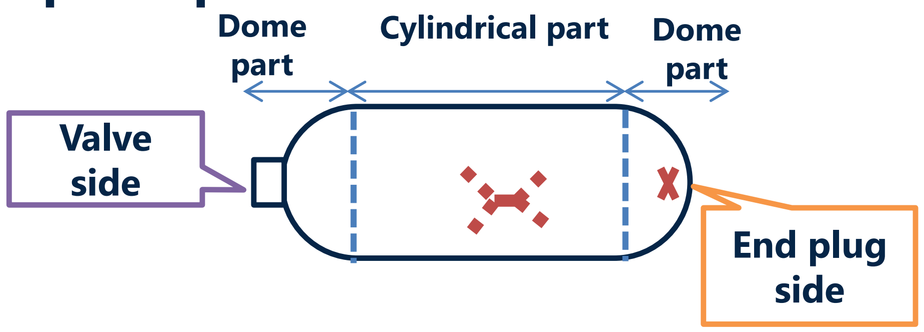
In current GTR13, an initial burst pressure at the beginning of life is defined to be 225%NWP.

⇒ 225%NWP has been validated using conventional requirements.
It is not correlated with EOL burst pressure.
An appropriate minimum burst pressure criterion is required to reduce the cost and weight of the container.

Back ground：Previous study about initial burst pressure



Rupture point



	Cylindrical part	Dome part (End plug side)
BOL	10	0
EOL	7	7

- The residual burst pressure at the End-of-Life decreased by about 5% from the initial burst pressure.
- The variations of the residual burst pressure at the End-of-Life were increased from the initial.
- An impact site during vertical drop test may become the initial rupture point.

Tomioka, J., et al., Influences of Hydraulic Sequential Tests on the Burst Strength of Compressed-hydrogen Tanks, Transactions of Society of Automotive Engineers of Japan, 49, No. 2, 2018, pp. 296–300.

Objective：

Recent investigation

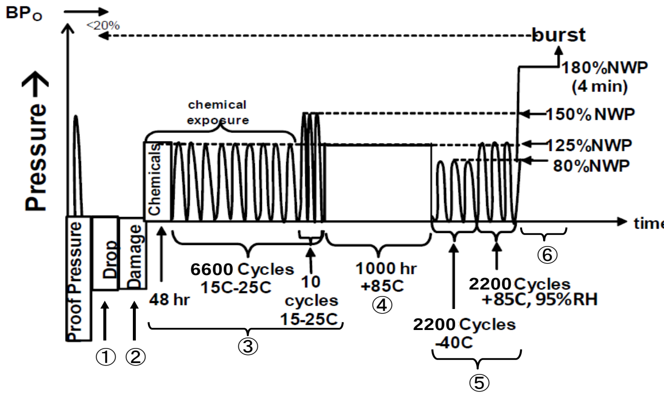
・The residual burst pressure at the End-of-Life decreased by about 5% from the initial burst pressure.

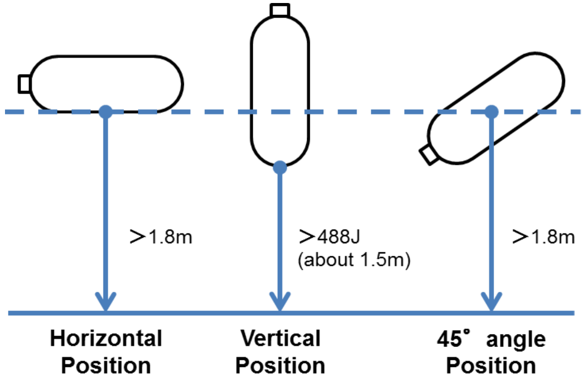
・The variations of the residual burst pressure at the End-of-Life were increased from the initial.

・An impact site during vertical drop test may become the initial rupture point.

→ It seems to be affected by drop test that directly damages the dome part.

- ◆ **The container damages caused by hydraulic sequential tests are analyzed in detail by performing various nondestructive evaluations**
- ◆ **The mechanism of container deterioration is clarified.**





JARI
JAPAN AUTOMOBILE RESEARCH INSTITUTE

Agenda

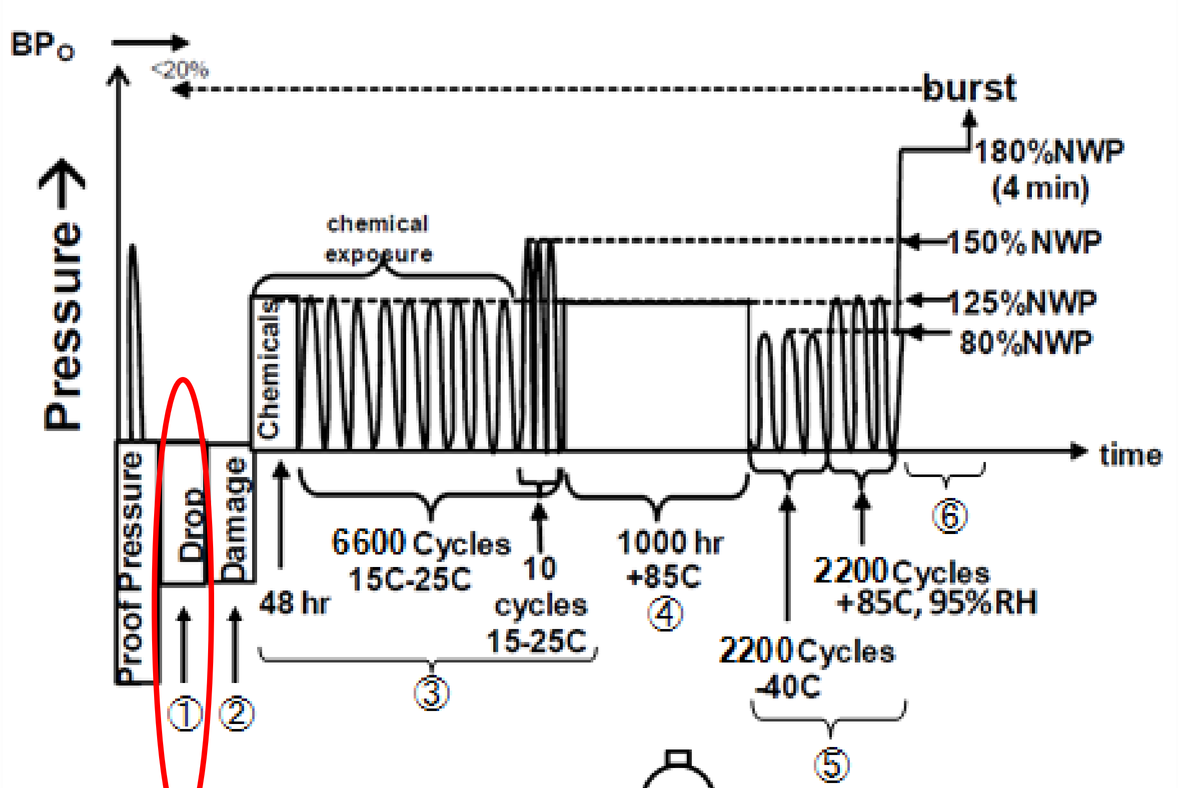
- 1.Back ground
- 2.Objective
- **3.Research method**
- 4.Test Result
  - 4-1：Ultrasonic Flaw Inspection
  - 4-2：X-ray CT Imaging
  - 4-3：Carbon Fiber Damage Inspection
  - 4-4：Influence of the Pressure Cycling Test on the Drop Test Damage
  - 4-5：Discussion
- 5.Conclusions

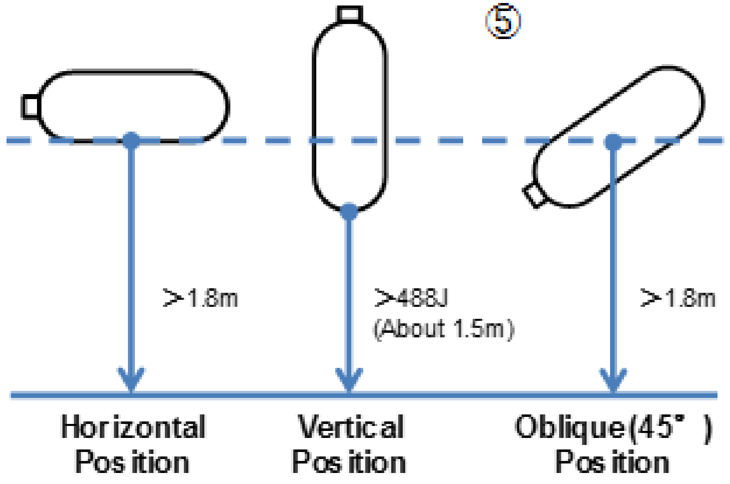
Research method

◆ Specifications of the tested type 4 container

Reinforcing material	CFRP
Molding method	Filament winding
Nominal working pressure	70 MPa
Volume	36 L
Application criteria	EC79
Liner material	Plastic
Protector	No protector

