European Union Aviation Safety Agency

Final Report EASA_REP_RESEA_2016_2

Research Project:

DoSS
Disbond of Sandwich Structures

An agency of the European Union

Disclaimer

This study has been carried out for the European Union Aviation Safety Agency by an external organization and expresses the opinion of the organization undertaking the study. It is provided for information purposes only and the views expressed in the study have not been adopted, endorsed or in any way approved by the European Union Aviation Safety Agency. Consequently it should not be relied upon as a statement, as any form of warranty, representation, undertaking, contractual, or other commitment binding in law upon the European Union Aviation Safety Agency.

Ownership of all copyright and other intellectual property rights in this material including any documentation, data and technical information, remains vested to the European Union Aviation Safety Agency. All logo, copyrights, trademarks, and registered trademarks that may be contained within are the property of their respective owners.

Reproduction of this study, in whole or in part, is permitted under the condition that the full body of this Disclaimer remains clearly and visibly affixed at all times with such reproduced part.

Disbond of Sandwich Structures – DoSS

EASA.2016.C20

Partners

DTU – Technical University of Denmark

Fraunhofer Institute for Microstructure of Materials and Systems IMWS

Associated Partners

Airbus Operations GmbH, Hamburg

Airbus Helicopters, Donauwörth

DuPont International Operations, Geneva

Preface

This report serves as a summary of the work conducted in relation to the project titled "*Disbond of Sandwich Structures – DoSS*" funded by the European Aviation Safety Agency (EASA), Cologne, Germany. The main partners of the project were Technical University of Denmark (DTU) and Fraunhofer Institute for Microstructure of Materials and Systems IMWS. Associated partners include, Airbus Operations GmbH, Hamburg, Airbus Helicopters, Donauwörth and DuPont International Operations Sàrl, Geneva.

The overall scope of the work was to bridge the gap between academy and industry with regard to the current fracture mechanics based analysis. Aerospace grade specimens provided by the industry were used to compare two prominent fracture testing methods, namely Single Cantilever Beam (SCB) and Double Cantilever Beam loaded with Uneven or unequal Bending Moments (DCB-UBM). In addition, numerical analysis tools were also developed during the scope of the project. The generated test results along with the detailed analysis of the fracture phenomenon associated with disbonds, provide the necessary input for more advanced analysis in the industry.

The current document serves as a summary report enlisting all the activities carried out by various partners under the ambit of *DoSS*. Detailed summary along with the test results from both SCB and DCB-UBM test methodologies are provided as supplement documents, which are listed below:

1. V. Saseendran and C. Berggreen, "Honeycomb Sandwich Face/Core Fracture Toughness Measurements using the DCB-UBM Test Method – DoSS Project", Department of Mechanical Engineering, Technical University of Denmark, Kgs. Lyngby, 2017.
2. R. Schäuble, M. Goldstein, and M. Petersilge, "SCB Fracture Toughness Tests on Honeycomb Sandwich Material - Technical Report," Internal report, Fraunhofer IMWS V793/2017, Halle, 2017.
3. S. Fimmen, "Mode I Fracture Toughness Tests on Sandwich Structures under constant amplitude fatigue loading", Airbus, Bremen, 2017.
4. Y. Albertone, "SCB - ASTM Round Robin DuPont Results" EASA/FAA Disbond Workshop, Cologne, 2016.
5. F. Hähnel, A. Bugiel, and K. Wolf, "Determination of macroscopic properties of different aramid paper based honeycomb cores" Technische Universität Dresden, Chair of Aircraft Engineering, Internal report ILR/LFT-IR17-19, Dresden, 2017.

Vishnu Saseendran, Christian Berggreen (DTU)	Kgs. Lyngby
Ralf Schäuble (Fraunhofer IMWS)	December 2017
Ralf Hilgers (Airbus Operations GmbH)	
Yannick Albertone (DuPont International Operations)	
Christian Reichensperger (Airbus Helicopters)	

Contents

Definition

Disbond – or “debond” A de-cohesion between face and core in a sandwich, which may be introduced during the manufacturing phase due to insufficient wetting of the surfaces or caused during service by tool drops, blunt body impacts or operating loads.

Phase angle (ψ) – A measure of the mode-mixity component at the crack tip, expressed in degrees. A 0° corresponds to pure mode I, whilst 90° corresponds to pure mode II conditions.

GAG - Ground Air Ground (GAG) cycle is a cyclic loading condition referred to a typical flight mission. In the loads act on the airframe under ambient pressure and temperature, whilst at the operating altitude (41,000 – 43,000 ft) a differential pressure and reduced temperature are experienced by the structure in addition to other loads.

SCB – Single Cantilever Beam (SCB) sandwich specimen is a peel dominant fracture specimen currently under consideration to be implemented as an ASTM International standard for mode I interface fracture characterization.

DCB-UBM – Double Cantilever Beam loaded with Uneven Bending Moment (DCB-UBM) sandwich specimen is used for interface fracture characterization of sandwich composites in mode I, II and mixed mode I/II conditions.

DoSS – Disbond of Sandwich Structures (DoSS) is the term referred to the project funded by EASA in the period from September 2016 – October 2017.

Summary

The overall aim of the DoSS project was to develop damage analysis tools to be able to address the disbond failure problem in sandwich structures. The initial phase of the project for which funding was provided in the period August 2016 – September 2017 is completed. In the first phase, focus was laid on specimen manufacturing and coupon testing. The coupon level testing provides critical fracture resistance, usually referred to as the fracture toughness of the face/core interface. The fracture toughness values along with the crack propagation rates will serve as input to numerical models which investigate damage on component level.

Primarily, fracture testing was performed using two prominent test methods: Single Cantilever Beam (SCB) sandwich specimen and Doubler Cantilever Beam loaded with Uneven Bending Moments (DCB-UBM). The current report covers the experimental work in terms of coupon testing performed at DTU, Fraunhofer Institute – IMWS, DuPont International and Airbus. A detailed summary of test setups and results can be found in the individual technical reports from the collaborators and are provided in the reference.

A comprehensive analysis of honeycomb core test coupons namely, SCB and DCB-UBM were carried out. Analytical as well as experimental methodologies were followed to solve the problem of excessive crack tip distortions associate, in particular with honeycomb cores. Comparison of fracture toughness test results (mode I condition) was seen to be consistent in room, elevated and sub-zero temperatures. The consistent data demonstrated that the production process could heavily influence the fracture toughness values based on the operational environment.

The tests performed in the DoSS project with various labs also demonstrated the feasibility to perform fracture characterization of both thin and thick skinned sandwich configurations intended for typical fixed-wing and rotorcraft applications. Comparison of SCB and DCB-UBM coupon test results in particular, demonstrated that the interface fracture toughness is a material property. Recommendations and a general outlook to extend the damage analysis of sandwich composite structures were also provided.

Overview of the DoSS Project

The primary objective of the DoSS project was to complement efforts in the European side as well as to support to the CMH-17 Honeycomb Sandwich Disbond Growth Group activity. Therefore, the project was aimed to keep the European Industry, Universities & Research Institutes engaged to implement and extend the European knowledge within this international working group.

Under the umbrella of the DoSS project, extensive interactions and participation in the CMH-17 working group were undertaken. The overall progress will be used to push the project toward the target of making reliable tools for damage assessment in sandwich composite structures.

Key initiation items for the project:

- Occurrence of in-service component failures associated with disbonding in honeycomb core sandwich components
- Structure integrity degradation due to disbonding affecting continued operational safety
- Concern that such failures may discourage use of composites in ‘future’ vehicles
- Methods for assessing propensity of sandwich to disbonding not fully matured, accepted and documented

The international Sandwich Disbond Growth Working Group is strongly supported by the airworthiness authorities, FAA and EASA. The DoSS Project was created with the support from EASA. A work package building block approach illustrates the project approach and the global context with the CMH-17 working group (see Figure 1). A brief explanation of each work package (WP) is provided below. It should be noted that work packages, WP3 and WP4 are not in the scope of the initial phase of the DoSS project covered in this report.

WP1 *Coupon Testing* focusses on activities to improve the coupon testing including test execution, test rig and set-up enhancements as well as substantiation of test conditions, specimen preparation and measurements.

WP2 *Fracture Mechanics Analysis* comprises the fracture mechanical analysis of the crack loading situation affected by varying test conditions, specimen set-up etc. primarily based on coupon level. It also includes investigations relating adaptation and enhancement of numerical (FEA) procedures to handle the specifics of the face sheet/honeycomb core interface crack problem. Concurrently data reduction procedure should be considered.

WP3 *Analysis Tools* includes the development of numerical analysis tools/models applicable to evaluate complex loading situations as well as systematic subcomponent level studies. A strong interaction particularly between WP1, WP2 and WP3 is implied. WP3 is not active in the initial phase of DoSS.

WP4 *Validation Test* provides panel/subcomponent damage tolerance test results in order to validate the analysis tools. WP4 is not active in the initial phase of DoSS.

WP5 *Panel Manufacturing* provides the honeycomb sandwich material within the scope of the project.

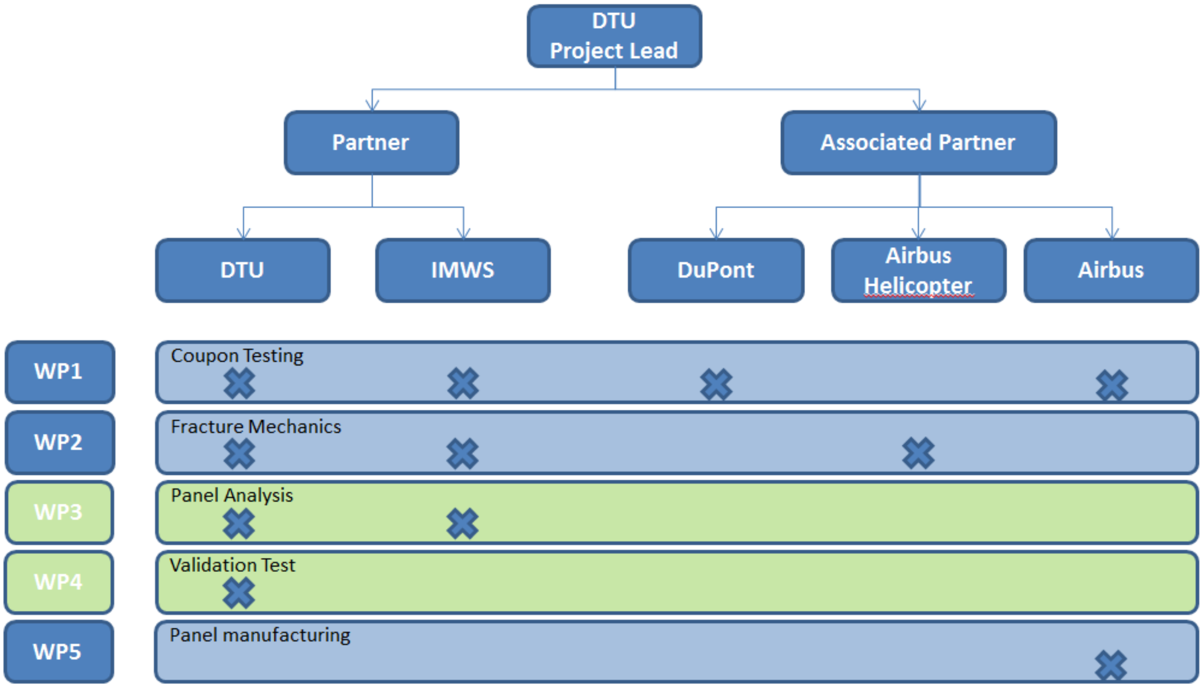


Figure 1. Task sub divisions and activities under the DoSS project. (Green WP's are not included in the current phase of the DoSS project)

General aspects required by EASA to be addressed in this report:

- Brief summary of previous and existing sandwich structure design philosophies, configurations, and applications, highlighting criticality of the various applications used and associated 'lessons learned', including consideration of incidents and accidents (baseline structure and repairs). Design and process related events are also to be included.

