June 2009

FAA Workshop for Composite Damage Tolerance & Maintenance in Tokyo 2009

Presented by

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Composite Structure

Substantiation of Damage Growth within Sandwich Structures

AIRBUS

Damage growth within sandwich structures

- **Background**
- **Scope**
- **Damage propagation & failure mode**
- **Fracture toughness (G1C) & propagation rates**
- **FE Analysis**
- **Tests vs. Analysis**
- **Conclusions**

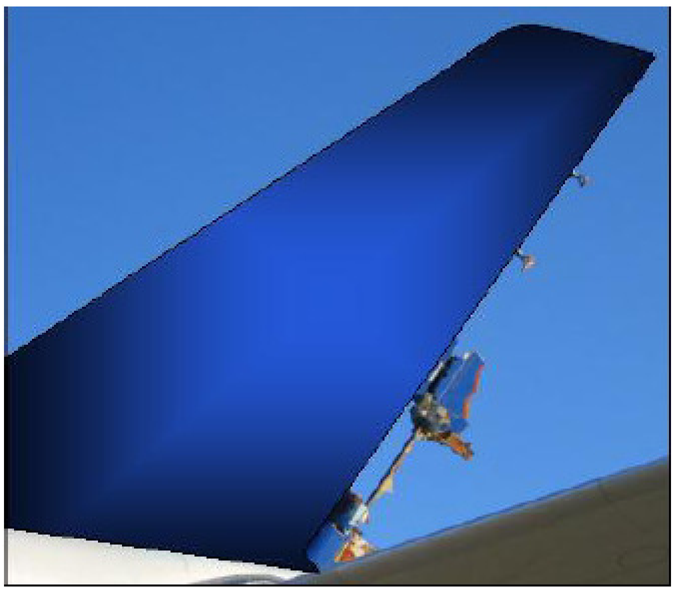
Damage growth within sandwich structures

Background

Background

During the Amsterdam Damage Tolerance Workshop in May 2007 Airbus presented a status of the two following rudder structural investigations:

- Rudder structural failure in flight March 2005



- Rudder disbond detected during maintenance in November 2005

These two events triggered comprehensive studies which some aspects are detailed in this presentation

Damage growth within sandwich structures

Background

Scope

Sandwich structure study

Introduction

- **Phenomenon**

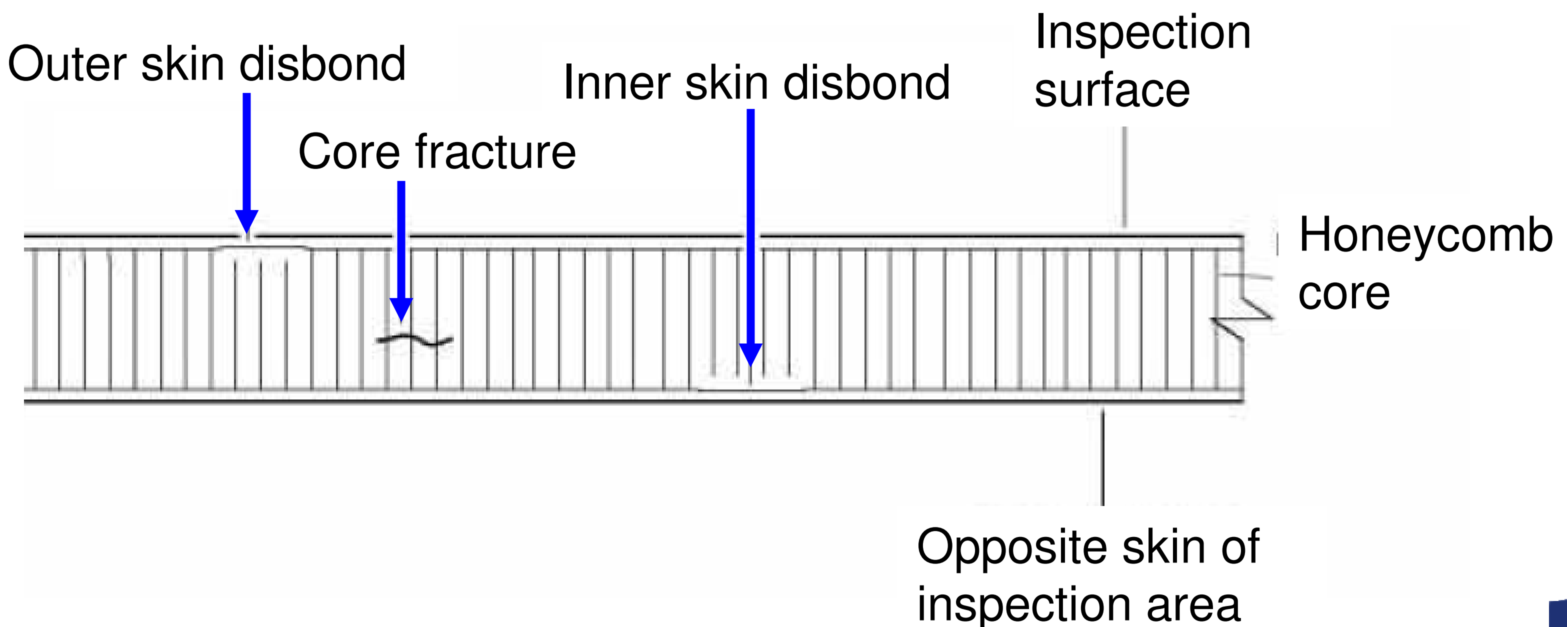
  An initial damage within a tight sandwich structure, like a face-sheet to core separation or a core fracture, can propagate mainly thru the ground-air-ground effect.

- **Motivation**
  - Source of disbond or core damage initiation
  - Effect on damage growth
- **Scope**
  - Sandwich structures with thin face sheets
  - Three honeycomb core suppliers were tested
  - Honeycomb core density: 24, 32 and 48kg/m^3
  - ARAMID paper always of the same type and thickness

Sandwich structure study

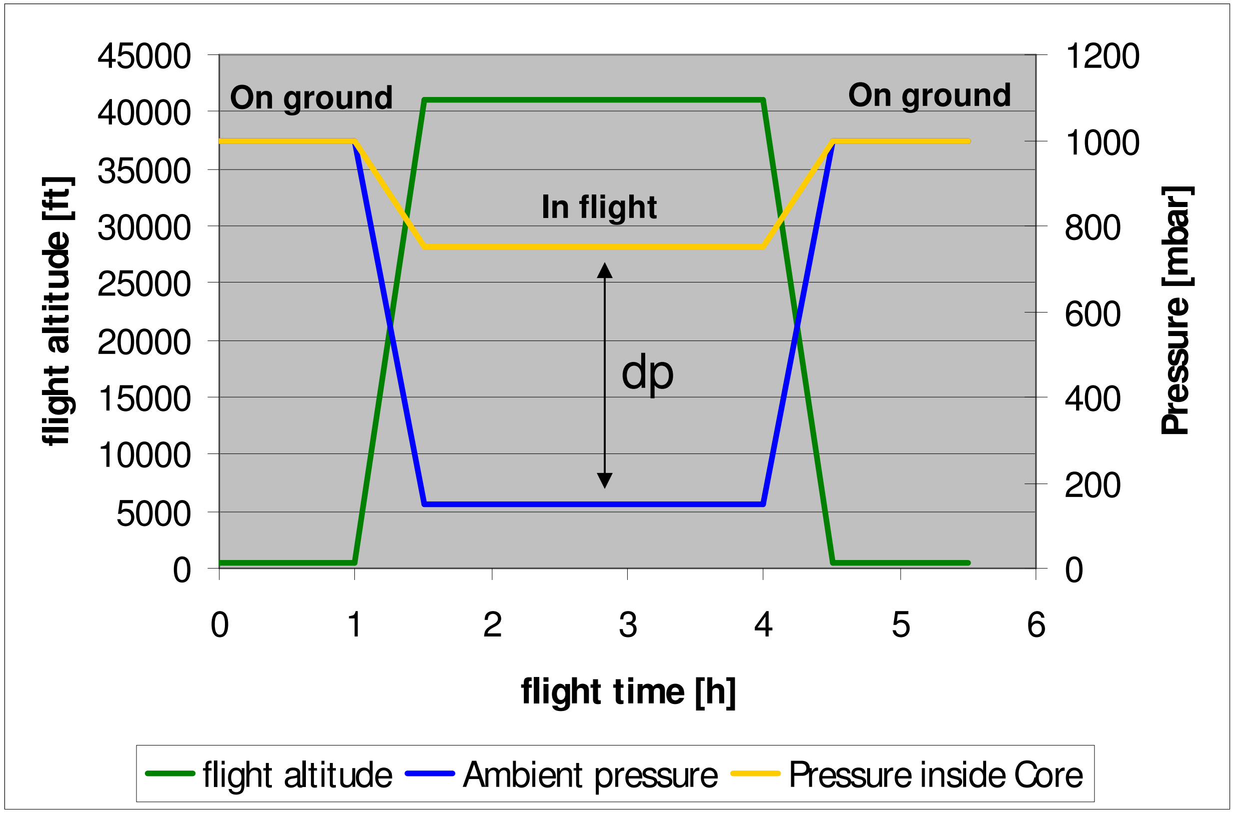
Different types of sandwich structure damage

- Relevant types prone to ground-air-ground effect
- Outer skin disbond (Inspection surface)
- Core fracture
- Inner skin disbond (Opposite skin of inspection area)

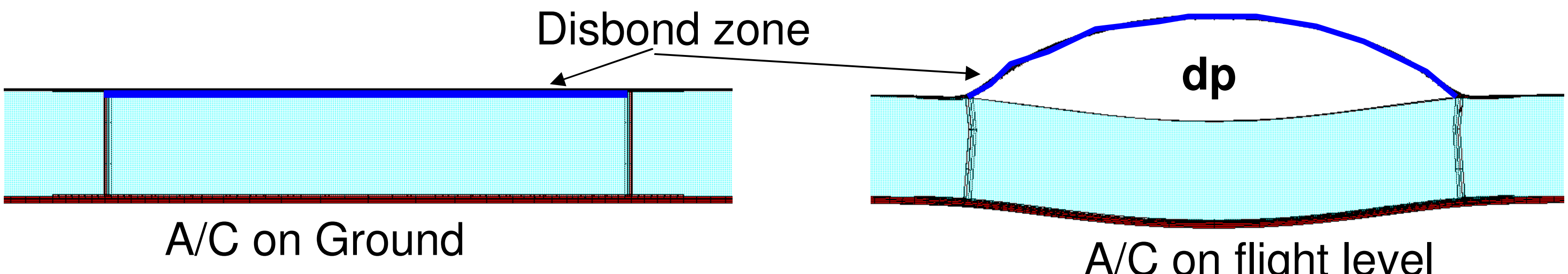


Sandwich structure study

Ground-Air-Ground effect



dp= pressure difference between ambient pressure and pressure underneath a disbond



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Sandwich structure study

Source of damage

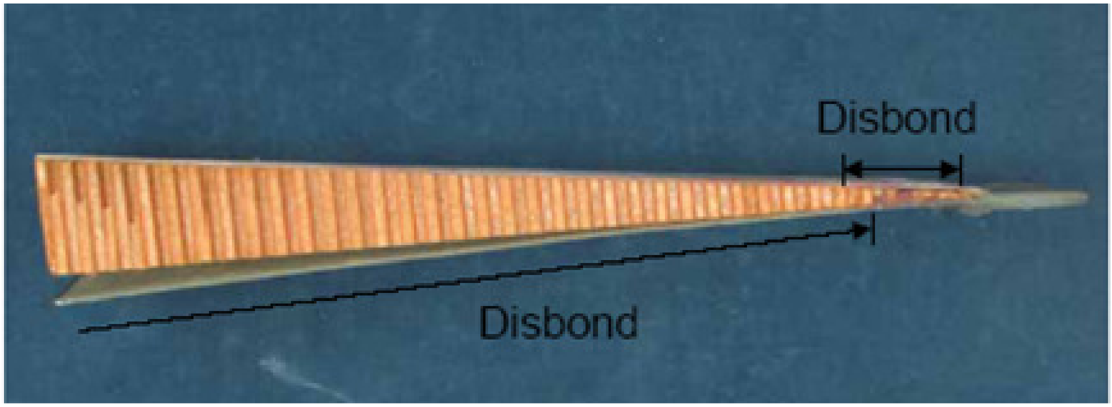
For disbond initiation within sandwich structure possible source were studied:

- **Repairs**
- **Impacts (sharp & blunt)**
- **Fluid (freezing & vaporize)**

Sandwich structure study

Source of damage → Improperly performed repairs

- Airbus in-service experience showed few cases
- For one case the disbond was detected with an Elasticity Laminate Checker (ELCH) inspection performed on subject structure after the repair
- The knowledge on the consequences of an improperly performed sandwich repair is important
    - Deviation from the defined repair instruction, like overheating during curing
    - Deviation to the required environmental conditions (temperature, moisture, cleanness, …)

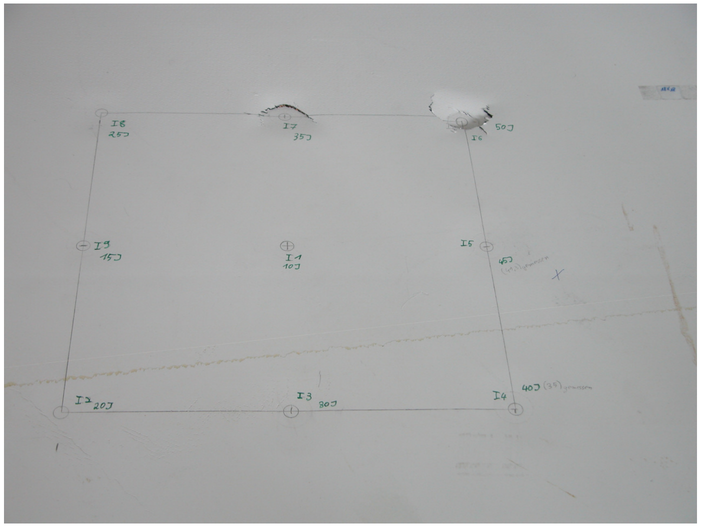


Inner skin repair

Sandwich structure study

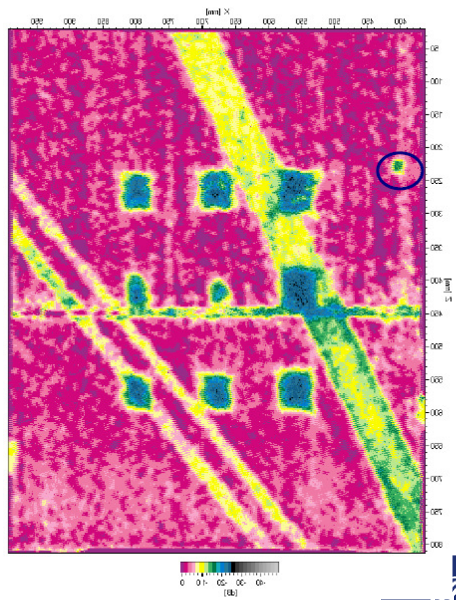
Source of damage → Sharp impact damages

- Skin thickness (t=0.5mm)
- Skin penetration or local crushed core achieved as shown with standard impact
- No hidden damage like disbond or core fracture identified



R	Skin penetration
[mm]	[J]
12.5	4-6
25	12-15
100	35-50

Air coupled ultrasound inspection



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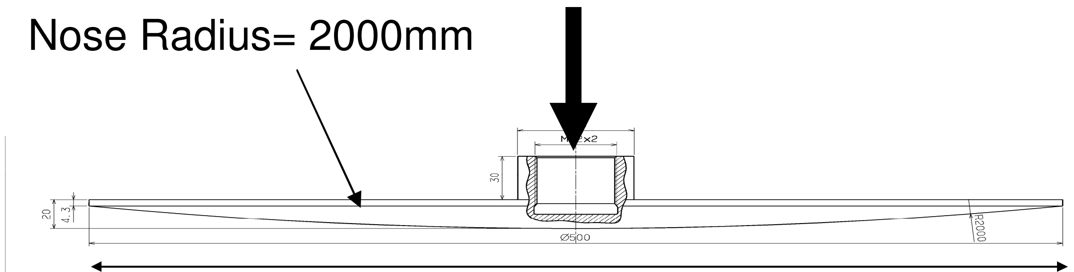
Sandwich structure study

Source of damage → Large blunt impact damages

- Energy levels: 200 and 300J
- Low velocity impacts

Nose Radius= 2000mm



Diameter =500mm

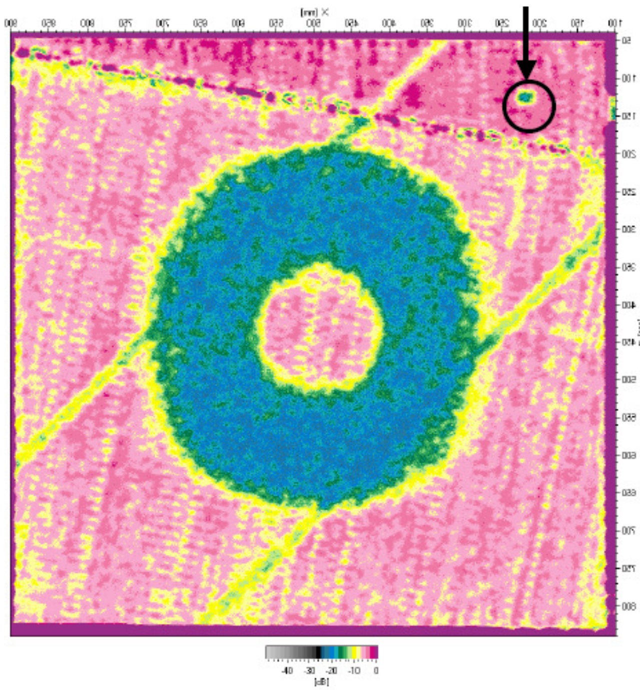
Impactor geometry

Impact Tower

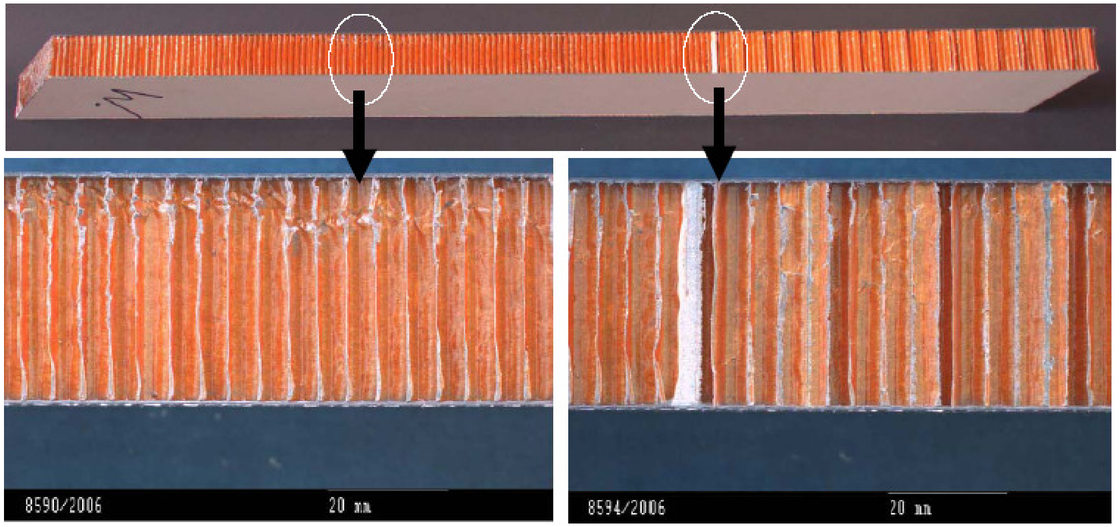
Sandwich structure study

Source of damage → Large blunt impact damages

- The blunt impact test on both panel configurations revealed that hidden disbond or core fracture does not occur.
- Subsequent ground-air ground cycling showed no disbond initiation



Air-coupled ultrasound inspection image



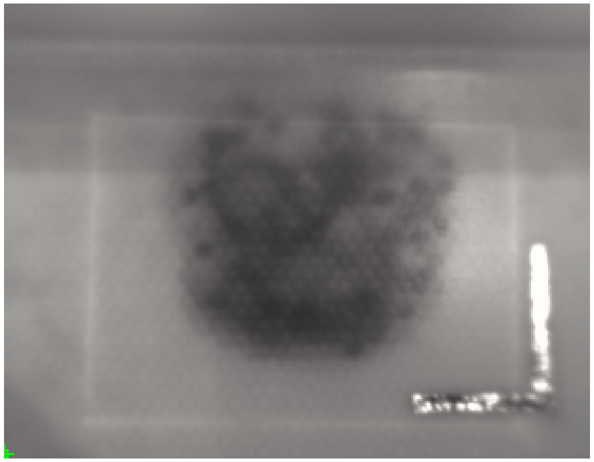
Section cut showed only crushed core

Sandwich structure study

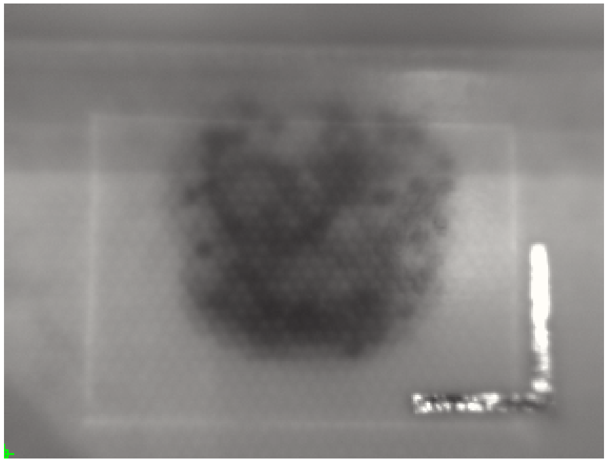
Source of damage →Fluid ingress – thaw & freeze cycle

- **Concern**: Can fluid ingress create a damage due to thermal expansion
- **Test program**: 10.000 thaw & freeze cycle with different location of fluid
- **Intermediate Results**: After 6000 cycles no disbond or core damage initiated