Research method





◆ Hydraulic sequential test

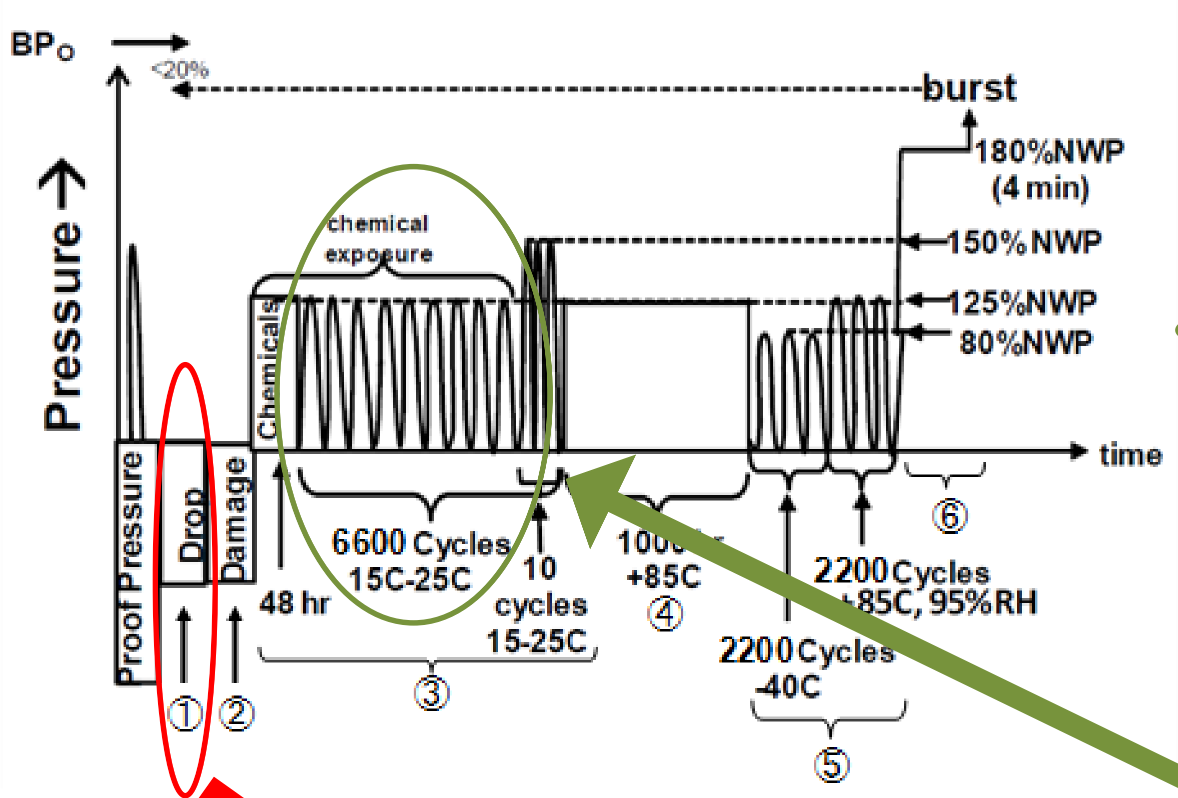
①Drop test
②Surface damage
③Ambient temperature pressure cycling tests
④High temperature static pressure test
⑤Extreme temperature pressure cycling
⑥Residual strength Burst Test

◆ Drop test

This test simulates an accidental container drop during manufacturing.

JARI
JAPAN AUTOMOBILE RESEARCH INSTITUTE

Research method



- Ultrasonic Flaw Inspection
- X-ray CT Imaging
- Carbon Fiber Damage Inspection

◆ Hydraulic sequential test

①Drop test
②Surface damage
③Ambient temperature pressure cycling tests
④High temperature static pressure test
⑤Extreme temperature pressure cycling
⑥Residual strength Burst Test

◆ Influence of the Pressure Cycling Test on the Drop Test Damage (X-ray CT Imaging)

Agenda

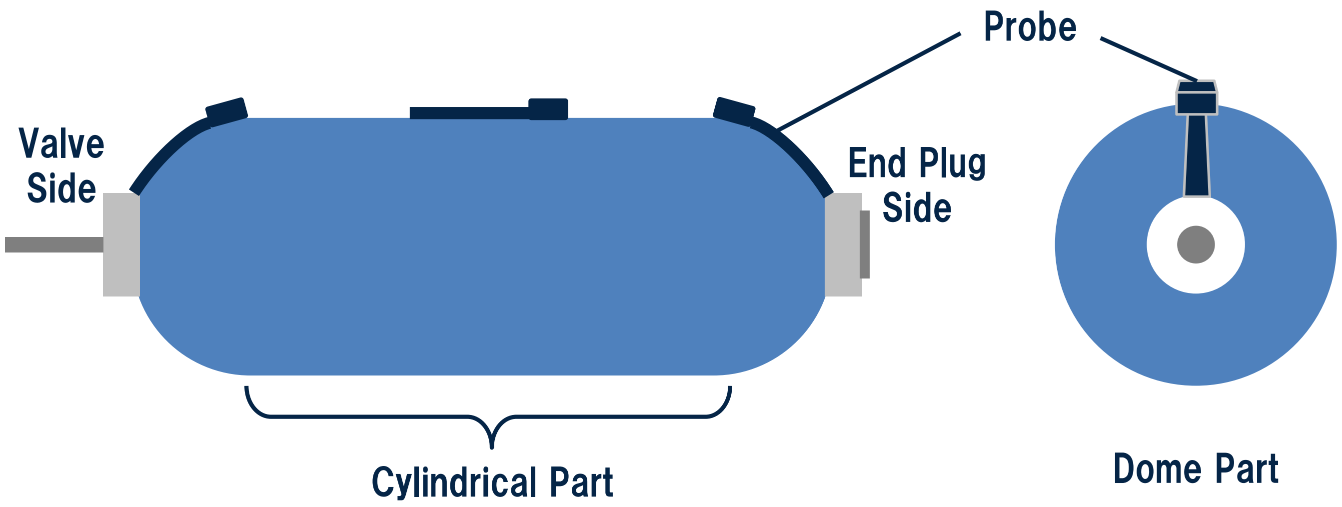
- 1.Back ground
- 2.Objective
- 3.Research method
- **4.Test Result**
  - **4-1 ：Ultrasonic Flaw Inspection**
  - 4-2 ：X-ray CT Imaging
  - 4-3 ：Carbon Fiber Damage Inspction
  - 4-4 ：Influence of the Pressure Cycling Test on the Drop Test Damage
  - 4-5 ：Discussion
- 5.Conclusions

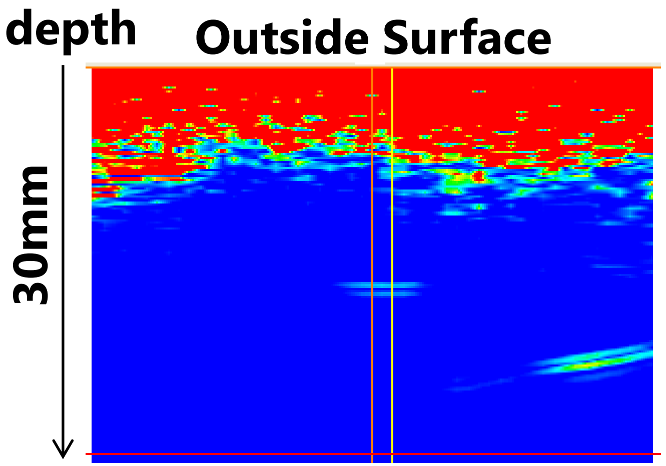
Ultrasonic Flaw Inspection

◆ Phased array ultrasonic inspection

This method can set the direction and depth of the ultrasonic beam arbitrarily.