- A summary of current international progresses regarding developments in the understanding of sandwich structure failure behaviour and the development of practical and meaningful design certification standards.
- Support for a more efficient certification process (original baseline structure and repairs).
- Provide assessment over the potential transfer of knowledge gained from the current investigations on thin skinned structures to other configurations, e.g. monocoque rotorcraft structures and other thick skinned sandwich structures.
- Proposals for practical and meaningful engineering standard(s) which could provide for better understanding and characterization of skin to core damage modes and mechanisms in sandwich structures, including the potential for disbanding.

SW disbond studied here should be seen from the perspective of overall certification requirements of 23.573a5, AC20-107B and AMC 20-29. CS23 amdt 4 moves the intent to ASTM, whilst the intent is also to be retained the original intent of 23.573a5 in future revisions to AC20-107B and AMC 20-29

1. Introduction

Honeycomb sandwich composites, consisting of a low-density core material reinforced with thin or thicker stiff facings, is attractive for utilization in aerospace applications due to its high specific bending stiffness (see Figure 2). The sandwich technology applied over the last decades showed very good in-service behavior in general and have accumulated millions of flight hours. In particular, good detectability of accidental impact damages was possible due to thin face sheet damage already visible at small impact energy levels. A considerable amount of sandwich construction is present throughout the world’s commercial aviation fleet, both in the form of primary and secondary structures. This type of composite structure is well known to exhibit several damage mechanisms that may potentially lead to component failure. There are many ways in which a sandwich structure can fail, e.g. core compression, shear crimping, face sheet buckling and face/core disbonding. The disbond led separation of face sheet from core is one of the most severe damage modes, as it requires fracture mechanics based tools to assess as well as to predict the failure. Moreover, some in-service failures of several flight components have been attributed to disbond failure. An example includes the loss of an Airbus A310 rudder at altitude [1]. The disbond growth can lead to significant reduction in structural integrity and can have an influence on the operational safety of the aircraft. The sensitivity of sandwich structure disbond growth is influenced by face sheet and core material properties (face sheet and core thickness, flat or curved panel etc.).

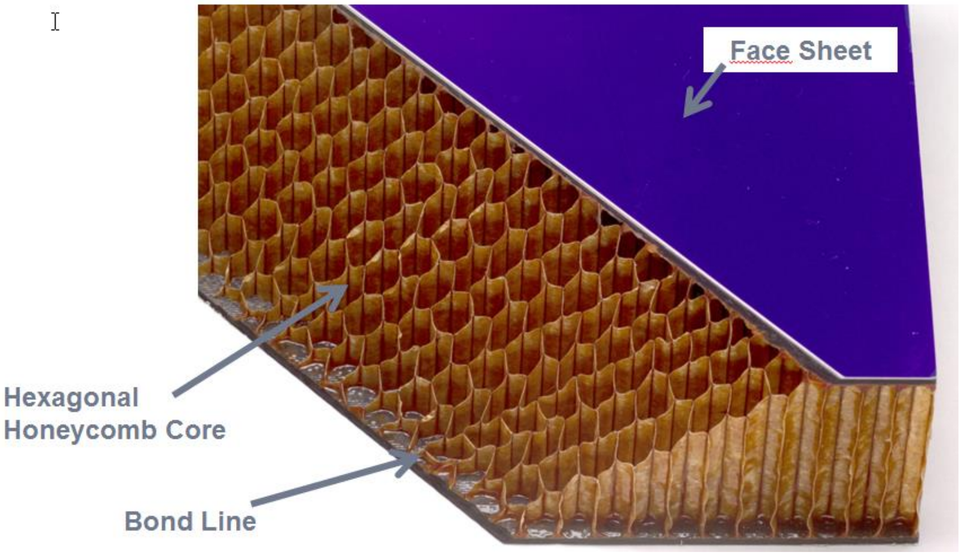


Figure 2. A typical honeycomb core sandwich composite.

A few issues in the early 80’s, most notably of lack of water tightness were recorded. A crucial factor determining the integrity of a sandwich structure is the bonding between face sheet and core. The face/core disbonding (or “disbonding”) can be instigated through a bird strike, hail strike, blunt body impact or tool drop, as well as during the manufacturing phase due to insufficient wetting of face and core surfaces. The presence of disbond have led to several in-service incidents [1], [2]. A number of instances have occurred involving component failure via this damage mechanism. An example includes the loss of an Airbus A310 rudder, see Figure 3. The structural integrity degradation can affect the continued operational safety of the aircraft. In a disbonded sandwich structure, the propensity of the crack to propagate through the interface or kink into the core is driven by the loading conditions. Therefore, the critical energy release rate required to separate the face from core, referred to as the fracture toughness must be ascertained to aid in design of sandwich structural components. The interface fracture toughness must be determined for a range of mode-mixity phase angle to serve as input into numerical models, as the load conditions may induce mode conditions varying from mode I to mode II, an even to mode III for some loading conditions. The crack tip mode-mixity, expressed using the phase angle, ψ, can be attributed to the ratio of mode II to mode I loading – mode III is not considered in this report.

Figure 3. Vertical tail plane and rudder residuals of Air Transat Airbus A310 [1].

In addition to the present use of sandwich composites in primary aircraft structures such as control surfaces, sandwich structures can potentially offer an attractive and lighter alternative to present stiffened monolithic composite primary structures, such as fuselage and wings. However, certification authorities as well as the industry in general are concerned that a possible proliferation of sandwich damage failures, due to a technological gap in the design process in terms of inadequate damage analysis tools as well as certified test methods, will inhibit acceptance of the general utilization of composite materials in future airframes. Due to the importance of the subject to continued operational safety, the FAA launched in 2011 the Honeycomb Sandwich Disbond Growth under the CMH-17 organization, several joint US-European group meetings have been held in period 2011 – 2016.

The main parameter to characterize honeycomb sandwich disbond growth sensitivity is the fracture toughness related to the fracture mode and location. Airbus conducted a series of studies to understand the cause of disbond initiation due to the Ground Air Ground (GAG) cycle phenomenon in the wake of the rudder failure experienced during service. During the GAG cycle the sandwich composites are subjected to pressure change during in-service due to the change of altitude, see Figure 4. There are additional loads introduced on the structural component apart from the pressure change, for instance, gust loads, wind shear, temperature gradient etc.

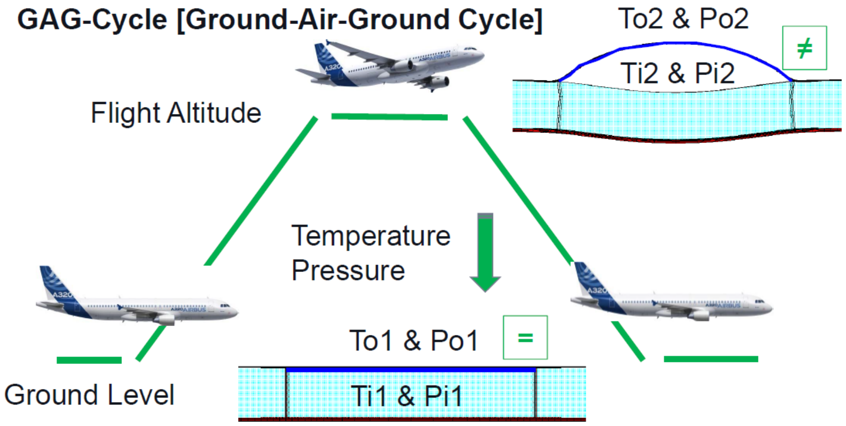


Figure 4. Illustration of the GAG-Cycle Phenomenon.

The structural disbond growth sensitivity for GAG-Cycle and/or in-plane loading is related to the sandwich part stiffness. For thin face sheet and low honeycomb core density structures the GAG-Cycle effect is dominant. For thicker face sheet cases, the in-plane loading will become the dominant loading. The investigation and in-service inspection campaign revealed the following disbond initiation sources:1) sandwich repairs 2) structural local overheating and 3) bond line degradation through internal contamination creating a damage thread between the face sheet and the honeycomb core. The main outcomes of sandwich disbond growth due to GAG-Cycle & in-plane loading was presented to the industry on FAA request. The presentations were given at:

- 2007 in Amsterdam - FAA Workshop for Composite Damage Tolerance
- 2009 in Tokyo - FAA Workshop for Composite Damage Tolerance
- 2010 in Costa Mesa, USA - CMH-17 Workshop

Sandwich disbond growth and subsequent failure of components were not recognized by the industry and FAA/EASA until then as a critical failure mode. Now, activities are focused in order to understand the disbond growth phenomenon and address it under generalized loading conditions. One such example is the development of an ASTM mode I fracture testing standard undertaken at the international level with cooperation of various entities involving academia, industry and premier research organizations. Throughout the Airbus active presentation of sandwich disbond growth due to Ground air Ground (GAG) cycle phenomenon at FAA Damage Tolerance Workshop in Amsterdam 2007 the FAA initiated in 2011 an international working group.