Initial configuration



After 6000 cycle

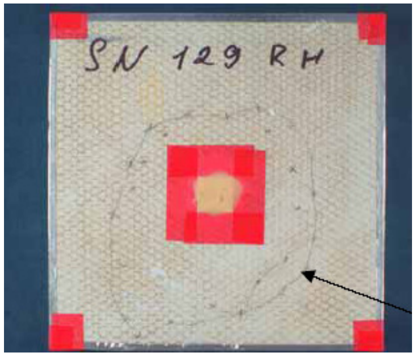


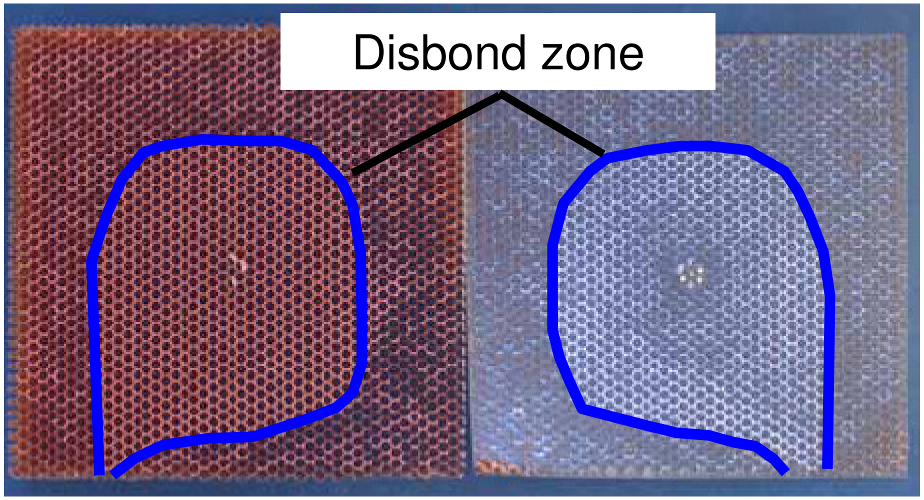
Thermography image of the affected area

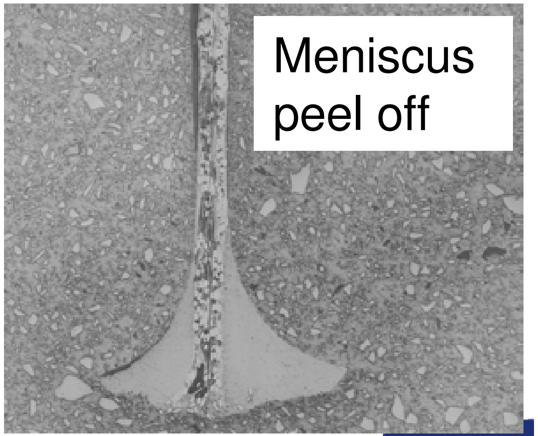
Sandwich structure study

Source of damage → Fluid ingress – Physical test of structure temperature exceeding 100°C

- **Concern**: Effect of fluid ingress and structure temperature above 100°C
- **Phenomenon**: Well known effect that water vaporized above T=100°C → producing high pressure
- **Test specimen**: 5 cells with 5mm water at 110°C/1h
- **Result**: Disbond detected by tap test
- Performing repairs in areas not checked concering fluid ingress in the surrounding







Sandwich structure study

Conclusion

- Possible sources for disbond initiation in sandwich structure
  - Improperly performed repair (deviation to the repair instruction e.g. overheating)
  - Fluid exceeding T=100°C
- Impact damages and freezing fluid showed no hidden disbond or core fracture initiation

Damage growth within sandwich structures

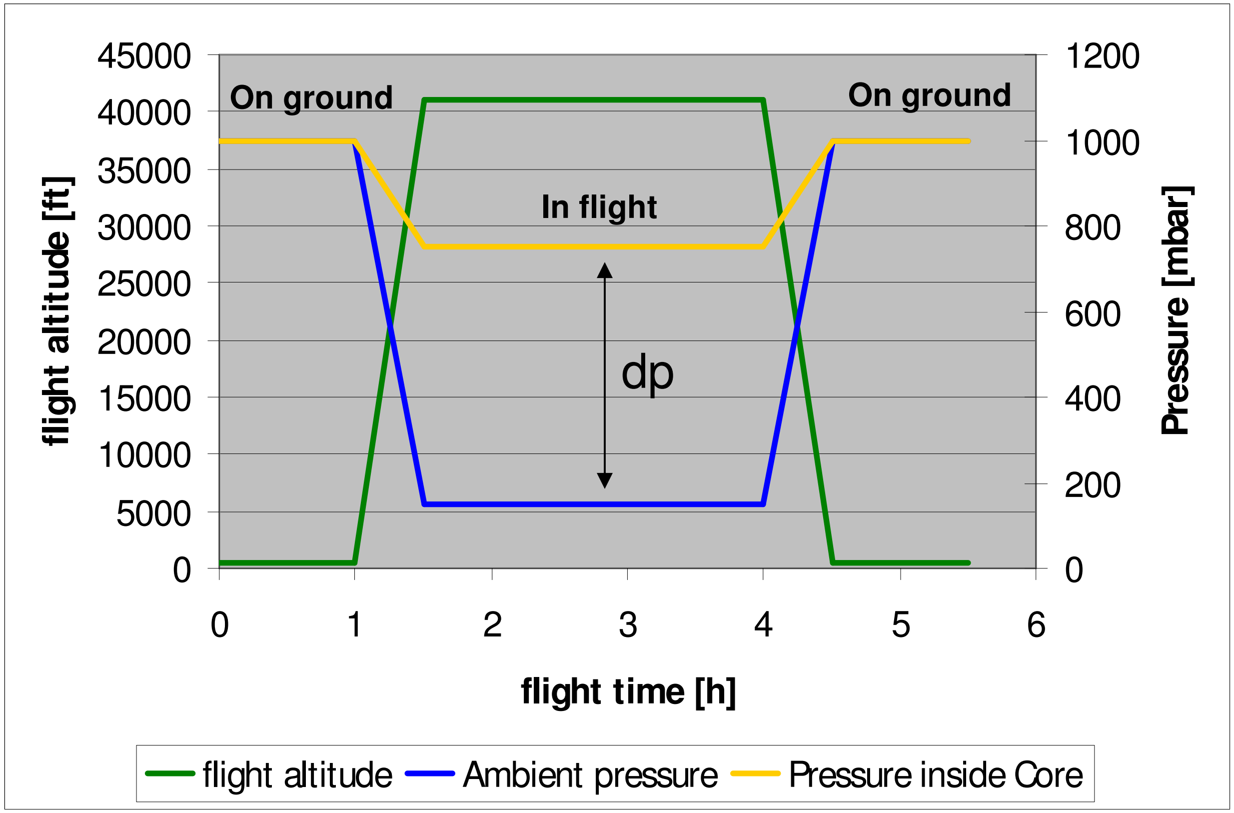
Background

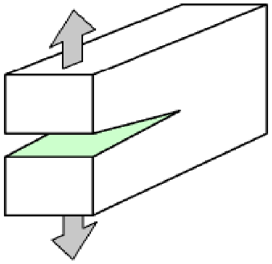
Scope

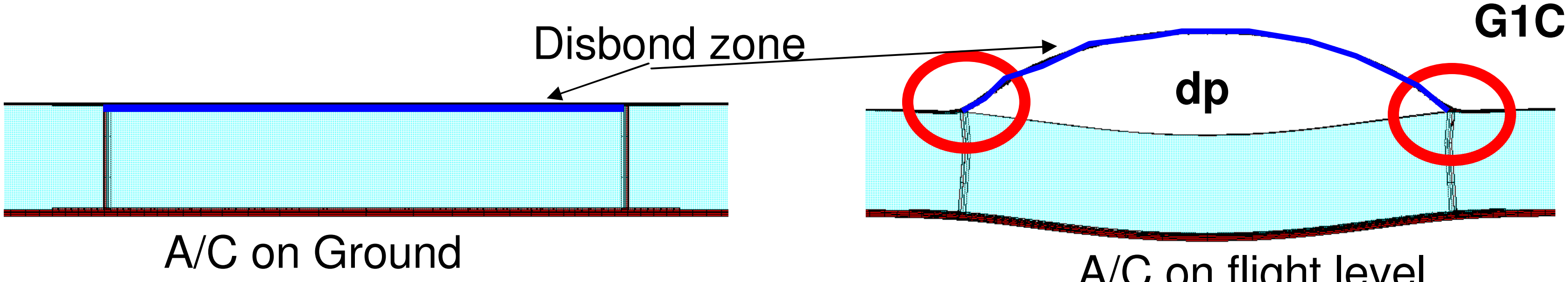
Damage propagation & failure mode

Damage propagation & failure mode

Ground-Air-Ground effect





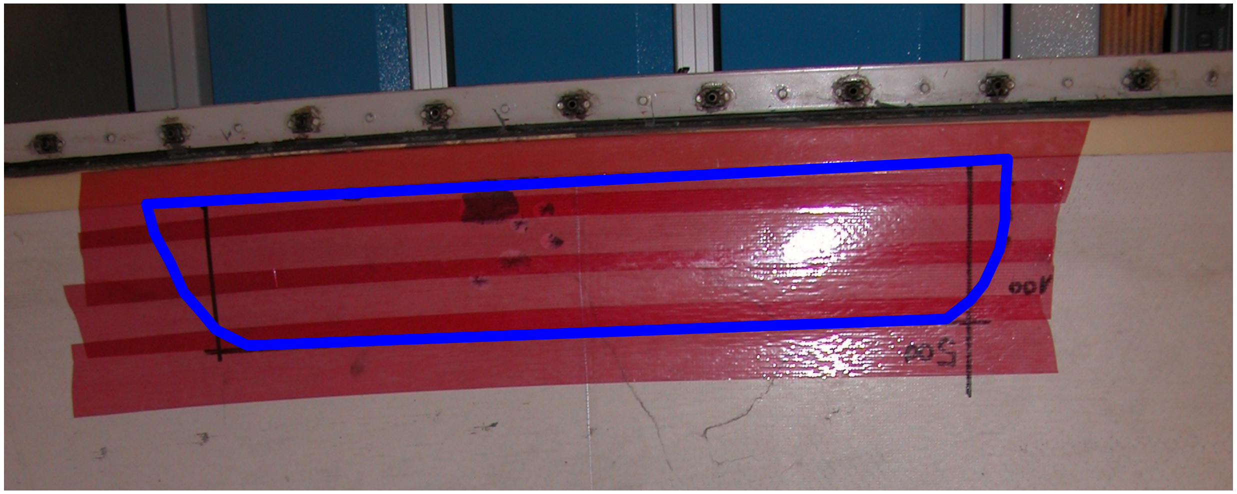


Damage propagation & failure mode

Sandwich panel propagation test

- A face-sheet to core separation of 500x100mm was introduced in a sandwich panel.
- The vacuum chamber pressure was decreased from ambient pressure (P=1000mbar) down to 200mbar in 20minutes.

100mm



500mm

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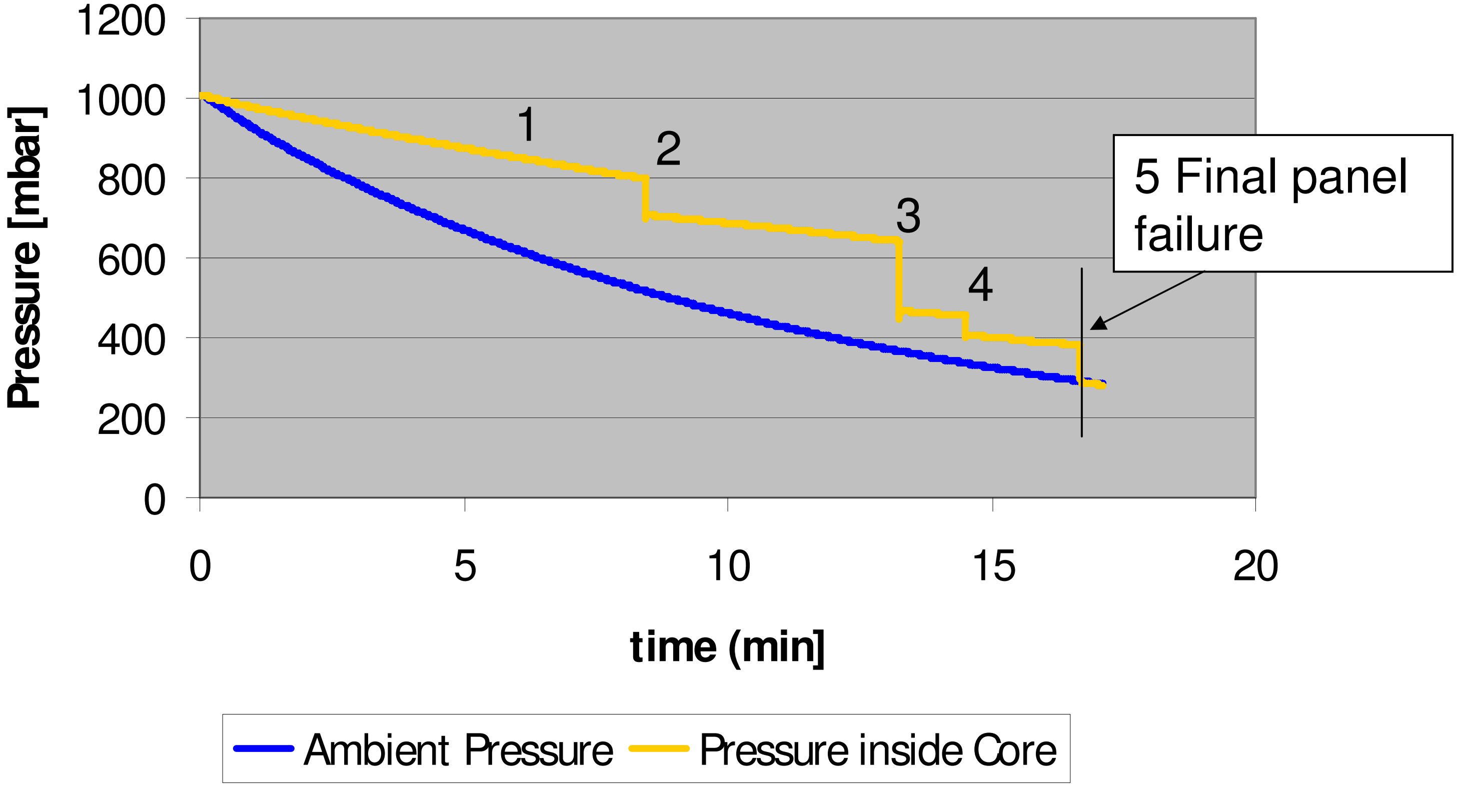
Damage propagation & failure mode