Probe	Flexible probe
Pulse voltage	200V
Pulse width	100 ns
Incident angle of wave	0°

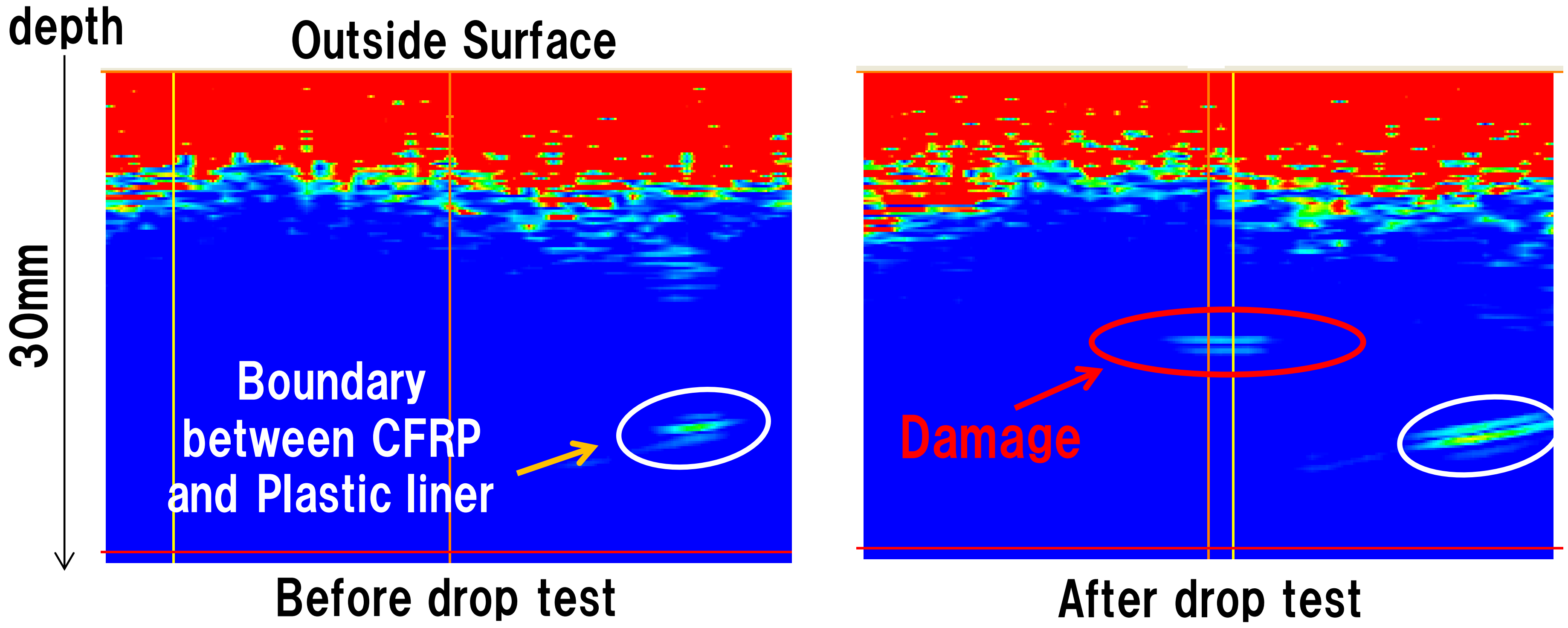




- **No sound-wave reflection : Blue**
- **Sound-wave reflection (Flaw) : Green or Yerrow**
- **Layer boundary or imperfection (e.g., air layer) : Red**

Ultrasonic Flaw Inspection

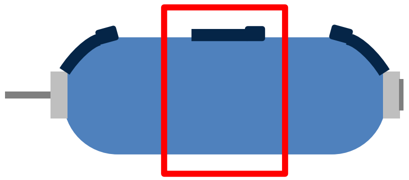
◆ Dome part

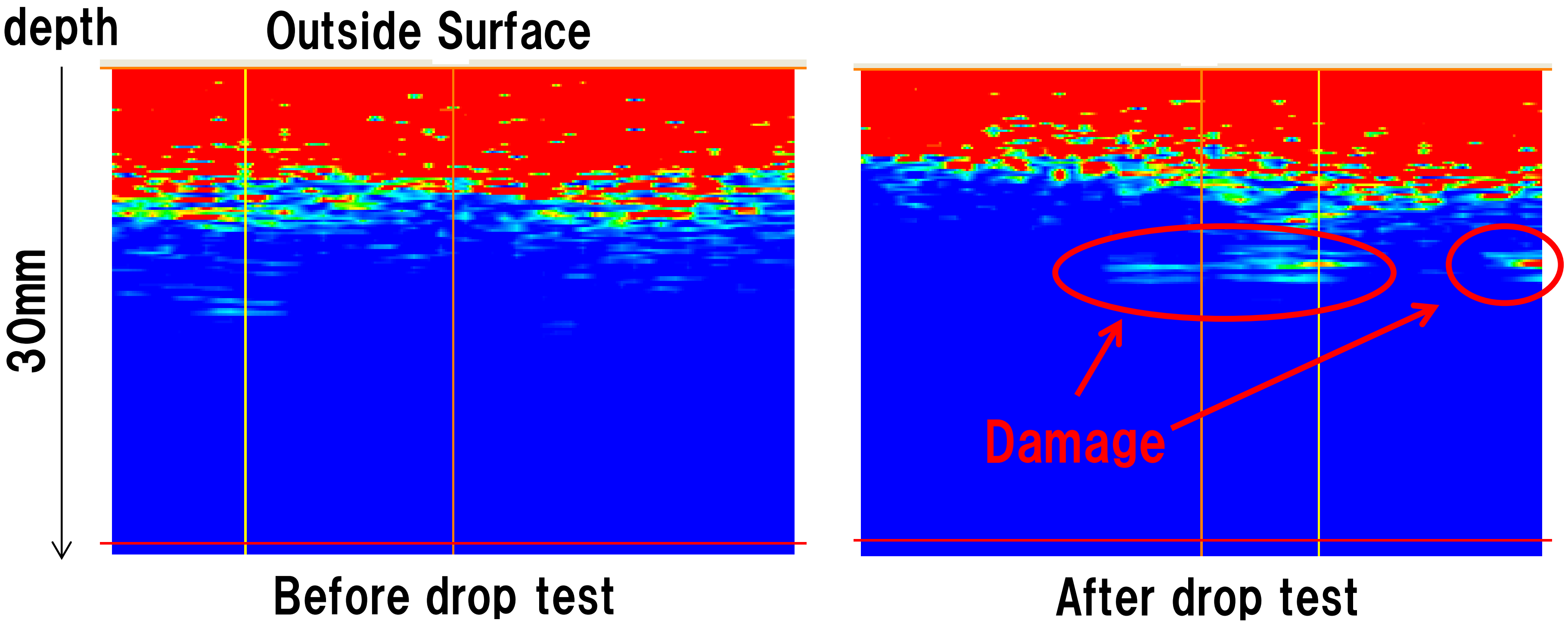


◆ **Some reflection are observed at a depth of approximately 15 mm after the drop test and extends parallel to the CFRP surface**