Under the CMH-17 organization the Sandwich Disbond Growth Team was put in place to document sandwich failure modes and provide an Engineering Approach to cover continued operational safety of aerospace application. The pertinent problems faced by the industry can be summarized as:

- Occurrence of in-service component failures associated with disbonding in honeycomb core sandwich
- Structural integrity degradation due to disbonding affects continued operational safety
- Concern that such failures may discourage use of composites in ‘future’ vehicles
- Methods for assessing propensity of sandwich to disbonding not fully matured, accepted and documented

The founding goals of the Sandwich Disbond Growth team can be outlined as:

- Develop robust characterization test methods and accurate analysis techniques, in order to understand and predict face sheet/core disbonding in honeycomb sandwich components
- Improve sandwich design and maintenance practices by disseminating the developed methodology through ASTM test standards, CMH-17 handbook chapters, and safety regulations and guidelines

A schematic illustration of the major milestones of the CMH-17 Sandwich Disbond Growth Team road map is provided in Figure 5.

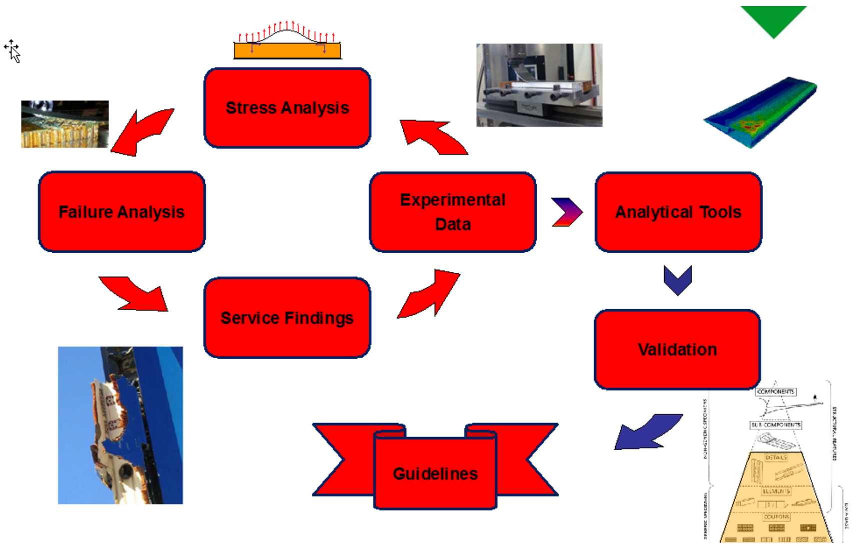


Figure 5. CMH-17 Sandwich Disbond Growth Team Road Map.

1.1.Presentations on project progress and technical discussions

On the European side, meetings were hosted by one of the associated partners which often spanned as one or two days' workshop paving the way for detailed technical discussions, specifically related to sandwich disbond growth. In addition, the main partners and the associated partners are active contributors to the SCB mode I test standard development. All partners participated in the recently concluded international round robin exercise and are actively participating in the monthly WebEx phone meetings, which connects the sandwich disbond community. The international round robin exercise explored the feasibility of employing the SCB test method to assess mode I fracture toughness measurements of aerospace grade honeycomb core sandwich composite. The results are slated to be presented as a NASA technical report in the first quarter of 2018. The activities carried out on the European side along with some of the technical conferences/meetings that the associated members participated are given below:

***EASA Composite Materials Safety Sandwich Structures, EASA/FAA/CMH-17 Disbond Team TG Meeting*, Cologne, 20-21 October 2017.**

- Berggreen, C., "EASA DoSS Project – General Overview".
- Hilgers, R., "Aerospace Perspective Needs and Boundaries".
- Albertone, Y., "Preliminary WP1 Coupon Test Results".
- Fimmen, S., "Mode I dominated Fatigue Tests on Sandwich Coupons".
- Saseendran, V., "Analysis of the SCB and DCB-UBM Test Specimens".

- Schäuble, R., “Honeycomb Sandwich Property Measurements”.
- Saseendran, V., “Coupon DCB-UBM Tests – Mode I/Mixed-mode Static and Fatigue”.
- Bugiel, A., Hähnel, F. and Wolf, K., “Face sheet and Nomex-honeycomb Core Properties of DoSS, project sandwich test-samples”.
- Farshidi, A, “Fracture Mechanics Analysis of Sandwich Composite Beams and Plates”.
- Farshidi, A., “Analysis Round-Robin, Phase 0”.

***DoSS Interim Project Meeting*, Technical University of Denmark, Kgs. Lyngby, 10 – 11 May 2017.**

- Saseendran, V., “Mixed Mode Fracture Testing Using the DCB-UBM Test Method: On-going work”.
- Reichensperger, C., “SCB Tests conducted at Fraunhofer on Honeycomb Core Specimens for Airbus Helicopter”.
- Saseendran, V., “Energy Release Rate and Mode-Mixity of a Reinforced Disbonded Sandwich Beam”.
- Saseendran, V., “Parametric Study and Analysis of the SCB Specimen”.
- Albertone, Y., “SCB Test Results and On-going Work at DuPont”.
- Schäuble, R., “SCB Test Results and On-going Work at Fraunhofer”.
- Berggreen, C., “Disbond of Sandwich Structures – DoSS: Interim Project Meeting”
- Hähnel, F. “Measurement of Face and Core Material Properties at TU Dresden”.
- Farshidi, A., “Fracture Mechanics Analysis of Beam and Plates”.
- Carlsson, L. A., “Activities in FAA-Funded Project at FAU and Georgia-Tech”
- Schäuble, R., “Analysis Round Robin Phase 0 - Preliminary Results & Discussion”.
- Schäuble, R., "TFSanDis Project - Airbus Sandwich Panels Facesheet Properties"

***CMH-17 Sandwich Disbond Workshop*, Airbus GmbH, Hamburg, 14 February 2017.**

- Schäuble, R., “TFSandDis project update (tasks, tests & results)”.
- Saseendran, V., “DCB-UBM Static and Fatigue Test Matrix”.
- Hilgers, R., “Definition of DoSS Project Test and Analysis Tasks”.

***Honeycomb Core Material Modeling Workshop*, Dresden, 30 August 2016.**

- Bugiel, A., Hähnel, F. and Wolf, K., “Current Work on Nomex® - honeycomb Material and Cores”.
- Hähnel, F. “Nomex® Honeycomb Sandwich Experimental and Numerical Work”.
- Schäuble, R., “Influence of Honeycomb Core In-plane Poisson’s ratio – Recent results”.
- Hohe, J., “Honeycomb Core Modeling Experience at Fraunhofer IWM, Freiburg”.

- Farshidi, A., “Modeling of Disbond in Honeycomb Sandwich Composites along the Analysis Round Robin”.
- Saseendran, V., “Numerical Homogenization of Nomex® Honeycomb Core Sandwich Composite”.

***FAA Funded Project Meeting,* Florida Atlantic University, Boca Raton, 10 – 11 January 2017**

- Saseendran, V., “Fracture Characterization and Analysis of Sandwich Composites.”
- Saseendran, V., “Introduction to CSDE Method and Implementation”

***EASA/FAA Sandwich Structure Meeting and CMH-17 Disbond/Delamination TG Meeting,* Cologne, 18-20 October 2016**

- Berggreen, C., “Round-Robin Mode-I Face/Core Fracture Toughness Characterization of Honeycomb Sandwich Composites using the SCB and DCB-UBM Test Methods”
- Berggreen, C., “EASA.2016.HVP.14: Disbond of Sandwich Structures – DoSS”
- Farshidi, A., “An overview of earlier and planned work at DTU on disbond propagation analysis in sandwich panels –static and fatigue loading”
- Saseendran, V., Berggreen, C. and Carlsson, L.A., “On-going work at DTU on mode-mixity determination in disbonded honeycomb sandwich composites”
- Schäuble, R., "Suitability and Robustness of the SCB Fracture Toughness Test for Honeycomb Sandwich with Very Thin Face Sheets”
- Schäuble, R., "SCB Test Round Robin - Results Lab5 (Fraunhofer)”
- Schäuble, R., "German National Funded Project: Thin Face sheet Sandwich Disbond (TFSanDis)"
- Schäuble, R., "FEA Studies on Disbond of Honeycomb Sandwich at Fraunhofer IMWS - Influence of Honeycomb Core in-plane Poisson’s Ratio”
- Albertone, Y., “SCB - ASTM Round Robin DuPont Results”.

***ASC 31st Technical Conference & ASTM Committee D30 Meeting, Williamsburg*, Virginia, September 19–21, 2016**

Presentation: R. Schäuble: "Single Cantilever Beam Test for Honeycomb Sandwich Materials with Very Thin Facesheets – Effects of Test Conditions and Material Properties"

Proceedings of the American Society for Composites: *Thirty-First Technical Conference*, Williamsburg, Virginia, September 19–21, 2016. DEStech Publications, Inc., CD-ROM, Paper 3208, 13 pp.

FAA/EASA Workshop (CMH-17 Sandwich Disbond Group), March 2017, Salt Lake City

- Albertone, Y., “Single Cantilever Beam Test – FAA/EASA Workshop”.
- Saseendran, V. and Berggreen, C. “Parametric Study and Analysis of the SCB Specimen”
- Berggreen, C., “EASA.2016.HVP.14: Disbond of Sandwich Structures – DoSS”
- Berggreen, C., “Future Variable Mixed Mode Sandwich Debond Characterisation Methods for Standards Implementation”

2. Documentation on the SCB and DCB-UBM test methods

The SCB specimen shown in Figure 6, consists of a sandwich construction containing a non-adhesive insert on one sandwich face sheet/core interface, spanning a distance, a0, along the specimen length, that serves as a disbond initiator. Opening forces are applied to the SCB specimen by means of a hinge or loading block (hinge depicted in Figure 6) bonded to the end of the disbonded face sheet. The opposing face sheet of the specimen is fixed to a base plate. The SCB specimen is opened by controlling either the opening displacement or the crosshead movement, while the load and disbond length are recorded. Nominal dimensions and constituent materials for the SCB specimen used in the DoSS test series are provided in the test matrix given in Table 1. The SCB tests were carried out at Fraunhofer and DuPont. In addition, pilot tests on fatigue implementation of SCB test rig was also performed by Airbus GmbH. A SCB test setup also exists at DTU, but has not been utilized in the DoSS project. The DCB-UBM test setup is only located and details can be found at the end of this section. Detailed descriptions of all equipment and data acquisition techniques follow below.