Sandwich panel propagation test

The chamber pressure and pressure inside the core vs. time indicates several disbond propagation steps, before the complete panel fails at $p_{ambient}$=240mbar.

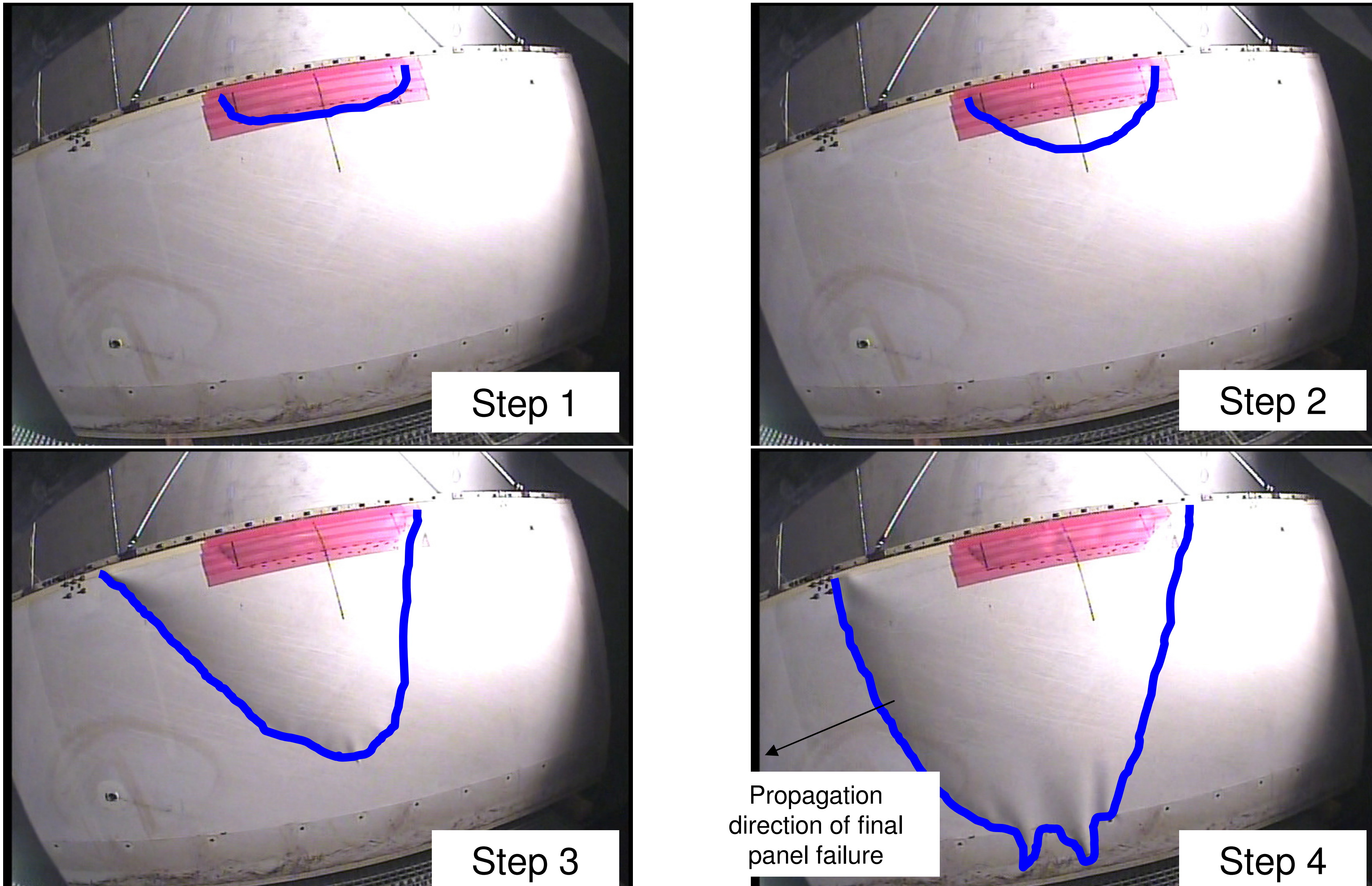
Ambient pressure → continuous decrease

Pressure inside core → stepwise decrease → damage propagation [2 – 5]



Damage propagation & failure mode

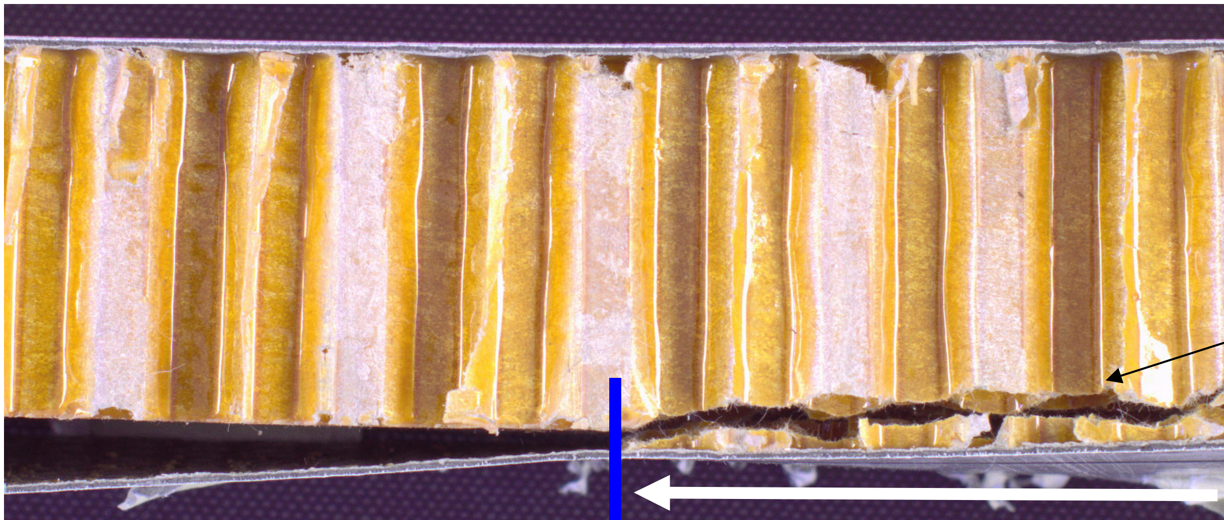
Test results (Extract from video clip)

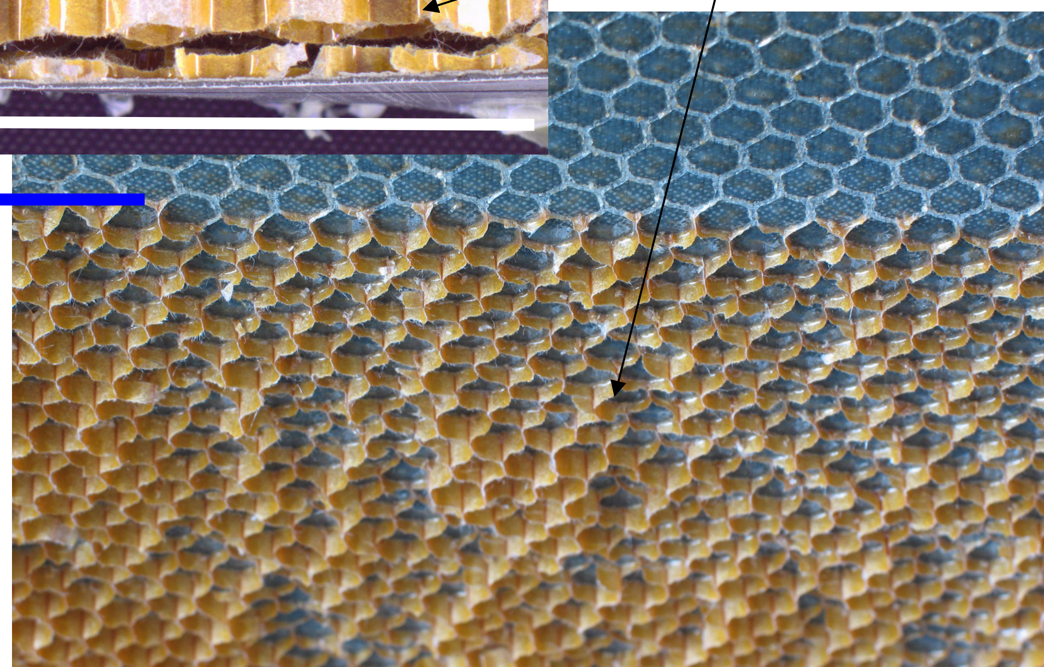


Damage propagation & failure mode

Sandwich panel propagation test

Disbond propagation occurred within the paper





Paper fracture in the disbond propagation zone

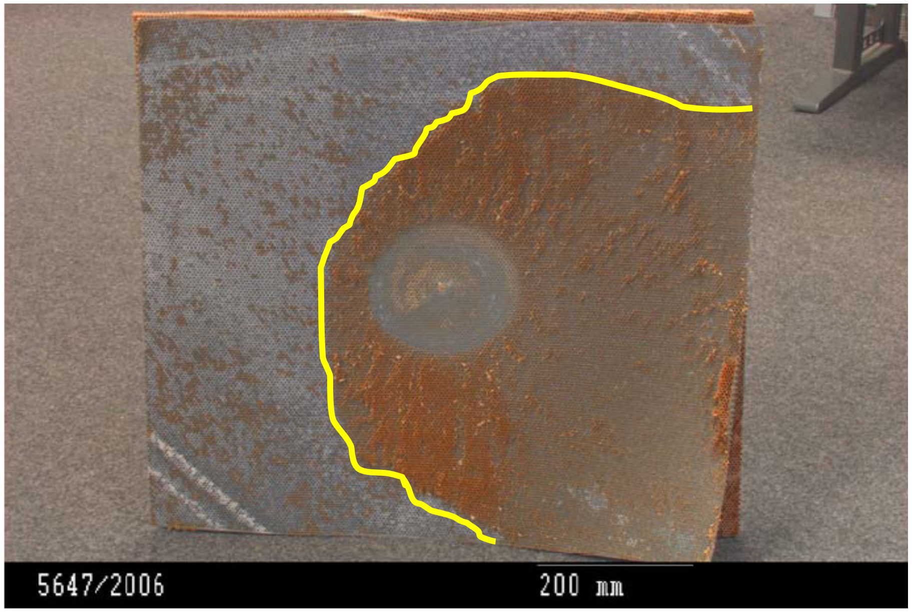
Initial disbond introduced by heat application (meniscus peel off)