Ultrasonic Flaw Inspection

◆ Cylindrical part

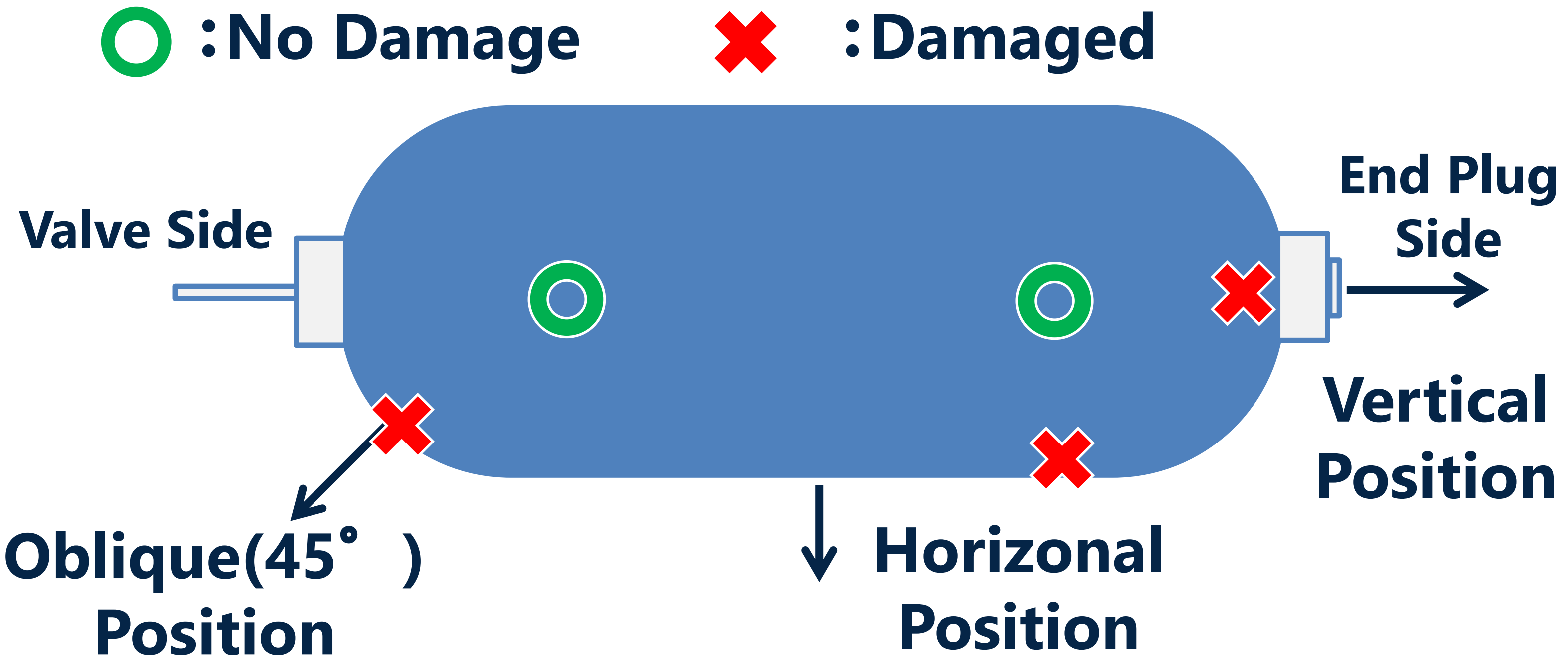




◆ **Some reflection are observed at a depth of approximately 10-15 mm after the drop test and extends parallel to the CFRP surface**

Ultrasonic Flaw Inspection

◆ Summary of the Ultrasonic flaw inspection result



◆ CFRP layer was damaged in all three directions (vertical, horizontal, and oblique directions) near the landing site.

◆ No damage was incurred away from the landing site of the drop tests

Agenda

- ◆ 1.Back ground
- ◆ 2.Objective
- ◆ 3.Research method
- ◆ **4.Test Result**
  - ◆ 4-1 ：Ultrasonic Flaw Inspection
  - ◆ **4-2 ：X-ray CT Imaging**
  - ◆ 4-3 ：Carbon Fiber Damage at the Damaged Site
  - ◆ 4-4 ：Influence of the Pressure Cycling Test on the Drop Test Damage
  - ◆ 4-5 ：Discussion
- ◆ 5.Conclusions

X-ray CT Imaging

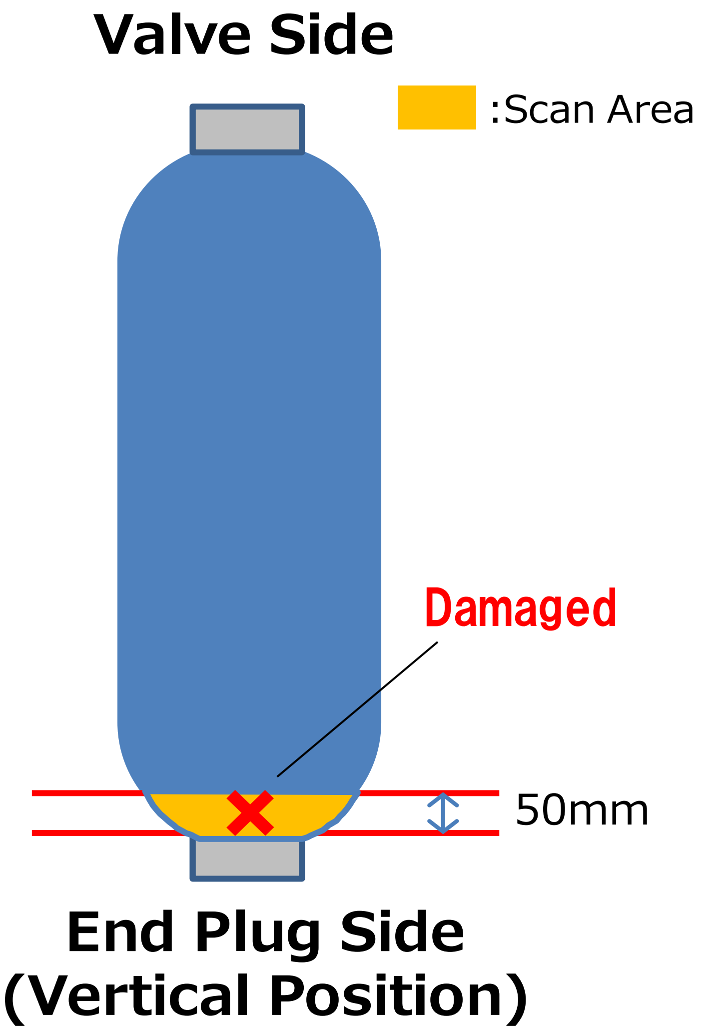
- **A conclusive interpretation cannot be made using only the ultrasonic flaw test results**

  →**X-ray CT imaging was performed to investigate the damage at the dome part of the containers in more detail.**

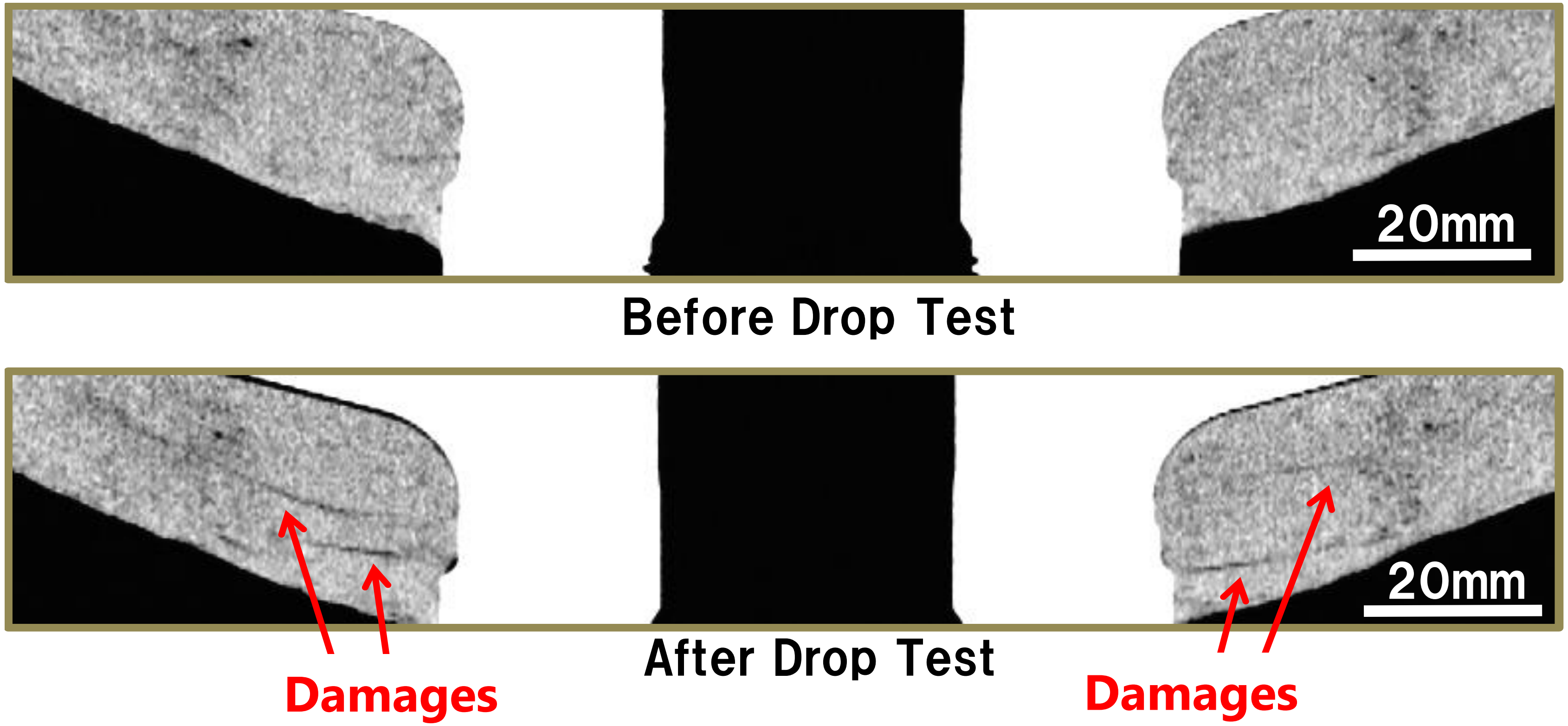
- **X-ray CT system**

  This system supplies high-resolution images while working at high energies.