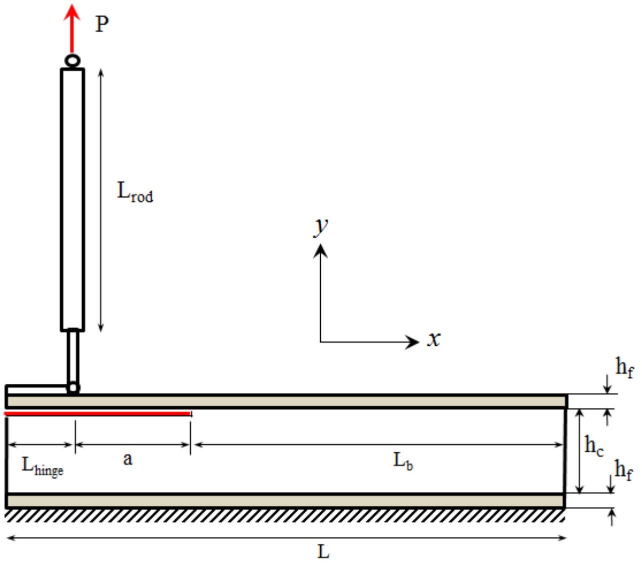


Figure 6. Schematic illustration of sandwich SCB specimen.

2.1. SCB Test Set-up at DuPont Lab, Geneva, Switzerland

The SCB test fixture employed at the DuPont lab in Geneva is shown in Figure 7. The specimen is first glued onto the base plate and mounted to the test rig. An alignment procedure is undertaken with the aid of stainless steel pins to ensure specimen and upper loading plaque positioning with regards to the base plate edges, see Figure 8a. The specimen as well as upper loading plaque are is then clamped to ensure that uniform pressure is imparted evenly during two-component epoxy adhesive curing on the bottom, see Figure 8b. Due to the large deflection of the face sheet and the fixation of the specimen a lateral movement of the loading point occurs. In order to keep the load direction as perpendicular as possible, the effective length of the movable loading rod is 500 mm measured as the distance between the pivot point of the piano hinge and joint head at the upper end of the leverage (see Figure 9). Disbond or Crack length a (mm) is measured using optical extensometer. Upper face sheet is divided into around 0.05 mm long segments. Optical extensometer does tracks upper faces sheet's segments vertical position at 5 Hz frequency. It identifies and records disbond position when segment vertical position change exceeds a threshold. Every cycle Dissipated Energy *dU* (J) as well as Disbond Growth increment *da* (mm) and Fracture Toughness *Gc* (J/m_2) are automatically calculated at the end of every cycle. Tests are also video recorded at 5x image/sec. Optical extensometer is periodically calibrated post-test and using video. During calibration, two observers visually record disbond position vs. ruler (bonded to test specimen). Calibration is currently performed once every test campaign. Inter-cycle *dU* overlap (e.g. face sheet hysteresis) is also automatically calculated. This data may be considered for later studies. The specifications of the test machine are provided in [3].

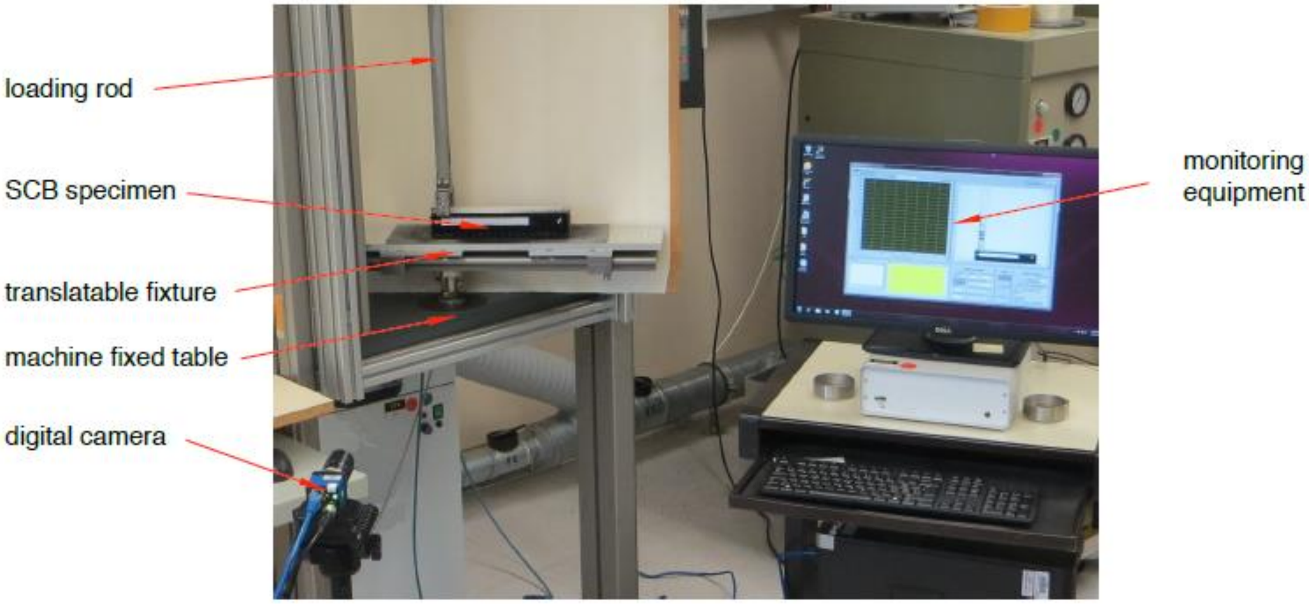
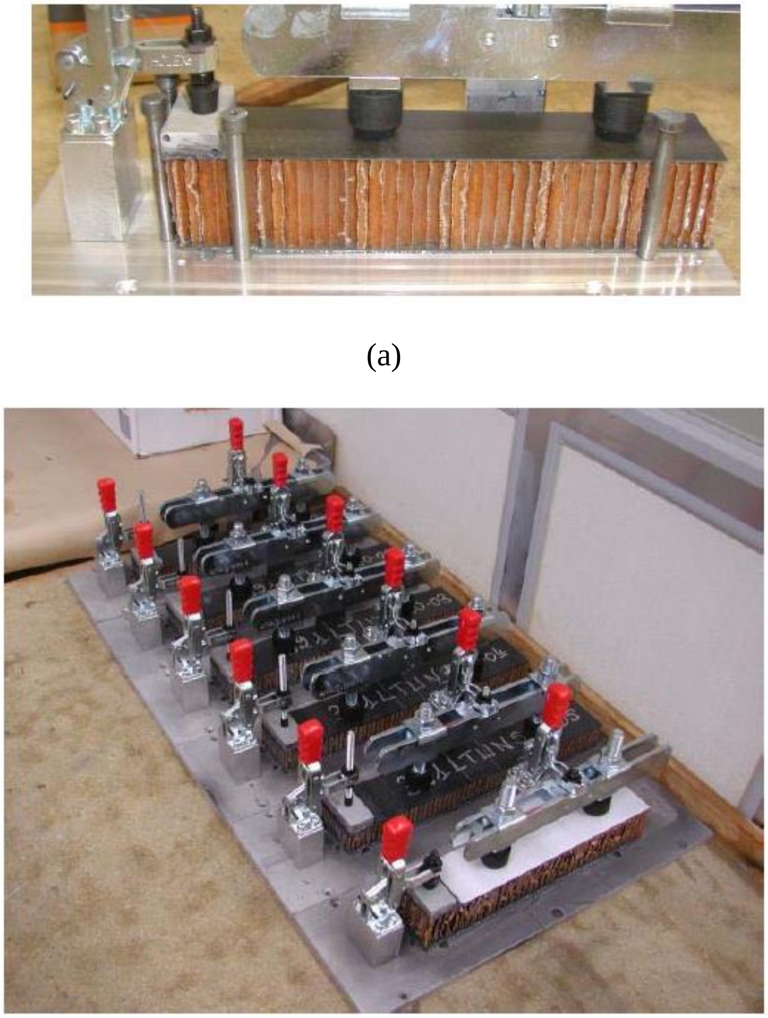


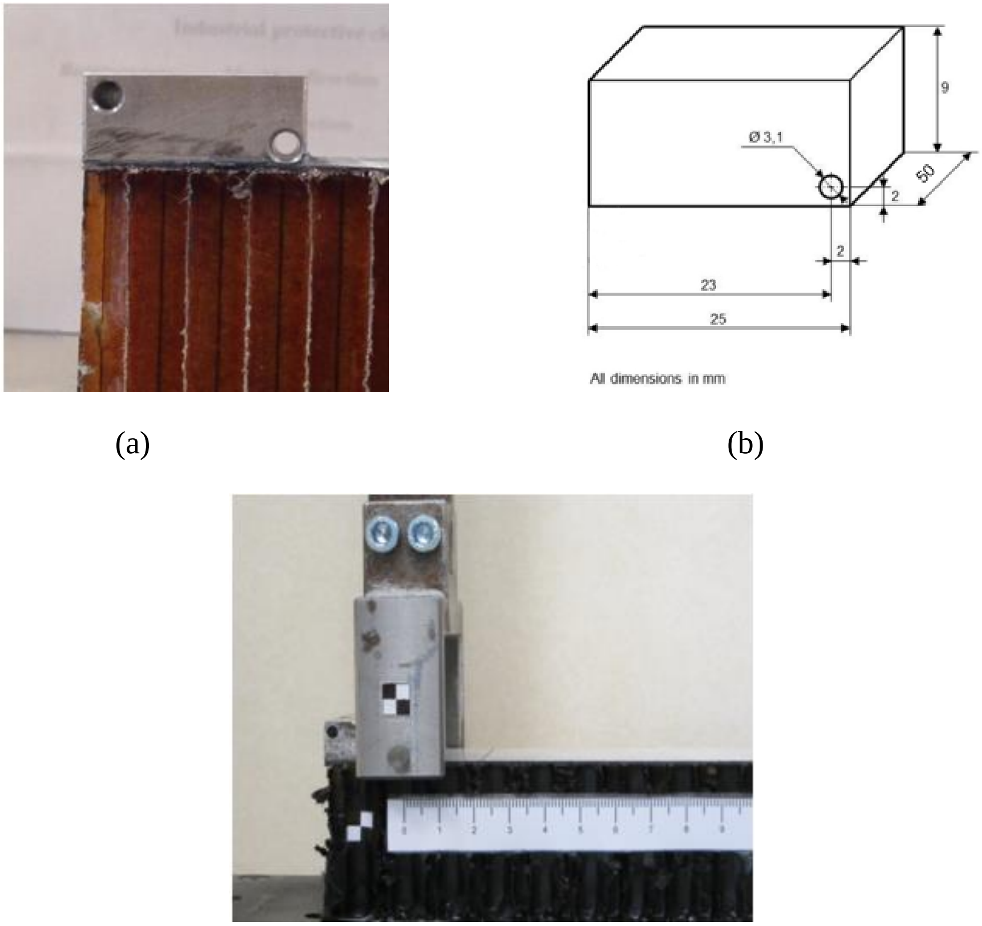
Figure 7. SCB test fixture at DuPont, Geneva.