Damage propagation & failure mode

Subcomponent sandwich panel test

- Ground-air-ground cycle tests performed for disbond propagation demonstration
- Different disbond sizes tested
- All tests showed paper fracture within the disbond propagation zone

Test panel

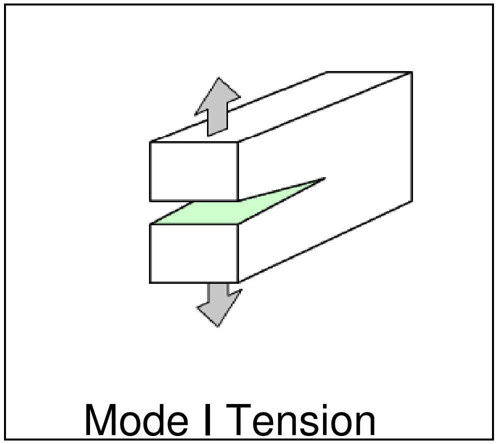


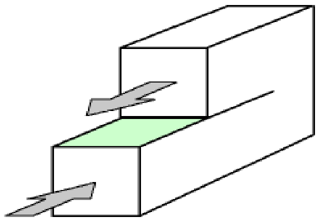
Inner skin of a failed panel

Damage propagation & failure mode

Conclusion

- Large disbond propagation due to ground-air-ground effect shown by test
- Critical size leading to propagation onset depends on fracture toughness G1C
- The fracture mechanism observation from failed sandwich parts showed a paper fracture under mode I tension failure
- Analysis confirmed that the disbond propagation is dominated by mode I fracture mode





Basic fracture modes

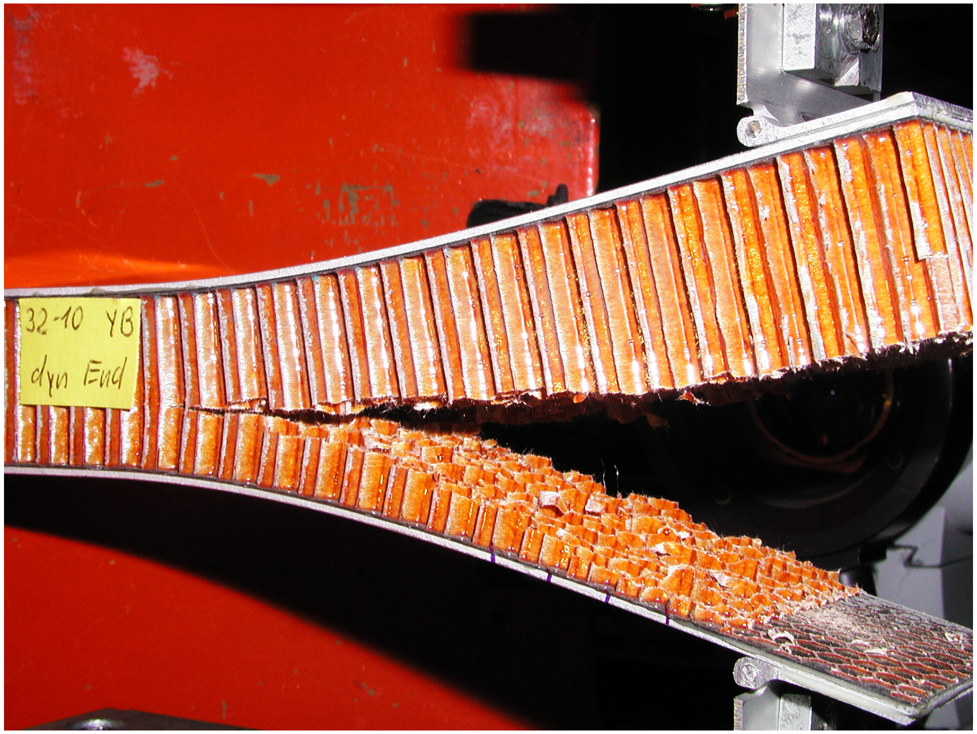
Damage growth within sandwich structures

- **Background**
- **Scope**
- **Damage propagation & failure mode**
- **Fracture toughness (G1C) & propagation rates**

Fracture toughness (G1C) & propagation rates

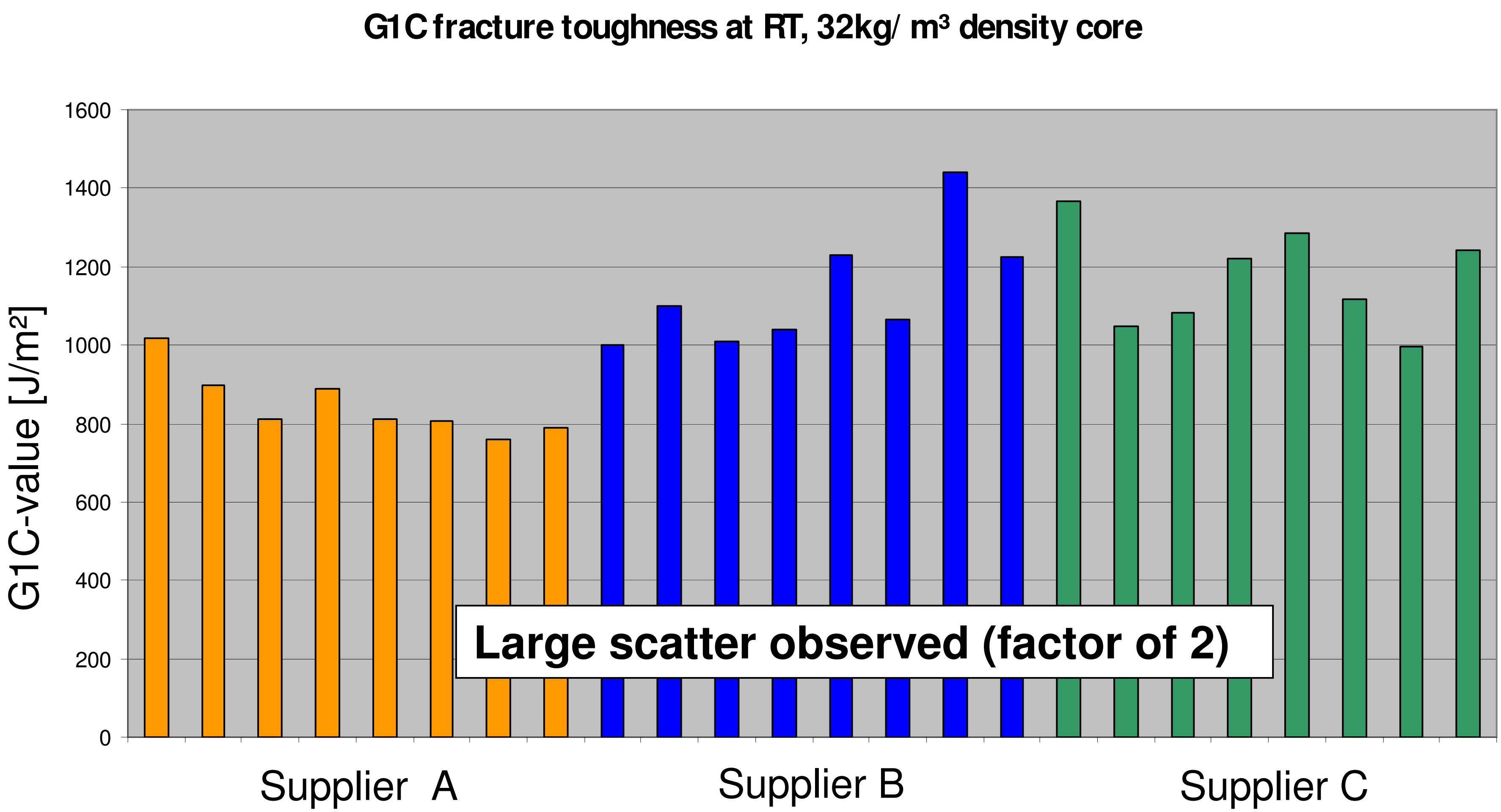
Definition

- DCB specimen used to measure core fracture toughness G1C and generate propagation rates.
- The fracture toughness G1C measured with double cantilever beam (DCB) specimen according to ASTM D5528 standard
- Static G1C value used for finite element analysis



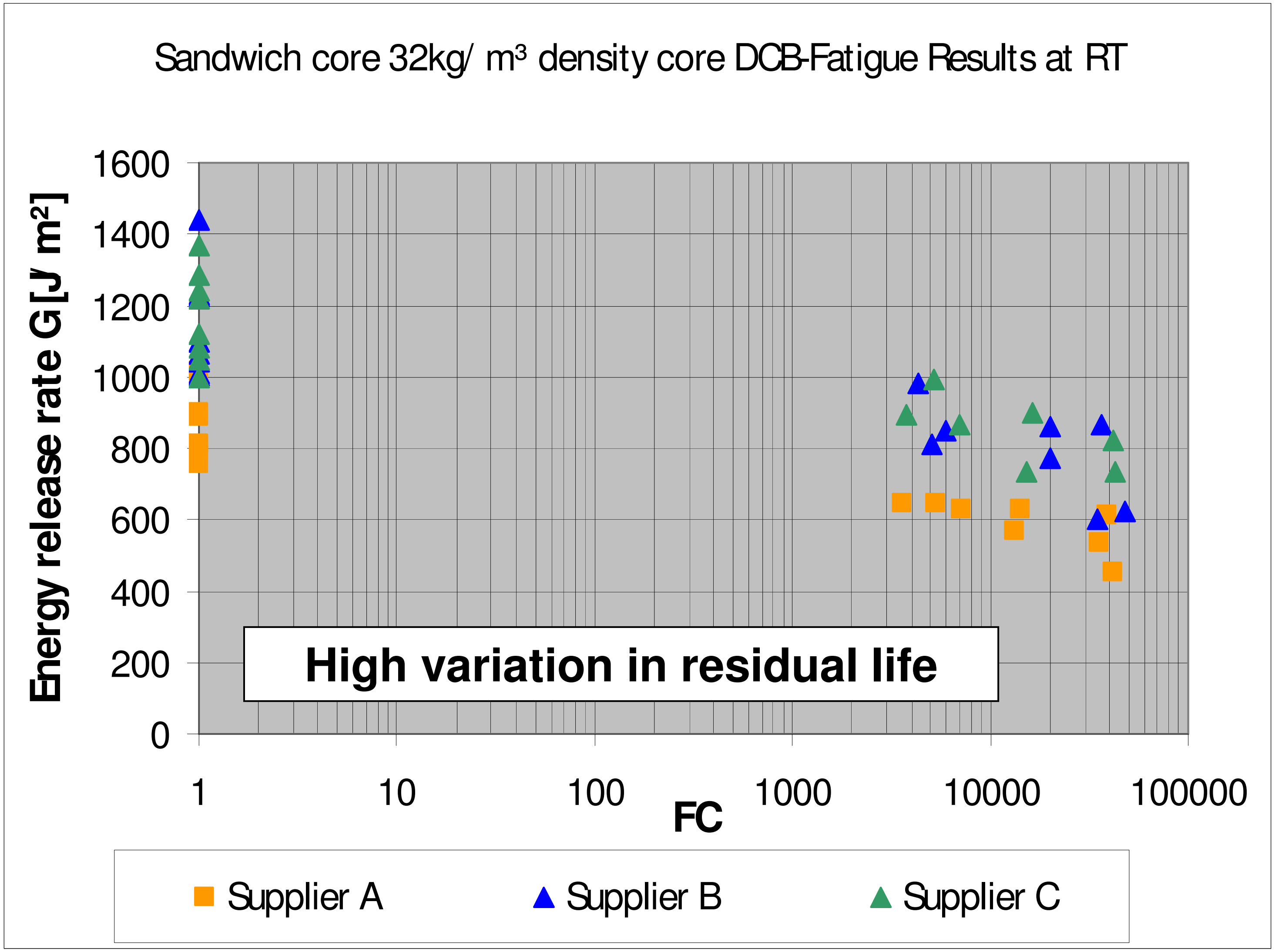
Fracture toughness (G1C) & propagation rates

Static G1C results



Fracture toughness (G1C) & propagation rates

Fatigue G1C results



Fracture toughness (G1C) & propagation rates

Conclusion

- DCB specimen failure mode representative for sandwich disbond propagation
- Fracture toughness test observed large scatter (factor of 2)
- Damage growth occurs inside the core for all applied core densities (24- 48kg/m^3)
- Large scatter in the sandwich G1C-values results in high variation of residual life
- Low propagation rates for high G1C values

Damage growth within sandwich structures

- **Background**
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- **Fracture toughness (G1C) & propagation rates**
- **FE Analysis**

FE Analysis

FEA-Type

Non-linear quasi-static simulation of the ground-air-ground effect on a disbonded sandwich structure.