Maximum X-ray energy	9 MeV
Slice thickness	0.5 mm
Image resolution	3000 pixels × 3000 pixels
Pixel size	0.2 mm × 0.2 mm



X-ray CT Imaging



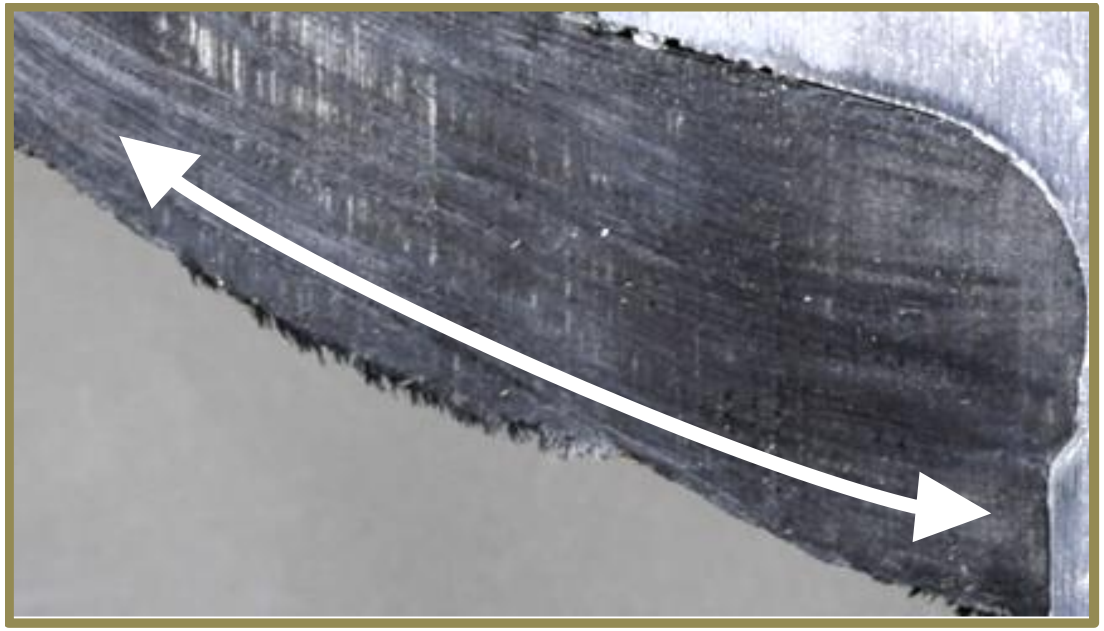
Before Drop Test

After Drop Test

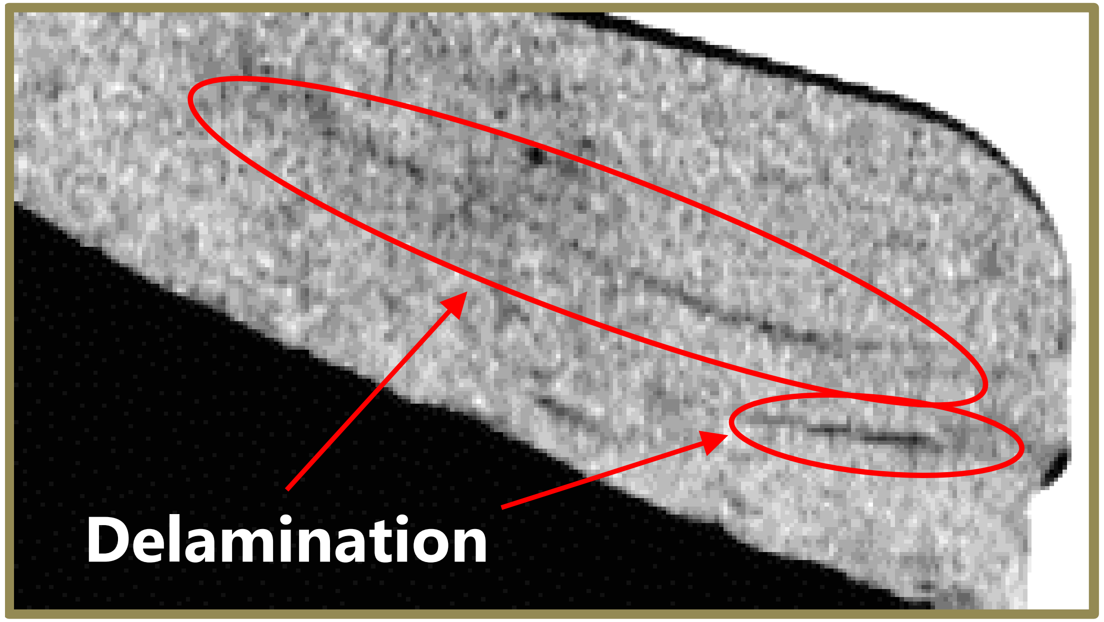
Air layer : Black
CFRP layer : Gray
Alminum boss : White

There were multiple damages in the middle of the CFRP layer near the boss on the plug side of the container after the drop test.

X-ray CT Imaging



Cross-section Image



CT Image

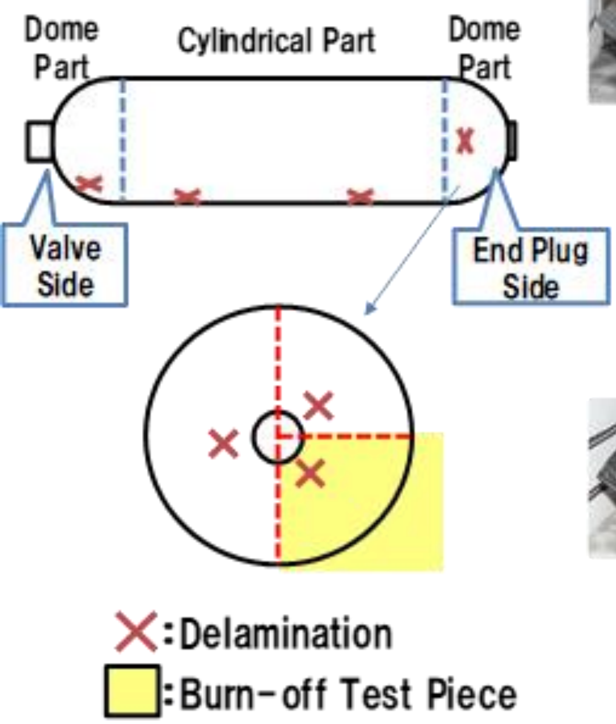
- One CFRP layer extends in the direction of the white arrow and forms the dome part by overlapping several layers.
- The damages are observed in the CFRP interlayer portion of the cross-section image.

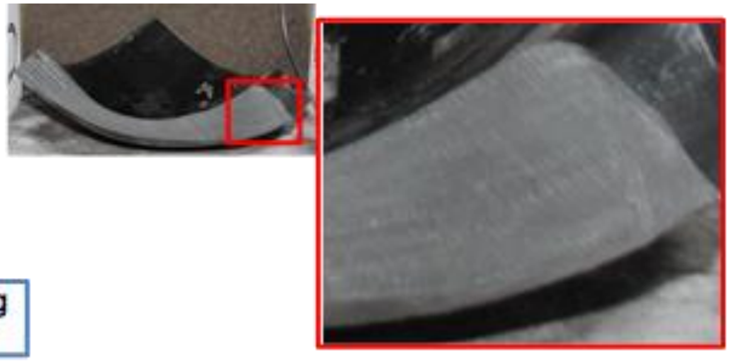
The delamination occurs near the boss on the plug side by the drop test (vertical drop direction).