(a)

(b)

Figure 8. (a) Specimen positioning (b) samples preparation.



(a) (b)

(c)

Figure 9. (a) Pulling plate bonded on specimen, (b) pulling plate and (c) side view of hinge clevis assembly and ruler for calibration.

2.2. SCB test set-up at Fraunhofer IMWS, Halle

The test fixture used for SCB testing at Fraunhofer, Halle, is shown in Figure 10. A piano hinge is bonded to the face sheet to be tested using a room temperature curing structural adhesive, see Figure 11. The lower (non-tested) face sheet of the specimen is clamped into the test fixture as shown in Figure 12. In order to avoid potential failure of hinge bonding additional fasteners can be applied if needed. This was done, for example, in the case of testing at elevated temperature (135°C). The pivot point of the piano hinge is located approximately 20 mm away from the end of the specimen. The pre-crack was generated manually using a thin saw blade. The exact position of the pivot point relative to the applied ruler is measured at both sides of the specimen before testing. The hinges are connected via a loading rod and load cell to the upper part of the test machine. The effective length of the movable loading rod is 520 mm, measured as the distance between the pivot point of the piano hinge and joint head at the upper end of the leverage. The specimen is clamped between the wedge-shaped clamping jaws onto the base plate as shown in Figure 12.

The crack opening displacement, δ, is measured continuously during the test (one data point per second at least). Crosshead displacement of the test machine is used. The load P, is measured continuously during the test (one data point per second at least) using the integrated load cell.

The crack lengths for propagation values will be observed during the test. Images on both the left and right specimen side will be recorded by two single lens reflex cameras with 3888 x 2592 pixels each. The visible region is adjusted to have a resolution of 16 pixel per 1 mm at least. Image recording is carried out based on time controlled triggering schemes. Mirrors are used in order to inspect both specimen sides simultaneously. The mean crack length a, is determined as the average of the visible crack length at both sides of the specimen for each recorded pair of images. The camera and mirror set-up is shown in Figure 13. Figure 14 shows the adaptions of the rig in a climatic chamber. A detailed description of the test machine is provided in [4].

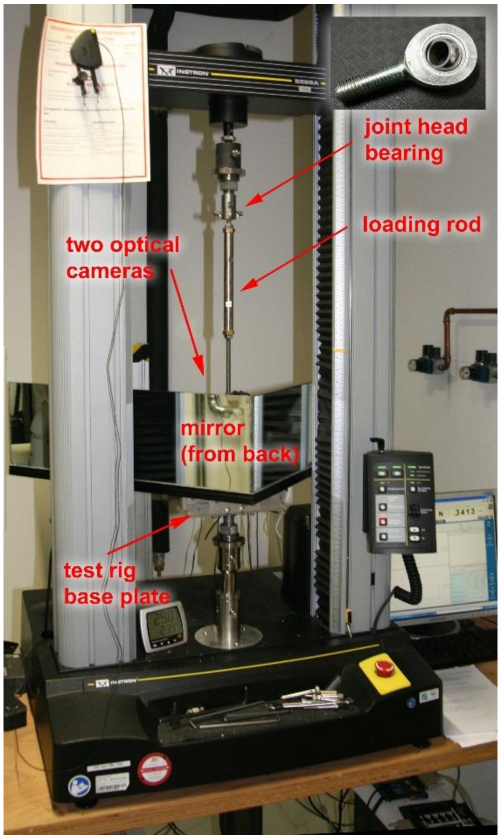


Figure 10. Test fixture at Fraunhofer IMWS, Halle.

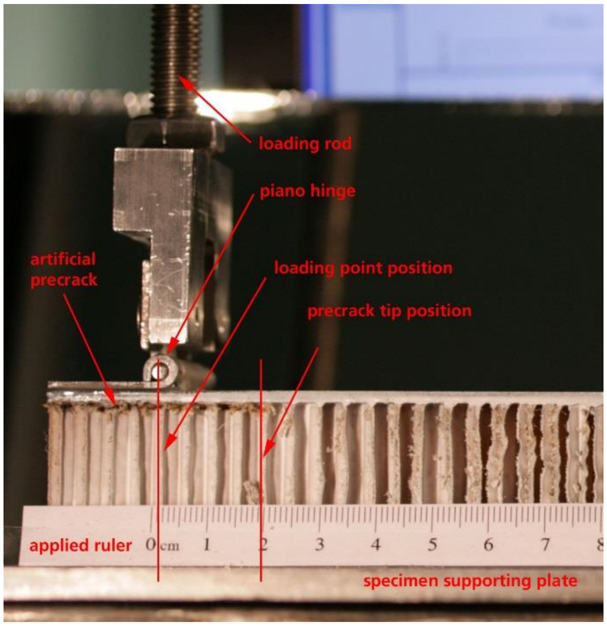


Figure 11. Example of a finally prepared specimen.

Figure 12. Clamping of the specimen to the test fixture

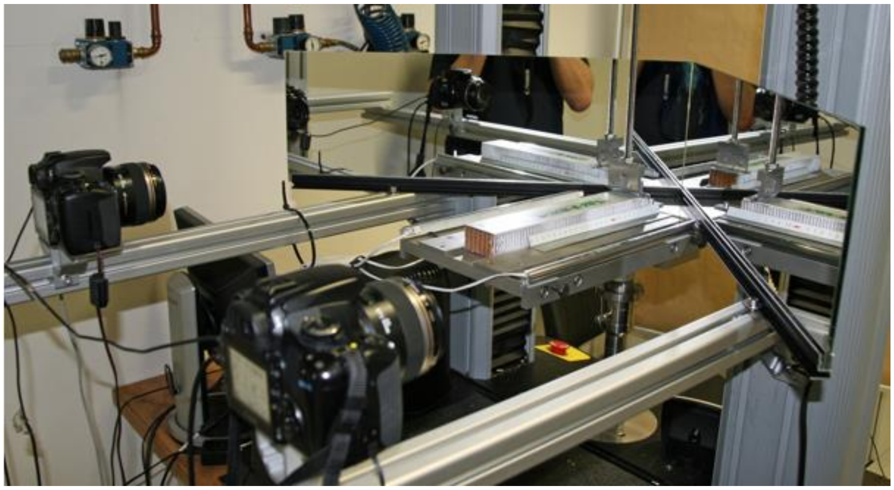


Figure 13. Camera and mirror set-up to record crack propagation.

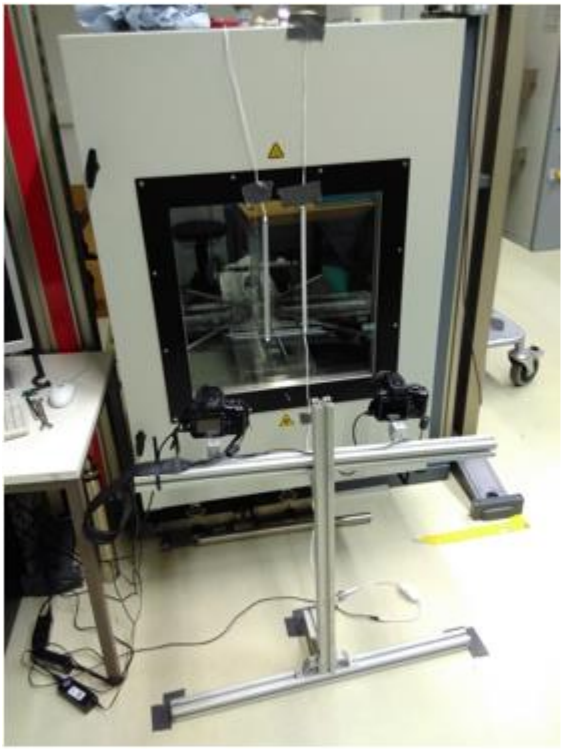


Figure 14. SCB test rig adapted to climate chamber.

2.3. SCB Test Set-up at Airbus Operations GmbH, Bremen, Germany

The principle of the test fixture is shown in Figure 15. The lower (non-tested) face sheet of the specimen is clamped into the test fixture as shown in Figure 16. The distance of the loading point of the block and the specimen surface is 2.5 mm. The blocks are connected via a loading rod and load cell to the upper part of the test machine. The effective length of the movable loading rod is 326 mm, measured as the distance between the pivot point of the load block and joint head at the upper end of the leverage. This test set up was used to conduct mode I fracture toughness testing under constant amplitude fatigue loading. Detailed description of the fixture and results are provided in [5]. Detailed description of test machine is provided in [5].

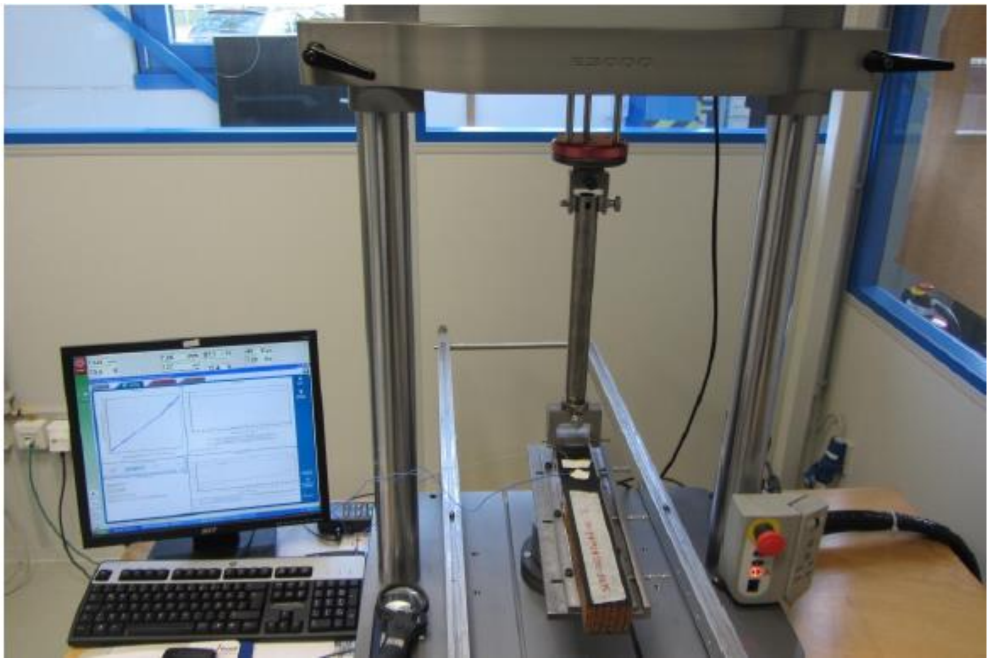


Figure 15.Test fixture at Airbus Operations GmbH, Bremen.