Parameters

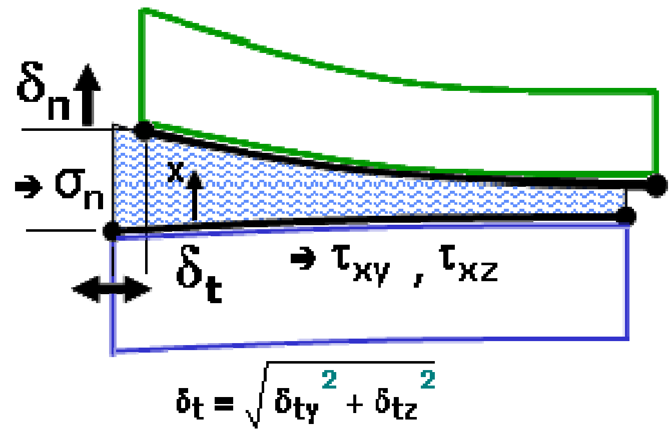
- Core density
- Core height
- Face sheet thickness
- Shape of disbond
- Location of disbond within the sandwich part
- Fracture toughness G1C

Outcome

- Criticality of disbond within a sandwich part
- Prediction of damage onset

FE Analysis

ANSYS Cohesive Interface Element



Element characteristics:

- Interface with zero thickness
- Primary interest in tension opening
- Fracture toughness (GC-value) of mode I tension and mode II shear are assumed identical

Element output:

δ_n	Normal separation distance
δ_t	Tangential separation distance
σ_n	Normal separation stress
τ_{xy}, τ_{xz}	Tangential separation shear stress

Material parameters:

$\sigma_{\max}$	Maximum normal separation stress
$\delta_{n,\max}$	Normal separation distance
$\delta_{t,\max}$	Tangential separation stress

Airbus performed the ANSYS Analysis with CADFEM GmbH Germany

FE Analysis

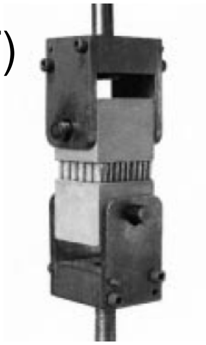
ANSYS Cohesive Interface Element- Parameter Definition

- G1C fracture toughness defined by DCB test
- Flat wise tensile strength of sandwich coupon tests

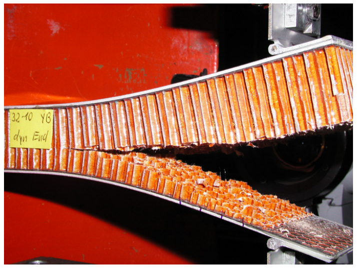
$$G_{1C} = \sigma_{FWT} \cdot \delta_{n,\max} \cdot e$$

Flat wise tension test(FWT)

e.g. 32kg/m³= 1.5MPa



G1C defined by DCB test



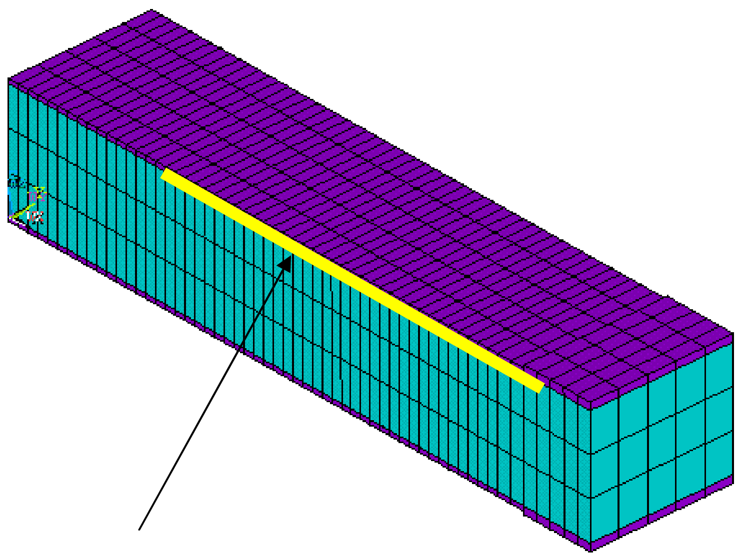
Typical parameter set for an 32kg/m³

$$G_{1C,RT} = 600 J/m^2, \sigma_{FWT} = 1.5 MPa$$
$$\rightarrow \delta_{n,\max} = 0.15 mm$$

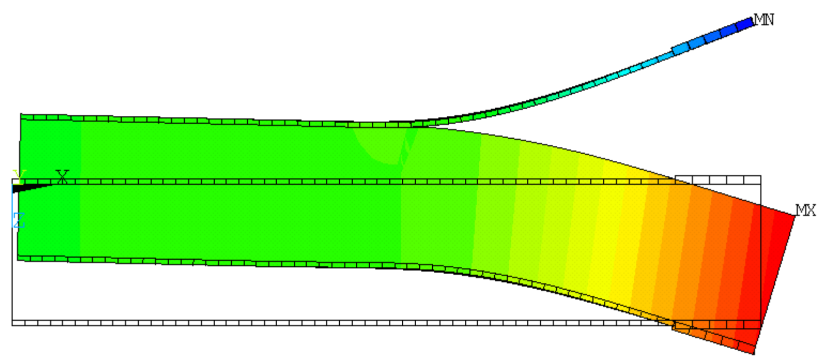
FE Analysis

DCB specimen FE-Model

- Face sheet laminate idealized with shell elements
- Core idealized with solid elements and anisotropic material property
- Cohesive interface elements located between the skin and the core
- Mesh sensitivity study to define appropriate element size



Location of cohesive interface elements



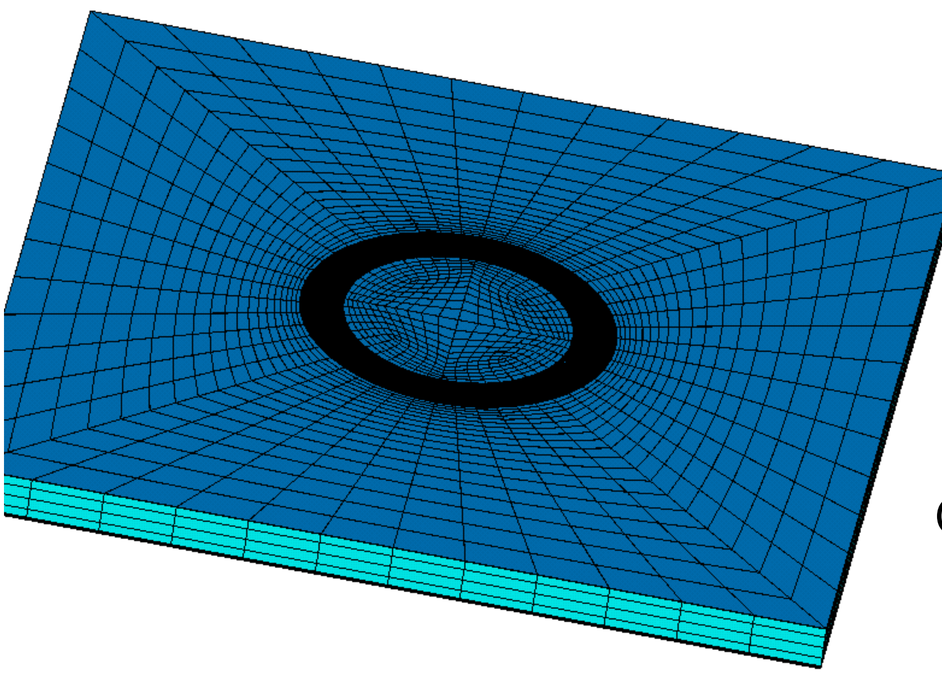
DCB specimen deformation

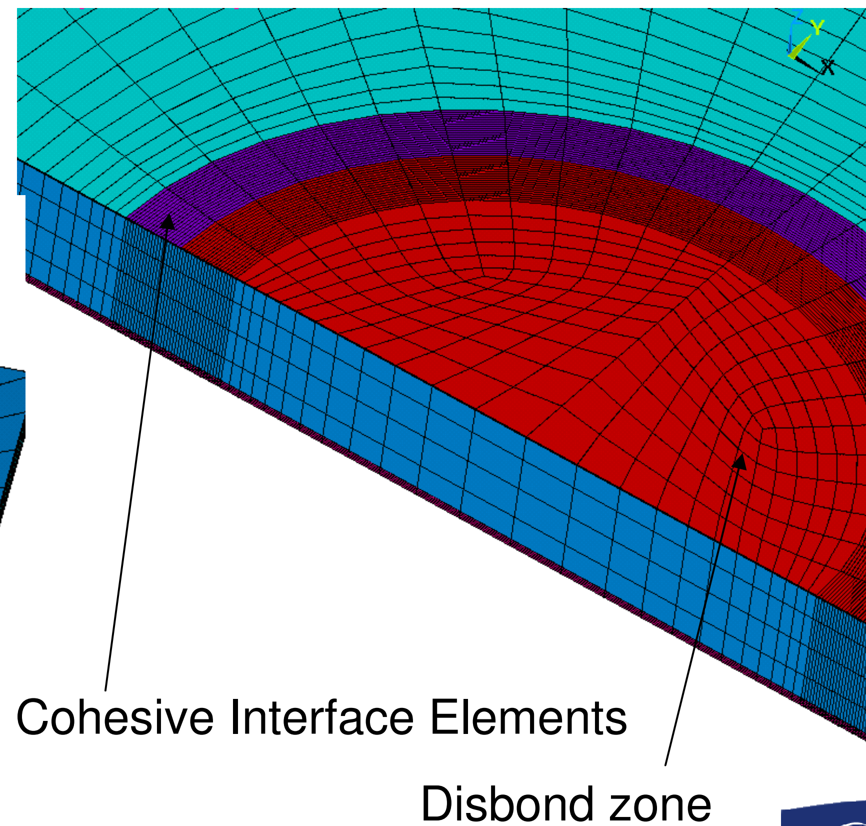
FE Analysis

Circular disbond analysis simulating ground-air-ground cycle

Analyse procedure for disbond ground-air-ground cycle simulation uses the ideal gas law to consider