Agenda

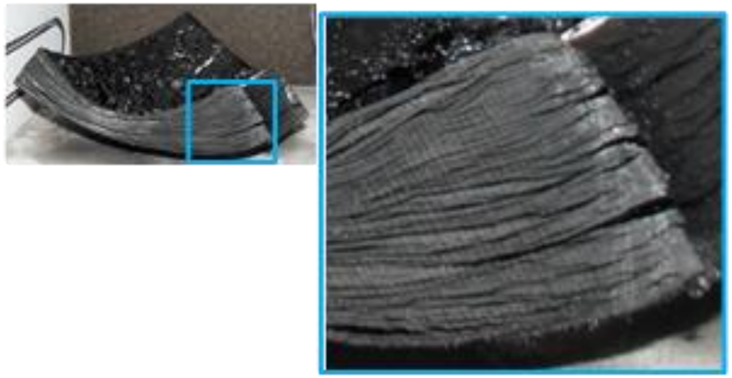
- 1.Back ground
- 2.Objective
- 3.Research method
- **4.Test Result**
  - 4-1 ：Ultrasonic Flaw Inspection
  - 4-2 ：X-ray CT Imaging
  - **4-3 ：Carbon Fiber Damage Inspection**
  - 4-4 ：Influence of the Pressure Cycling Test on the Drop Test Damage
  - 4-5 ：Discussion
- 5.Conclusions

Carbon Fiber Damage Inspection





Before Burn-off Test



After Burn-off Test

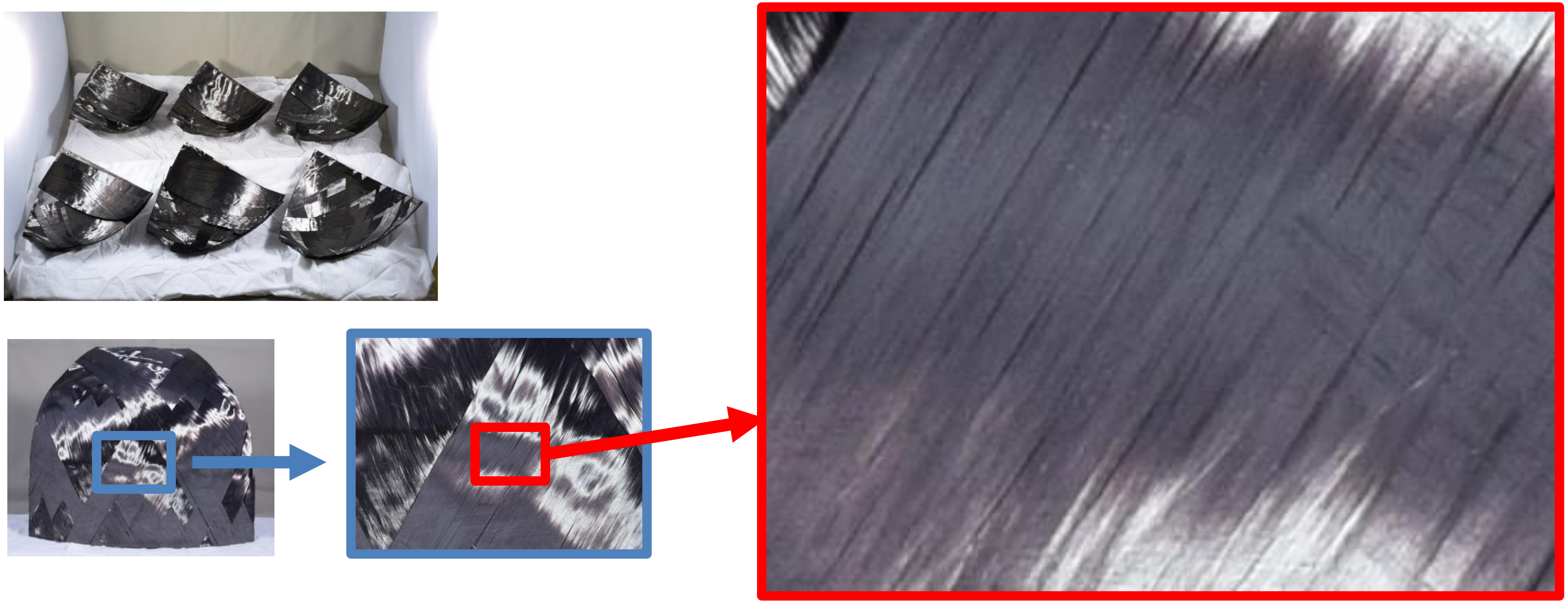
- The ultrasonic test and X-ray CT imaging **cannot observe carbon fiber breakage**.
- We conducted a burn-off test to examine the degree of carbon fiber damage within the CFRP layer.

- Burn-off Test

The test piece was then heated and maintained at approximately 500 °C by using an electric furnace.

The CFRP epoxy resin was gasified, and the carbon fiber was extracted.

Carbon Fiber Damage Inspection

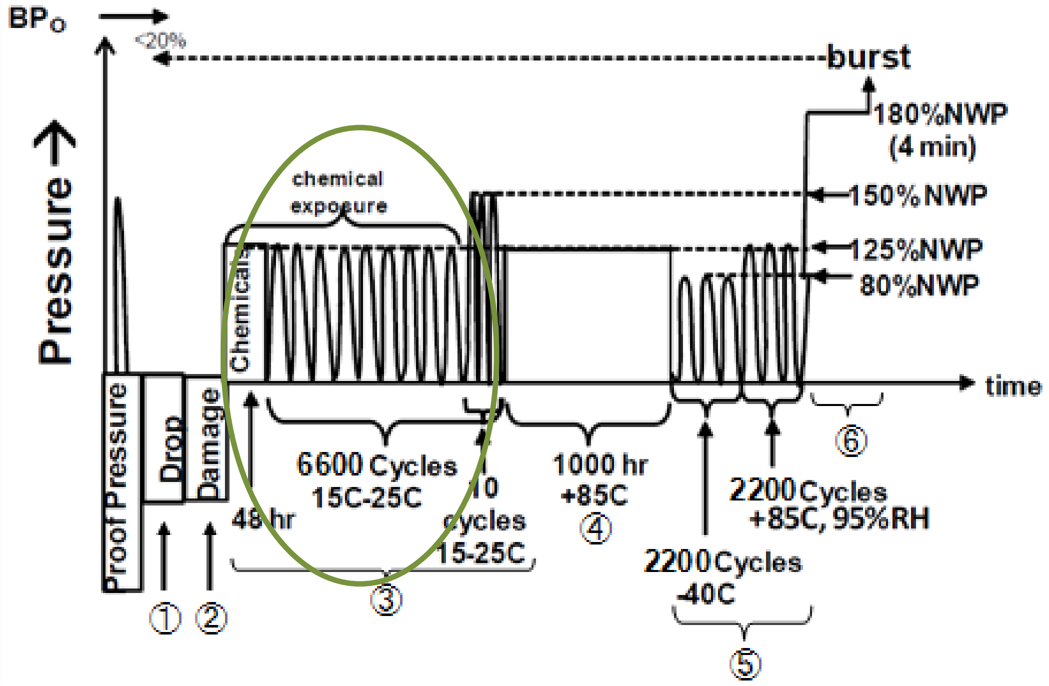


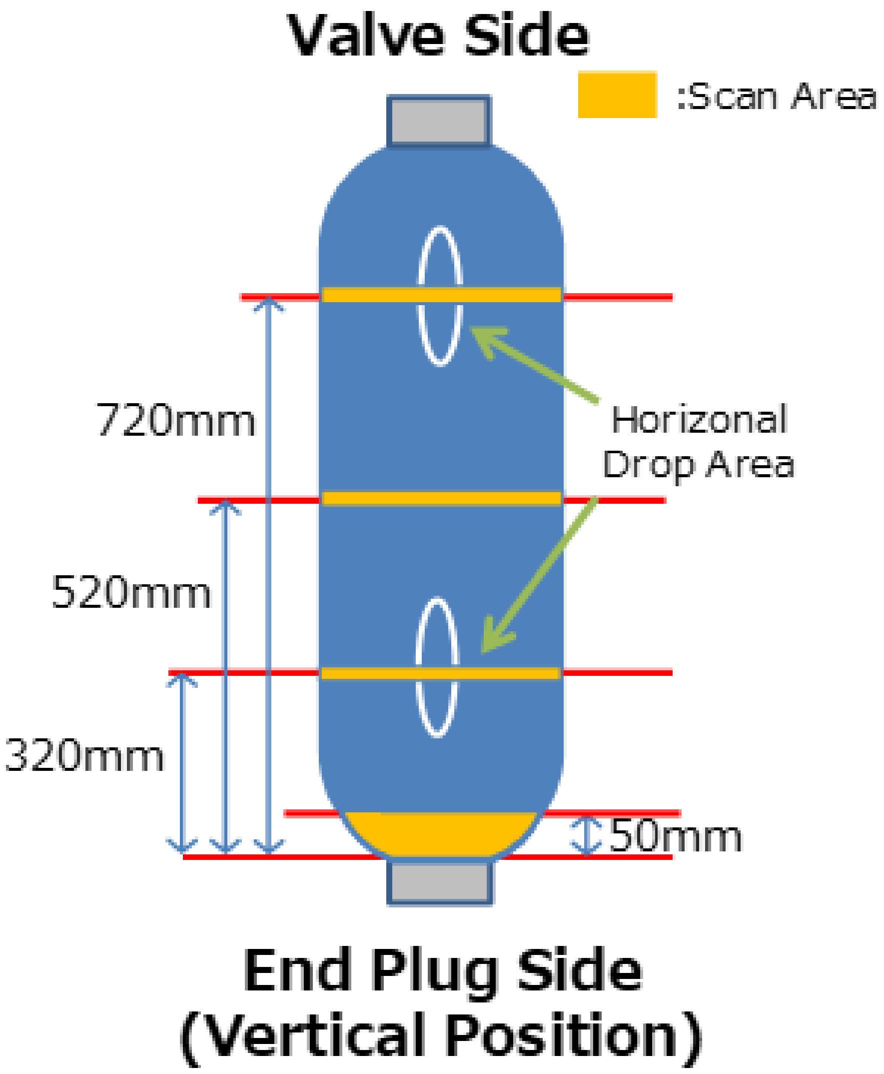
- No carbon fiber damage was observed in this test piece.
- CFRP damage during the vertical drop test was confined to delamination, with no damage to the carbon fibers