Figure 16. Specimen clamping.

2.4. DCB-UBM Test set-up description, DTU, Kgs. Lyngby, Denmark

The DCB-UBM test set up developed at DTU apply pure moments to the end of specimens with the help of independent torsional actuators, see Figure 17. The rig is built and assembled at the DTU Structural Lab, Kgs. Lyngby. The actuators are controlled independently using a controller which is tasked to control both arms simultaneously at a constant ratio of moment between each other. The specifications of the controller, load cell and angle transducer are provided in [6]. A Scotch-Weld^{TM} epoxy DP460 with a 60 minute work life is used to bond doubler layers onto the specimen [7]. Clamps are used for alignment and of the tabs and to apply a uniform pressure over the surface, see Figure 18.

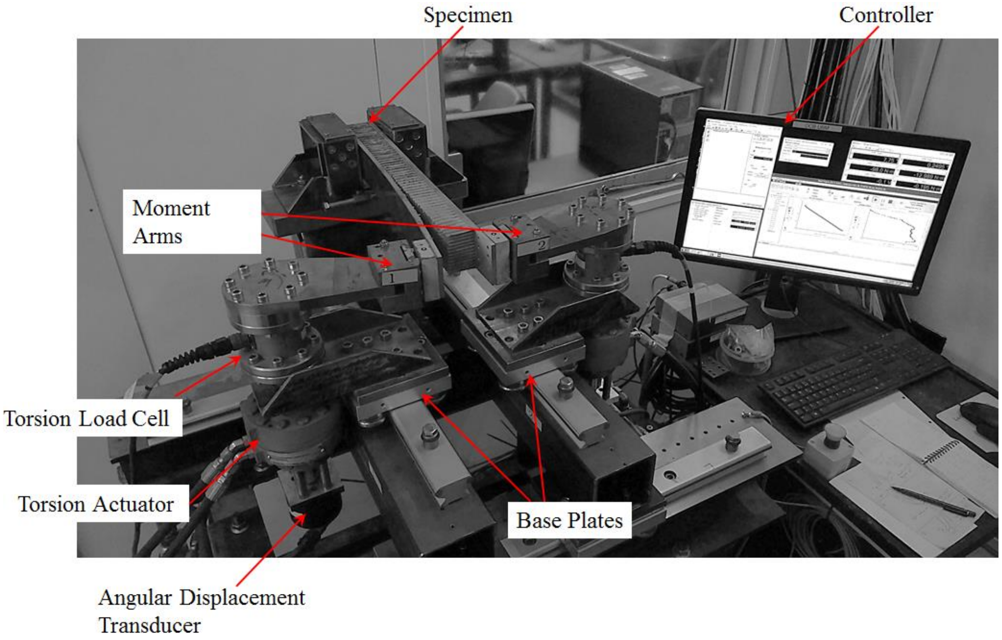


Figure 17. DCB-UBM Test set-up at DTU, Lyngby.

Figure 18. DCB-UBM specimen preparation.

3. SCB and DCB-UBM quasi-static fracture toughness data: A comparison

3.1. Test Matrix

Within the framework of the DoSS project SCB tests were performed on flat sandwich panels made of two different face sheet thicknesses and a variety of relevant honeycomb core densities and paper types. In addition to the previously conducted international SCB test round robin, test conditions were extended to an aircraft and helicopter relevant temperature range from -55°C (low temperature, LT) up to 20°C (room temperature, RT), +75°C/+80°C (high temperature, HT) and +135°C (very high temperature, VT) to investigate the specifics of the material behavior as well as the test rig performance and prospectively necessary upgrades. For a selected set of specimen mode-controlled DCB-UBM tests were performed in parallel for comparison.

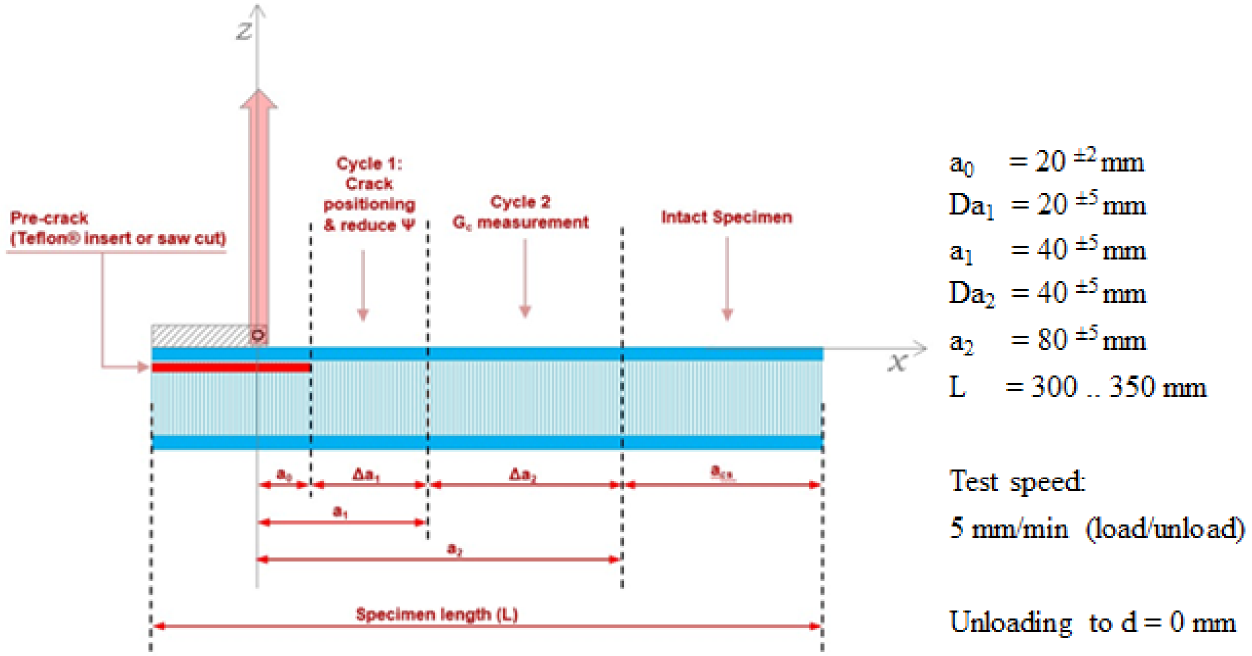
The sandwich panels were manufactured at CTC GmbH/Airbus, Stade, Germany, divided into sub-panels and provided to the labs participating the testing activities. Table 1 shows a condensed overview of the overall test matrix including the most significant test parameters. The test plan has been coordinated with other research activities of the project partners and gives a summary of experimental investigations started along with the DoSS project to substantiate and standardize SCB fracture toughness test. A number of test results acquired in the course of parallel projects were kindly contributed by the partners to broaden the basis for a sound analysis of SCB test characteristics. The plan partially lists also external tasks not yet completed.

Table 1. SCB/DCB-UBM test matrix.