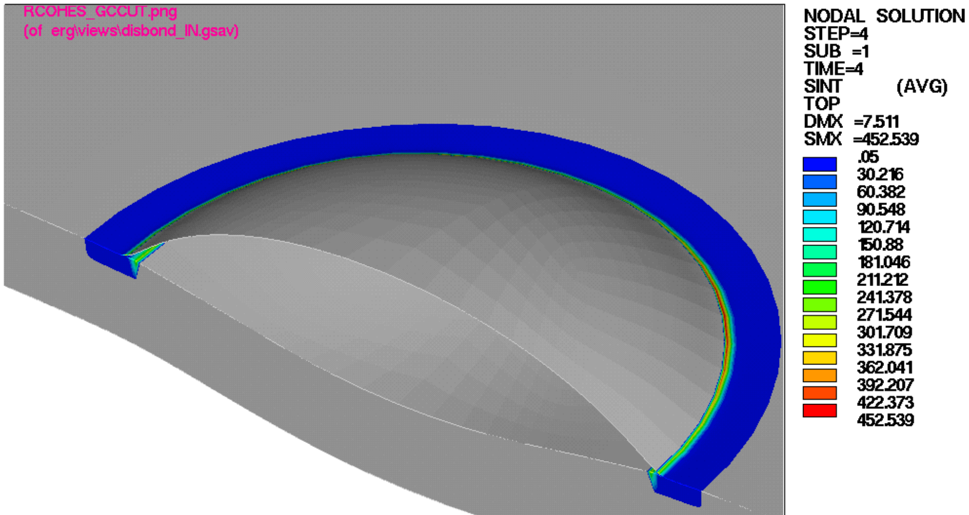
- Temperature difference ground to flight level
- Pressure differential ground to flight level
- Volume effect due to bulging of the disbonded area

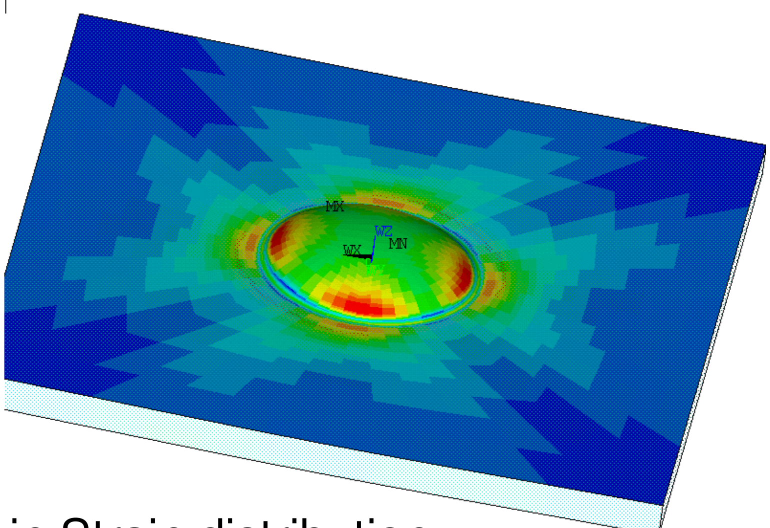




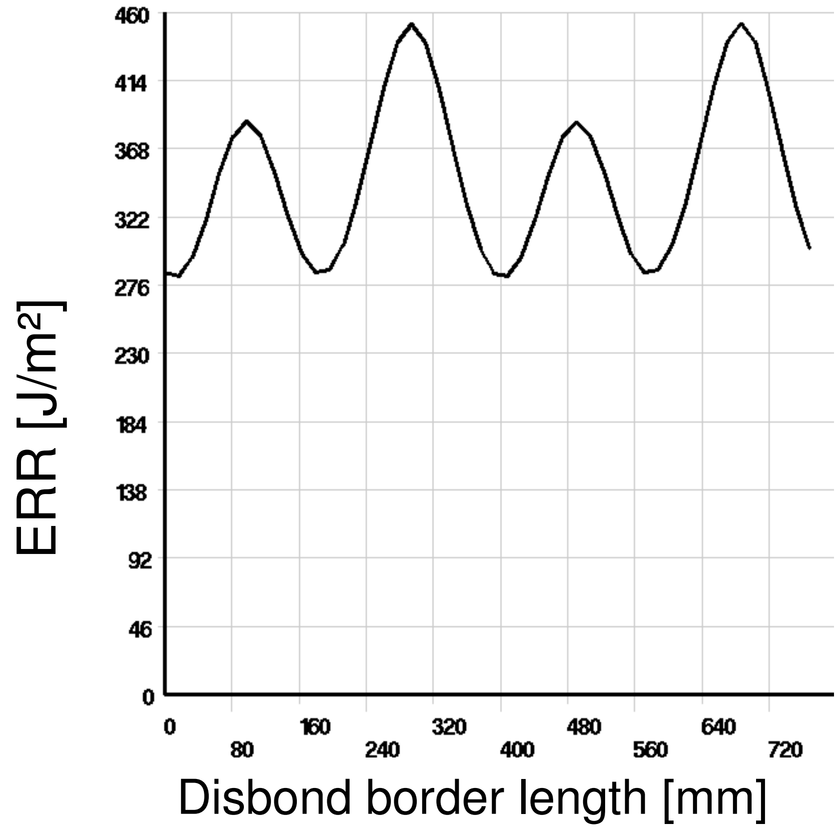
FE Analysis

Energy release rate ERR [J/m²] along disbond border





Skin Strain distribution



Sinusoidal shape of ERR due to anisotropic skin lay-up and core property

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FE Analysis

Conclusion

- Cohesive interface element adequate to simulate disbond propagation
- G1C- and G2C-relevant parameter variation confirmed disbond propagation is mode I tension domination
- Criticality of individual disbond sizes and location on ground-air-ground effect can be demonstrated
- FE Analysis revealed that disbond propagation is mainly due to ground-air-ground effect.
- In undisturbed areas the combination with aerodynamic loading showed an influence of 10% on the ERR
- FE Analysis assume constant G1C value over complete panel
- Prediction of disbond propagation onset validated by test

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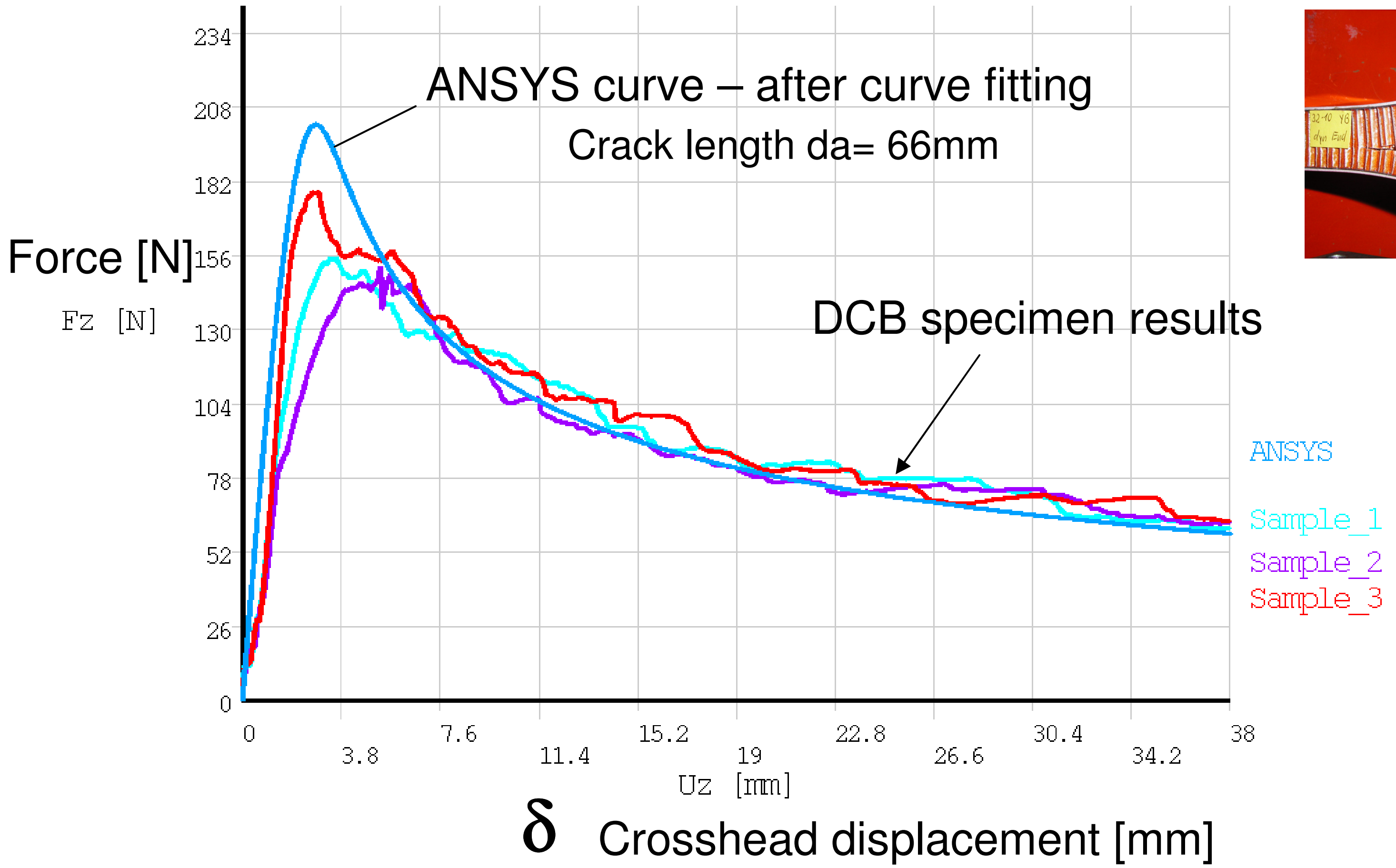
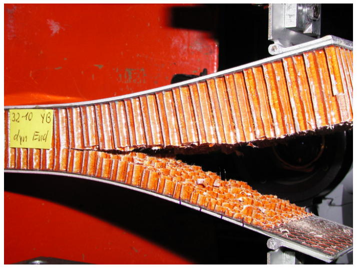
- **Tests vs. Analysis**

Test vs. Analysis

DCB specimen test results vs. analysis

- Cohesive interface element properties fitted with FWT- and G1C- test results
- Analysis showed good correlation with test results