Agenda

- 1.Back ground
- 2.Objective
- 3.Research method
- **4.Test Result**
  - 4-1：Ultrasonic Flaw Inspection
  - 4-2：X-ray CT Imaging
  - 4-3：Carbon Fiber Damage Inspection
  - **4-4：Influence of the Pressure Cycling Test on the Drop Test Damage**
  - 4-5：Discussion
- 5.Conclusions

Influence of the Pressure Cycling Test on the Drop Test Damage

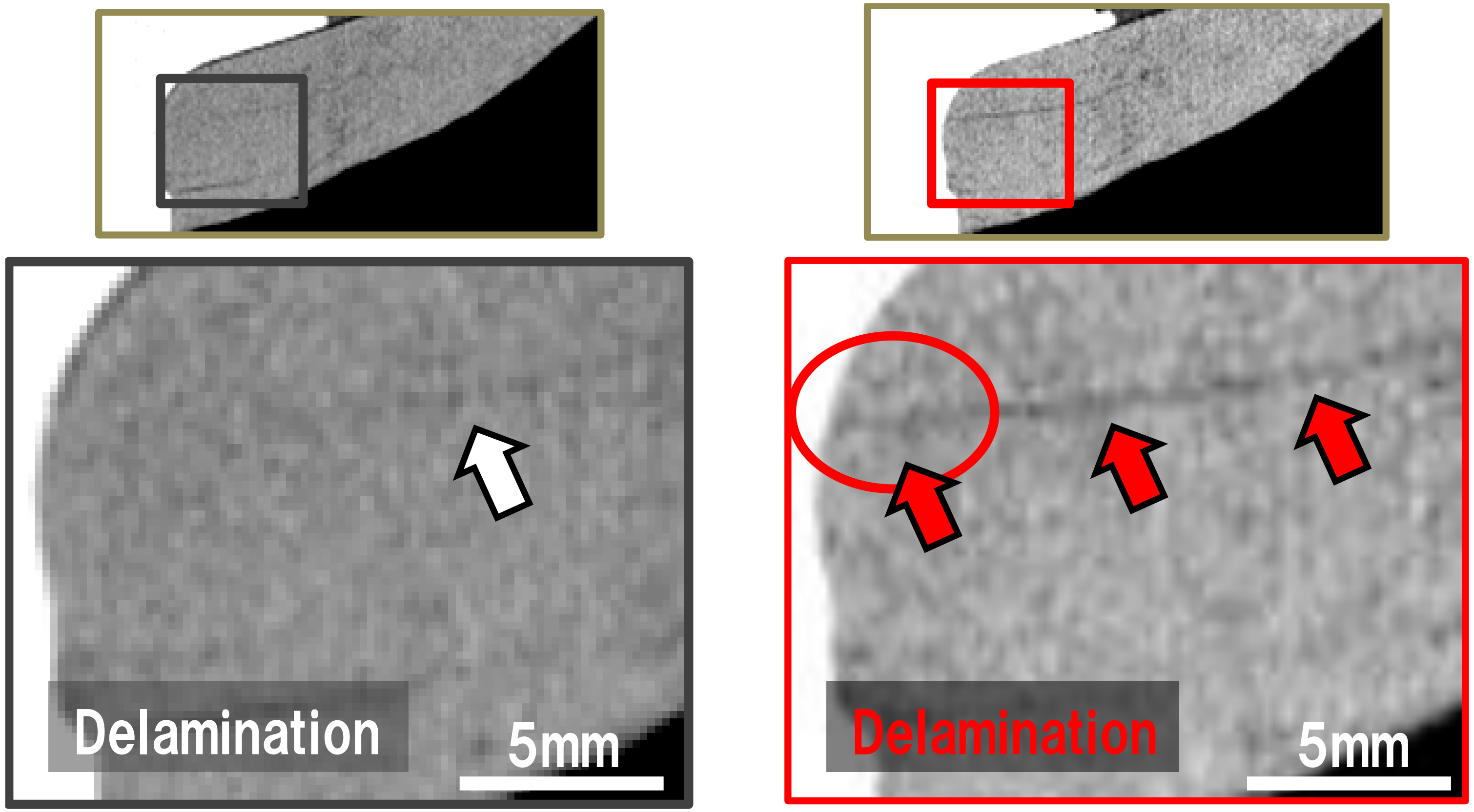




- **Pressure cycling test after the drop test may distort the container, thus possibly propagating delamination.**
- **X-ray CT imaging was performed on the container after the pressure cycling test to investigate the influence of the pressure cycling on the delamination.**

Influence of the Pressure Cycling Test on the Drop Test Damage

◆ Dome part



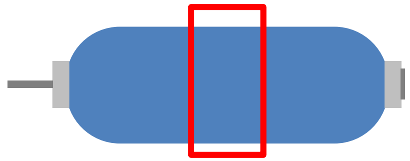
After Drop Test

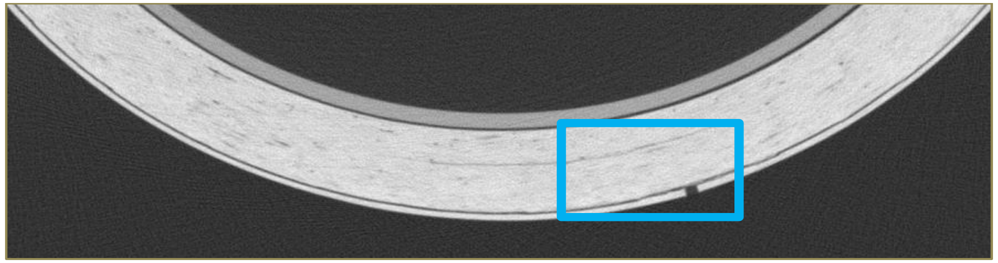
After Pressure Cycling Test

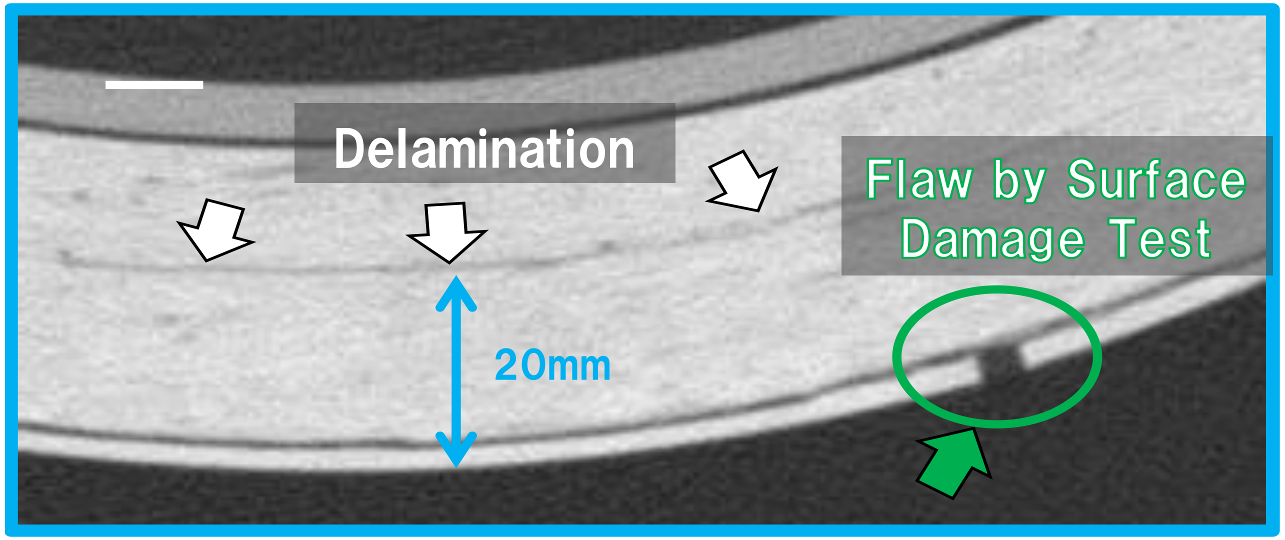
◆ The delamination that existed after the drop test further developed and became more **widespread** after the pressure cycling test, with part of the developed interlaminar separation **extending to the boss**.