Test Series	Lab	Test Type	Test ID	Panel/Sub-Panel ID	Number of Specimen	NOMEX Honeycomb Density [kg/m^3]	N636 Para-Aramid Honeycomb [kg/m^3]	Cell Size [mm]	Core Thickness [mm]	CFRP Facesheet Thickness [mm] (D if Doubler Applied)	Panel Side [Tool, Bag]	Crack Direction	Test Speed	SCB Loading Rod Length [mm]	Test Temperature Humid. (if controlled)
Baseline Study at RT 32 kg/m3 Core Density	IMWS	SCB	SCB-341-TW5R	1A-2-32-400-035	6	32		4.8	40	0.35	T	W	5 mm/min	520	RT
			SCB-341DTW5R	1A-2-32-400-035	6	32		4.8	40	0.35 (D)	T	W	5 mm/min	520	RT
			SCB-344-TW5R	2A-2-32-400-140	6	32		4.8	40	1.4	T	W	5 mm/min	520	RT
	DTU	DCB-UBM	DCB-UBM-341-WM1	1A-6-32-400-035	1	32		4.8	40	0.35	T	W	10 deg/min	-	RT
			DCB-UBM-344-WM1	2A-4-32-400-140	3	32		4.8	40	1.4	T	W	10 deg/min	-	RT
			DCB-UBM-314-WM2	5-3-32-100-140	3	32		4.8	10	1.4	T	W	10 deg/min	-	RT
	DuPont	SCB	1A-7-32-400-035-W	1A-7-32-400-035	4	32		4.8	40	0.35	B	W	5 mm/min	500	RT 60%RH
			3A-4-32-400-140-W	3A-4-32-400-140	4	32		4.8	40	1.4	B	W	5 mm/min	500	
Study at Low Temperature LT (-55°C)	IMWS	SCB	SCB-341-TW5L	1A-2-32-400-035	6	32		4.8	40	0.35	T	W	5 mm/min	520	-55°C
			SCB-344-TW5L	2A-2-32-400-140	6	32		4.8	40	1.4	T	W	5 mm/min	520	-55°C
			SCB-N44-TW5L	2B-10-32-400-140	6		32	4.8	40	1.4	T	W	5 mm/min	520	-55°C
	DTU	DCB-UBM	DCB-UBM-344LT-WM1	2A-4-32-400-140	2	32		4.8	40	1.4	T	W	10 deg/min	-	-55°C
			DCB-UBM-644LT-WM1	4-3-64-400-140	2	64		4.8	40	1.4	T	W	10 deg/min	-	-55°C
			DCB-UBM-944LT-WM1	3A-1-96-400-140	2	96		4.8	40	1.4	T	W	10 deg/min	-	-55°C
			DCB-UBM-344LT-LM1	2A-4-32-400-140	2	32		4.8	40	1,4	T	L	10 deg/min	-	-55°C
			DCB-UBM-644LT-LM1	4-3-64-400-140	2	64		4.8	40	1,4	T	L	10 deg/min	-	-55°C
			DCB-UBM-944LT-LM1	3A-1-96-400-140	2	96		4.8	40	1,4	T	L	10 deg/min	-	-55°C
Study at High Temp. HT (80°C)	IMWS	SCB	SCB-344-TW5H	2A-2(3)-32-400-140	6	32		4.8	40	1.4	T	W	5 mm/min	520	80°C
			SCB-N44-TW5H	2B-10-32-400-140	6		32	4.8	40	1,4	T	W	5 mm/min	520	80°C
Study on Core Type at RT	IMWS	SCB	SCB-644-TW5R	4-1-64-400-140	6	64		4.8	40	1,4	T	W	5 mm/min	520	RT
			SCB-944-TW5R	4-6-96-400-140	6	96		4.8	40	1,4	T	W	5 mm/min	520	RT
			SCB-N44-TW5R	2B-10-32-400-140	6		32	4.8	40	1,4	T	W	5 mm/min	520	RT
	DTU	DCB-UBM	DCB-UBM-N44-WM1	2B-4-32-400-140	2		32	4.8	40	1,4	T	W	10 deg/min	-	RT
			DCB-UBM-N44-LM1	2B-4-32-400-140	2		32	4.8	40	1,4	T	L	10 deg/min	-	RT
			DCB-UBM-644-WM1	4-3-64-400-140	2	64		4.8	40	1,4	T	W	10 deg/min	-	RT
			DCB-UBM-644-LM1	4-3-64-400-140	2	64		4.8	40	1,4	T	L	10 deg/min	-	RT
			DCB-UBM-944-WM1	3A-1-96-400-140	2	96		4.8	40	1,4	T	W	10 deg/min	-	RT
			DCB-UBM-944-LM1	3A-1-96-400-140	2	96		4.8	40	1,4	T	L	10 deg/min	-	RT
	DuPont	SCB	2B-1-32-400-140-W	2B-1-32-400-140	4		32	4.8	40	1.4	B	W	5 mm/min	500	RT 60%RH
			4-5-64-400-140-W	4-5-64-400-140	4	64		4.8	40	1.4	B	W	5 mm/min	500	
			4-7-96-400-140-W	4-7-96-400-140	4	96		4.8	40	1.4	B	W	5 mm/min	500	
Additional Study on Crack Direction	DTU	DCB-UBM	DCB-UBM-341-LM1	1A-6-32-400-035	2	32		4.8	40	0.35	T	L	10 deg/min	-	RT
			DCB-UBM-344-LM1	2A-4-32-400-140	3	32		4.8	40	1,4	T	L	10 deg/min	-	RT
			DCB-UBM-314-LM2	5-3-32-100-140	3	32		4.8	10	1,4	T	L	10 deg/min	-	RT
	DuPont	SCB	2B-1-32-400-140-L	2B-1-32-400-140	3		32	4.8	40	1.4	B	L	5 mm/min	500	RT 60%RH
			3A-4-32-400-140-L	3A-4-32-400-140	3	32		4.8	40	1.4	B	L	5 mm/min	500	
Study on SCB Rod Length	IMWS	SCB	SCB-341-TW2R-06	1A-1-32-400-035	6	32		4.8	40	0.35	T	W	5 mm/min	260	RT
			SCB-341-TW1R-01	1A-1-32-400-035	6	32		4.8	40	0.35	T	W	5 mm/min	130	RT
Fatigue Pilot Trial	Airbus	SCB-F	SCBF-344*TW*R	2A-3-32-400-140	3	32		4.8	40	1,4	T	W	...	...	RT
	DTU	DCB-UBM	DCB-UBM-344-WM1F	2A-4-32-400-140	2	32		4.8	40	1,4	T	W	10 deg/min	-	RT
			DCB-UBM-344-LM1F	2A-4-32-400-140	2	32		4.8	40	1,4	T	L	10 deg/min	-	RT
Helicopter Panel at Elevated Temp.	IMWS	SCB	SCB-413-TL5R	AH-17-06-07	4	48		3.2	12	0.95	T	L	5 mm/min	520	RT
			SCB-413-TL5H	AH-17-06-07	4	48		3.2	12	0.95	T	L	5 mm/min	520	75°C
			SCB-413-TL5V	AH-17-06-07	4	48		3.2	12	0.95	T	L	5 mm/min	520	135°C
Study on Humidity	DuPont	SCB	3A-4-32-400-140-W	3A-4-32-400-140	1	32		4.8	40	1.4	B	W	5 mm/min	500	RT 0%RH
			3A-4-32-400-140-W	3A-4-32-400-140	1	32		4.8	40	1.4	B	W	5 mm/min	500	
Study on Test Speed	DuPont	SCB	1A-7-32-400-035-W	1A-7-32-400-035	3	32		4.8	40	0.35	B	W	20 mm/min	500	RT 60%RH
			3A-4-32-400-140-W	3A-4-32-400-140	3	32		4.8	40	1.4	B	W	20 mm/min	500	
			4-7-96-400-140-W	4-7-96-400-140	3	96		4.8	40	1.4	B	W	20 mm/min	500	

3.2. SCB Test Procedure

As a result of the CMH-17 SCB round robin test conducted 2015/2016, improved test conditions were formulated for the test series by the DoSS participants. Figure 19 depicts the essential parameters defined, which also fed in the latest ASTM Standard Draft 2017 [8]. The test procedure was reduced here to only two load cycles. The initial loading/unloading cycle (cycle 1) transforms the artificial disbond to a natural crack, which is characteristic for the individual specimen/material with respect to shape, crack surface and crack location. Starting from this natural disbond the primary test cycle (cycle 2) is performed to produce a crack extension of $\Delta a = 40$ mm. Data reduction then is conducted based on load/displacement recordings of cycle 2 and the measured crack lengths a_1 and a_2. The dimensions a_i and Δa_i were chosen to guarantee best possible mode stability and consistent conditions within the primary test cycle for a wide range of honeycomb sandwich configurations used in aviation. The specifications are based on the preceding SCB test series experience as well as detailed numerical parametric studies, see Chapter 6 and technical reports [4], [9]. In addition to the standard two-cycle test procedure IMWS and DuPont labs performed extra loading/unloading cycles for a number of specimen for the purpose of improving the understanding of mechanisms and influence of various test conditions. Furthermore, specific test parameters were modified in some cases for comparison.



$a_0 = 20^{\pm 2}$ mm

$Da_1 = 20^{\pm 5}$ mm

$a_1 = 40^{\pm 5}$ mm

$Da_2 = 40^{\pm 5}$ mm

$a_2 = 80^{\pm 5}$ mm

L = 300 .. 350 mm

Test speed:

5 mm/min (load/unload)

Unloading to d = 0 mm

Figure 19. SCB test specification.

A representative load-displacement curve is given in Figure 21. Figure 20 shows side views of the loaded specimen during test execution at three different stages: 1) unloaded, 2) maximum face sheet deflection at the end of cycle 1 and 3) maximum stroke and final crack length of cycle 2. The specimen was tested at 85°C in the climate chamber.

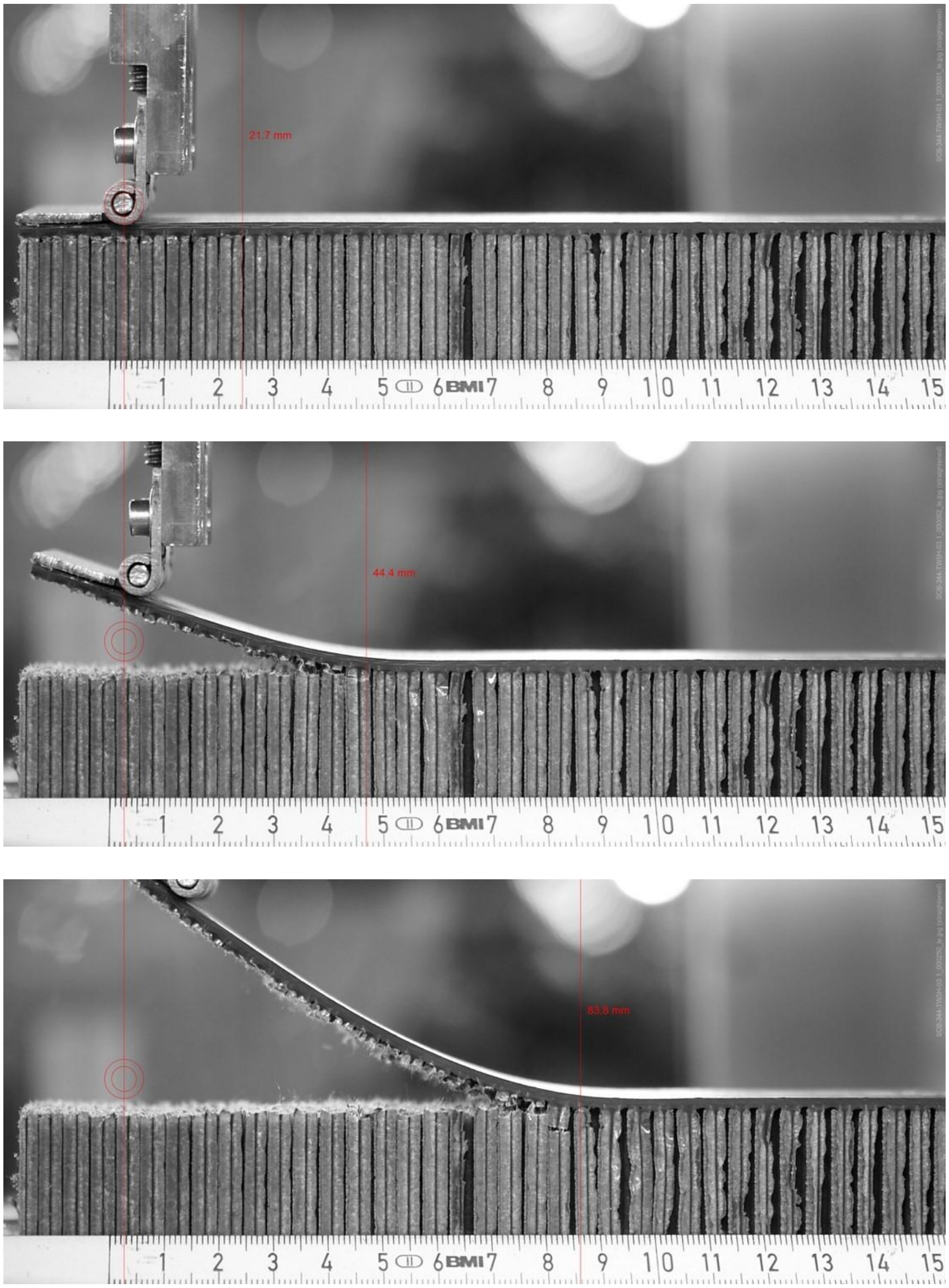


Figure 20. SCB specimen under load.