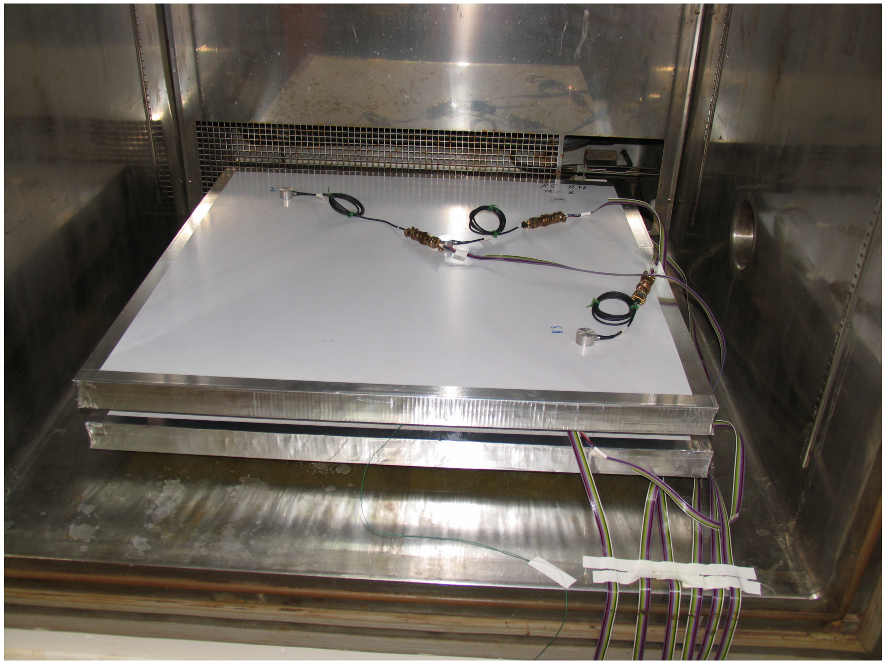




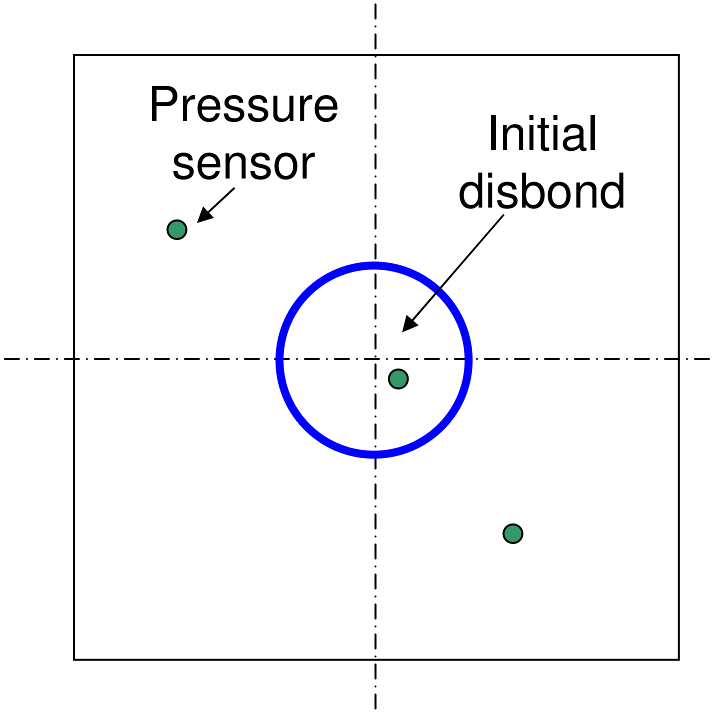
Test vs. Analysis

Sandwich panel tests including circular disbonds

- Sandwich panel with different face-sheet to core separation were tested in a vacuum chamber at RT and T=-55°C to demonstrate disbond propagation.
- Chamber pressure and the pressure inside the core underneath the disbond measured during test



Test panel within vacuum chamber

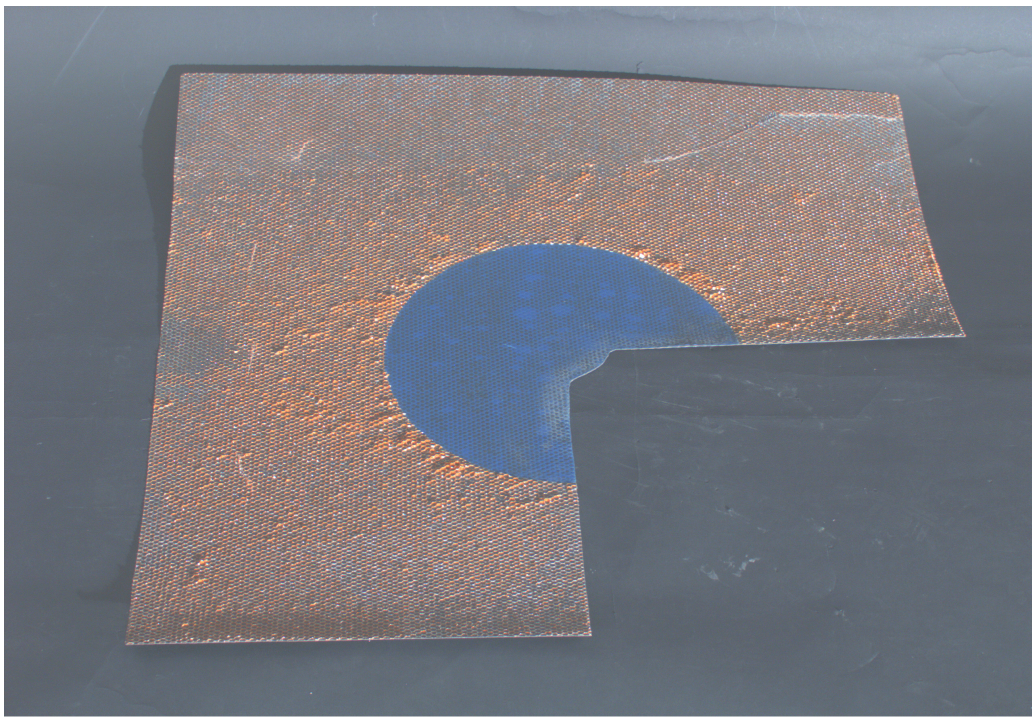


Test panel

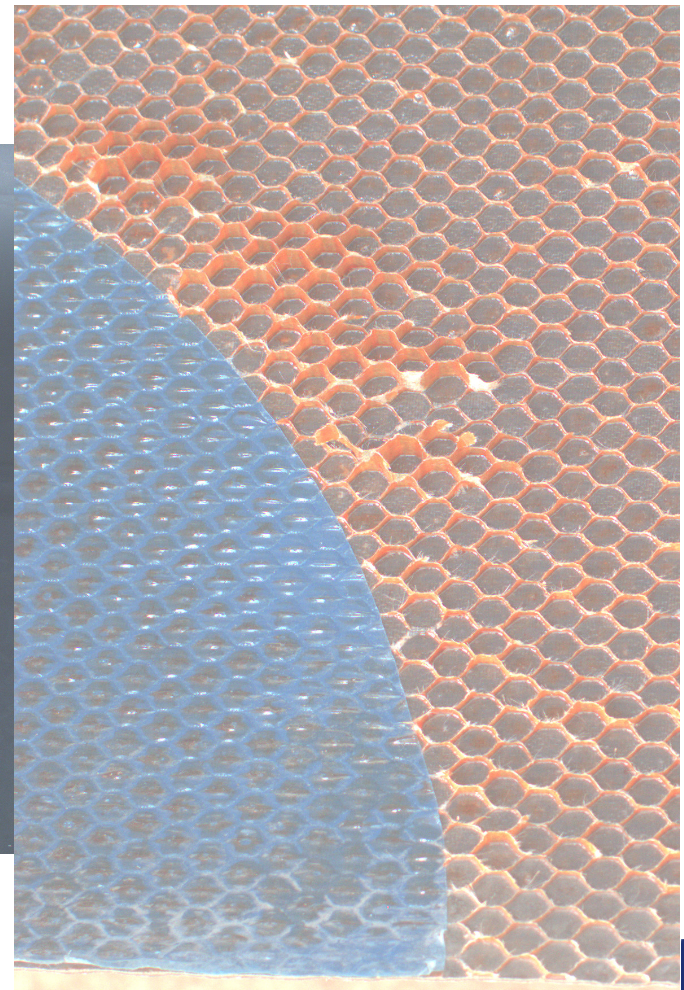
Test vs. Analysis

Sandwich panel tests including circular disbonds

- Face sheet of the disbond panel showed paper fracture

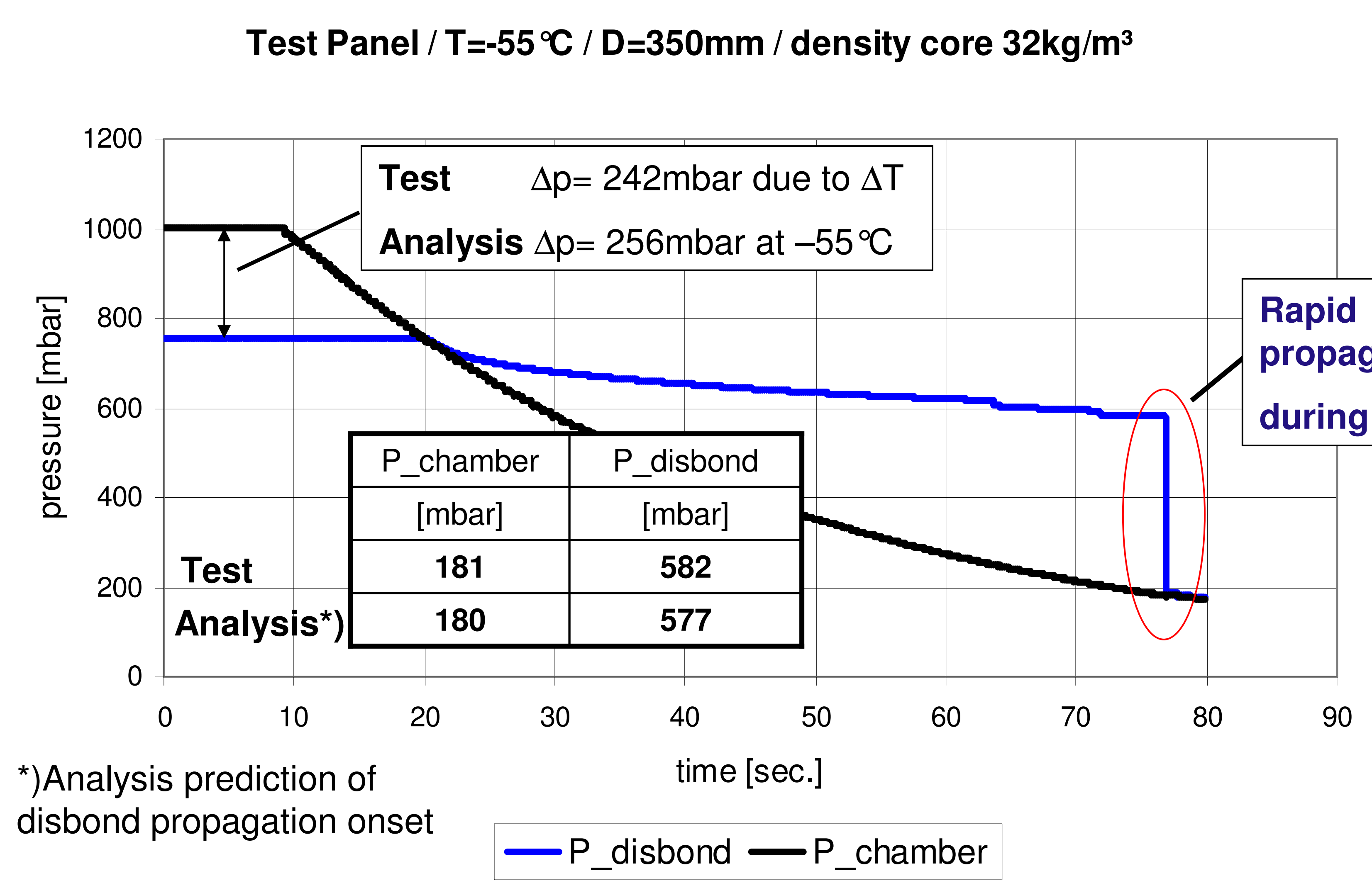


Inner skin of a failed test panel



Test vs. Analysis

Sandwich panel tests including circular disbonds



	P_chamber [mbar]	P_disbond [mbar]
Test	**181**	**582**
Analysis*)	**180**	**577**

*)Analysis prediction of disbond propagation onset

Test vs. Analysis

Conclusion

- DCB specimen test results and analysis in good correlation
- Analysis prediction of disbond propagation onset for sandwich part in good correlation in case of
  - G1C-value established on coupon tests represents the fracture toughness level at the disbond border
  - Low scatter within the fracture toughness at the disbond border

Damage growth within sandwich structures

- **Background**
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- **Fracture toughness (G1C) & propagation rates**
- **FE Analysis**
- **Tests vs. Analysis**
- **Conclusions**

Conclusions

- Airbus studies revealed that the disbond can
    - propagate due to the ground-air-ground cycle
    - and can lead to a significant reduction of the structural capability
- Presented results valid for sandwich configuration with thin face sheet and low core densities
- Possible sources for disbond initiation due to improperly performed repairs and fluid ingress heated over T=100℃
- Large disbond propagation due to ground-air-ground effect shown by test

Conclusions

- Disbond propagation within sandwich structure is mode I tension dominated
- Initial damage can propagate mainly by ground-air-ground cycle
- Core fracture properties (fracture toughness G_{1C}) observed large scatter
- Large scatter in the sandwich G1C-values results in high variation of residual life (low propagation rates for high G1C values)

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