Influence of the Pressure Cycling Test on the Drop Test Damage

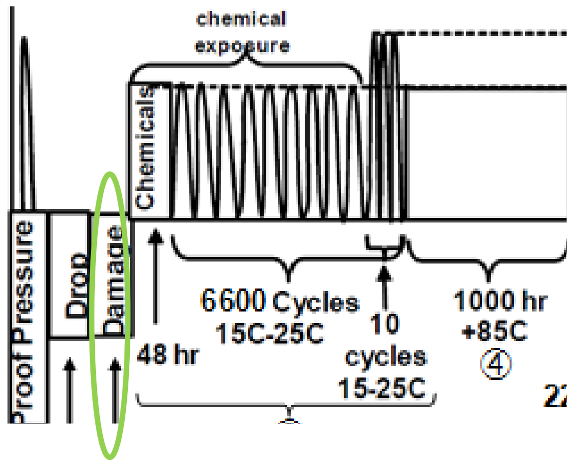
◆ Cylindrical part

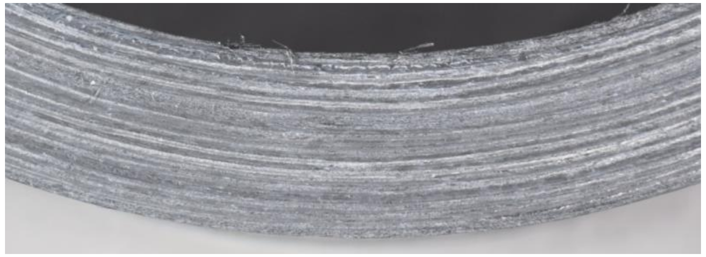






After Pressure Cycling Test





Sectional images

- ◆ **Delamination has occurred at cylindrical part**
- ◆ **The influence of the pressure cycling test on delamination in the cylindrical part of the container is not clarified since no X-ray CT images were acquired after the drop test.**

JAPAN AUTOMOBILE RESEARCH INSTITUTE

Agenda

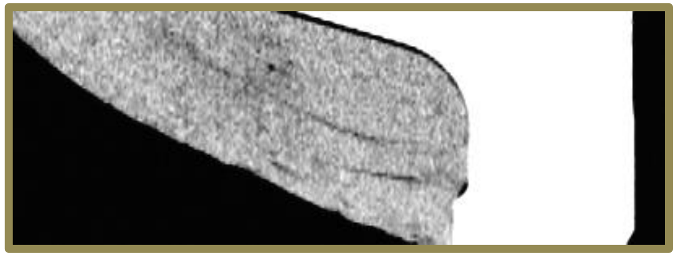
- 1.Back ground
- 2.Objective
- 3.Research method
- **4.Test Result**
  - 4-1 ： Ultrasonic Flaw Inspection
  - 4-2 ： X-ray CT Imaging
  - 4-3 ： Carbon Fiber Damage Inspection
  - 4-4 ： Influence of the Pressure Cycling Test on the Drop Test Damage
  - **4-5 ： Discussion**
- 5.Conclusions

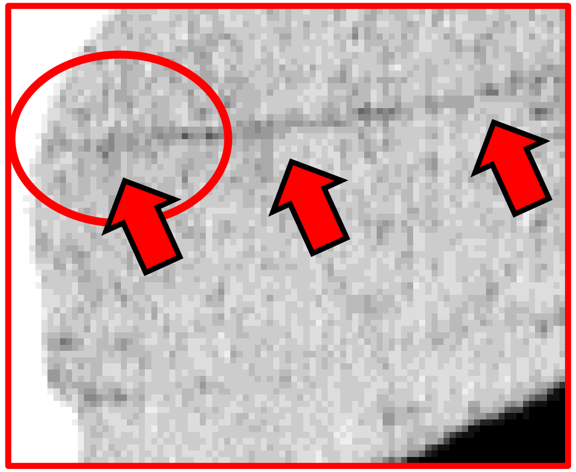
Discussion

◆ Dome Part

1.The pressure cycling test propagated some of the delamination in the dome part, which was generated via the vertical drop impact.

→The complex shape of the CFRP layer near the boss indicates that a complex 3D stress will likely be applied to the delamination when the container is distorted during the pressure cycling test.





2.Some of the developed delamination extended to the boss.

→This finding suggests that the load sharing of the CFRP layer due to the delamination displacement fluctuates, thus decreasing the burst strength of the dome part.

Delamination propagation during the pressure cycling test may be the primary factor that contributes to the decrease in the burst strength of the dome part.

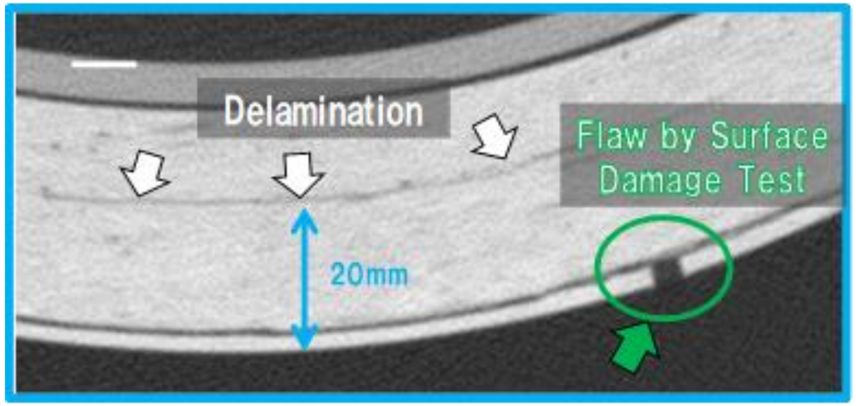
Discussion

◆ Cylindrical Part

1. Delamination has occurred by drop test.
2. The change in the delamination gap in the cylindrical part is unclear due to the lack of CT images before and after the pressure cycling test for comparison.
3. The cylindrical part is in a stable plane stress state that is parallel to the delamination.

   →Delamination does not propagate as easily as the dome part

4. The damage due to the surface damage test becomes the dominant factor in the decreased strength of the cylindrical part because the carbon fiber that is responsible for most of the CFRP strength is divided in the cylindrical part.



The damage to the cylindrical part via the drop test is expected to have little effect on burst strength

Agenda

- 1.Back ground
- 2.Objective
- 3.Research method
- 4.Test Result
  - 4-1 ： Ultrasonic Flaw Inspection
  - 4-2 ： X-ray CT Imaging
  - 4-3 ： Carbon Fiber Damage Inspection
  - 4-4 ： Influence of the Pressure Cycling Test on the Drop Test Damage
  - 4-5 ： Discussion
- **5.Conclusions**

Conclusions

A series of nondestructive evaluations were conducted to investigate the influence of the drop tests on both the container damage and burst pressure, thus yielding the following results:,

- **Delamination occurred in the CFRP layer in all drop directions (vertical, horizontal, and oblique [45°] directions) by the drop tests.**
- **No carbon fiber damage occurred in the dome part of the container during the vertical drop test, and only delamination was observed in the CFRP layer.**
- **The pressure cycling test propagated the delamination of the dome part, and extended some of the delamination to the boss.**

From the results, it is considerd that the drop test and surface damage test are the main factors for the decrease in the burst pressure and increase of the burst pressure variation by the hydraulic sequential test.

Thank you for your attention.

This study is summarizes part of the results of " research and development of technology for hydrogen utilization - research and development on improvement and international harmonization of compressed hydrogen container regulations for FCV" consigned by the new energy and industrial technology development organization (NEDO).