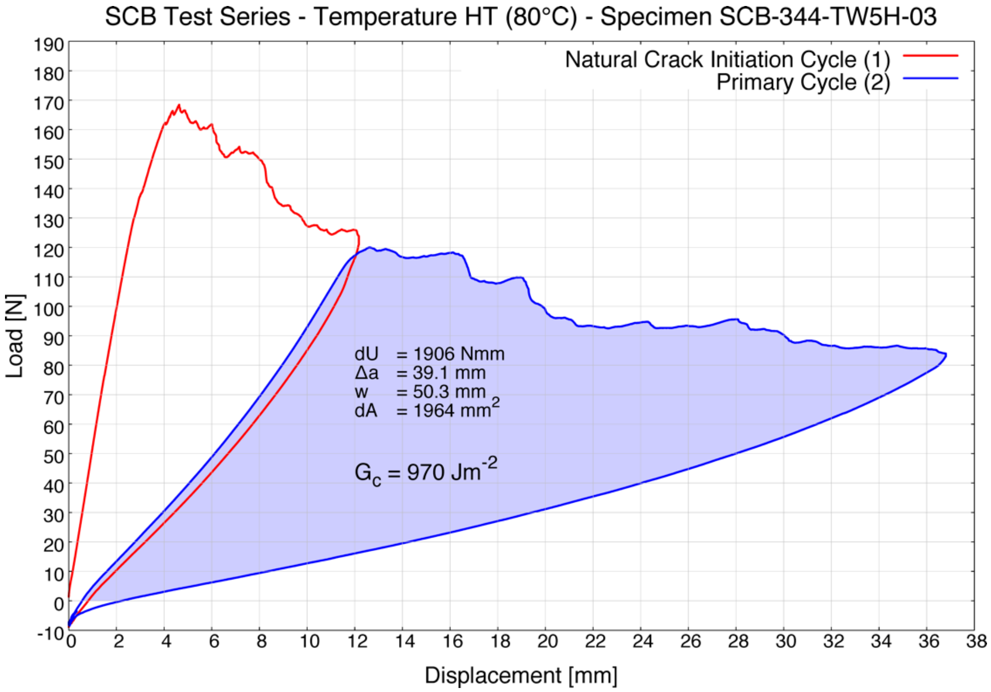


Figure 21. SCB test load-displacement curve of a 1.4 mm thick face sheet sandwich specimen.

3.3. Comparison of Results and Summary

More than 100 SCB and DCB-UBM specimens taken from the dedicated sandwich panels were tested and evaluated up to now. The tests were carried out not primarily to give fully statistical underpinned fracture toughness data for a specific material but to study characteristic trends and identify relevant aspects of the test method for the envisioned material class. However, to get a minimum statistical coverage 4 to 6 specimen per single test item of the test matrix were planned and conducted as far as possible for the SCB series. Nevertheless, for some series less results are available at this time but also included in the comparison to give a more complete picture. Table 2 provides a summary of the measured GIC according to the test matrix. In the following effects of specific material and test parameters are shown by selected examples. To analyze the data in detail comparison of a number of subsets were carried out, see [4].

Table 2. Summary of measured fracture toughness G_{Ic}.

Test Series	Test Type	Test ID	G_{IC}	No. Specimen Tested	NOMEX Honeycomb Density [kg/m^3]	N636 Para-Aramid Honeycomb [kg/m^3]	CFRP Facesheet Thickness [mm] (D if Doubler Applied)	Panel Side [Tool, Bag]	Crack Direction	Test Temperature Humid. (if controlled)
Baseline Study at RT 32 kg/m3 Core Density	SCB	SCB-341-TW5R	**1326**	1	32		0.35	T	W	RT
		SCB-341DTW5R	**1193**	2	32		0.35 (D)	T	W	RT
		SCB-344-TW5R	**1097**	6	32		1.4	T	W	RT
	DCB-UBM	DCB-UBM-344-WM1	**1095**	1	32		1.4	T	W	RT
	SCB	1A-7-32-400-035-W	**1368**	4	32		0.35	B	W	RT 60%RH
		3A-4-32-400-140-W	**795**	4	32		1.4	B	W	
Study at Low Temperature LT (-55°C)	SCB	SCB-341-TW5L	**1724**	1	32		0.35	T	W	-55°C
		SCB-344-TW5L	**995**	6	32		1.4	T	W	-55°C
		SCB-N44-TW5L	**586**	6		32	1.4	T	W	-55°C
Study at High Temp. HT (80°C)	SCB	SCB-344-TW5H	**887**	6	32		1.4	T	W	80°C
		SCB-N44-TW5H	**473**	6		32	1,4	T	W	80°C
Study on Core Type at RT	SCB	SCB-644-TW5R	**1308**	6	64		1,4	T	W	RT
		SCB-944-TW5R	**2432**	6	96		1,4	T	W	RT
		SCB-N44-TW5R	**486**	6		32	1,4	T	W	RT
	DCB-UBM	DCB-UBM-644-WM1	**1209**	1	64		1,4	T	W	RT
		DCB-UBM-944-WM1	**1511**	1	96		1,4	T	W	RT
		DCB-UBM-944-LM1	**1389**	1	96		1,4	T	L	RT
	SCB	4-5-64-400-140-W	**1253**	4	64		1.4	B	W	RT 60%RH
		4-7-96-400-140-W	**1824**	4	96		1.4	B	W	
Additional Study on Crack Direction	DCB-UBM	DCB-UBM-344-LM1	**872**	1	32		1,4	T	L	RT
	SCB	2B-1-32-400-140-L	**505**	3		32	1.4	B	L	RT 60%RH
		3A-4-32-400-140-L	**833**	4	32		1.4	B	L	
Helicopter Panel at Elevated Temp.	SCB	SCB-413-TL5R	**1261**	3	48		0.95	T	L	RT
		SCB-413-TL5H	**1125**	3	48		0.95	T	L	75°C
		SCB-413-TL5V	**976**	3	48		0.95	T	L	135°C

3.3.1. Effect of Temperature

Figure 22 displays three different sandwich material types tested at three temperatures each. The test series identifiers are plotted along the *x*-axis, whereby the bracketed numbers refer to the amount of tested and evaluated specimen. Green color indicates room temperature, blue color marks low temperature and orange/red highlights tests at 75, 80 and 135°C respectively.

The baseline material on the left is 32 kg/m^3 NOMEX$^®$ core (T412, C1), 4.8 mm cell width and 4-layer face sheet of 1.4 mm thickness. Results are available for -55°C, RT and 80°C. At the same temperature levels a KEVLAR$^®$ core type (Schütz CN1) was tested for comparison. The CN1 material offers considerable higher modulus at the same density but behaves more brittle in terms of fracture mechanics. The third set of specimen was taken from the Airbus helicopter panel, which is different in core height, cell width and facings. For all three materials the same characteristics of fracture path could be observed at all temperatures. The disbond propagates immediately below the meniscus layer.

The fracture toughness is affected mainly by the properties of the cell wall paper and thus G_{IC} could be considered as a material property in these cases. As known from previous studies a change in fracture mode could also occur. For a material with comparatively lower core to face sheet adhesion, for example, it was observed, that the disbond path could switch into the bond line at low temperature which would cause a significant drop of G_{IC}. In that case the interpretation of G_{IC} as a pure material property is no longer meaningful and it should be considered as a kind of 'material system' property.

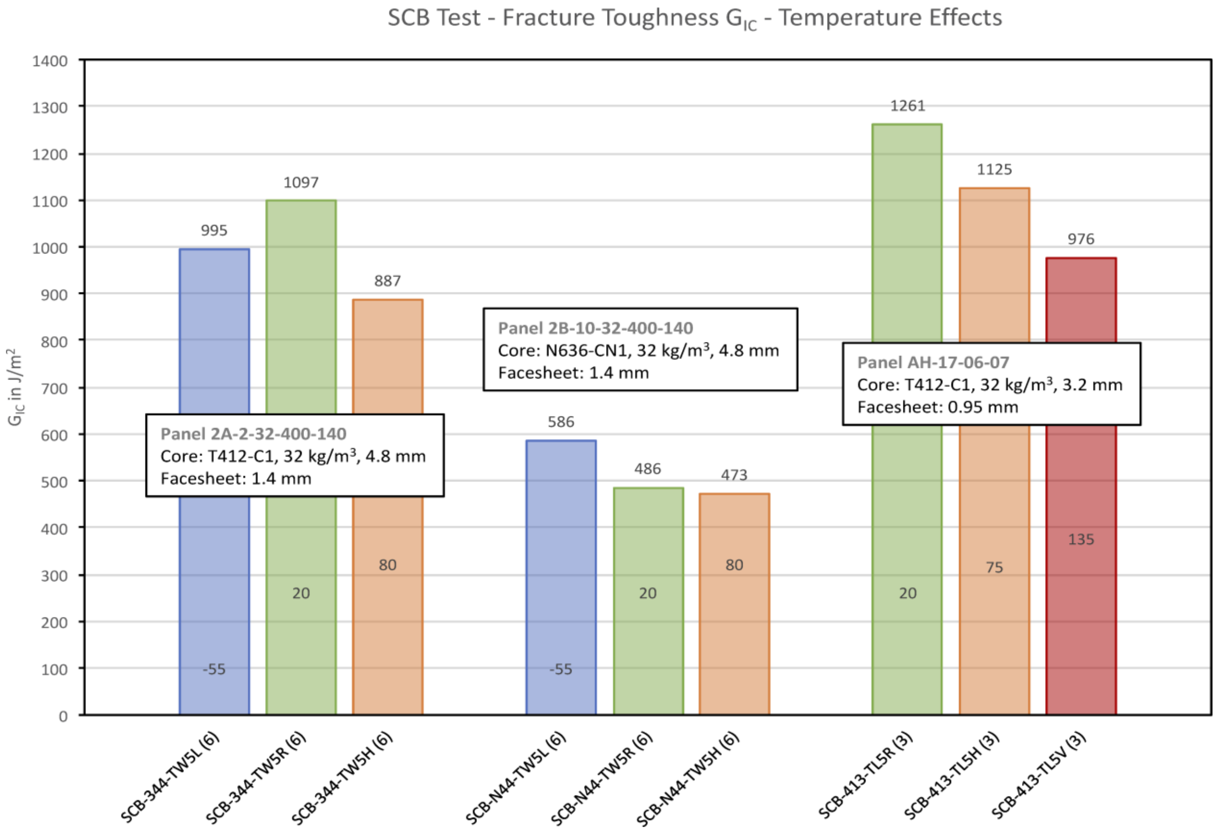


Figure 22. Summary of G_{IC} test results (SCB).

3.3.2. Effect of Core Density

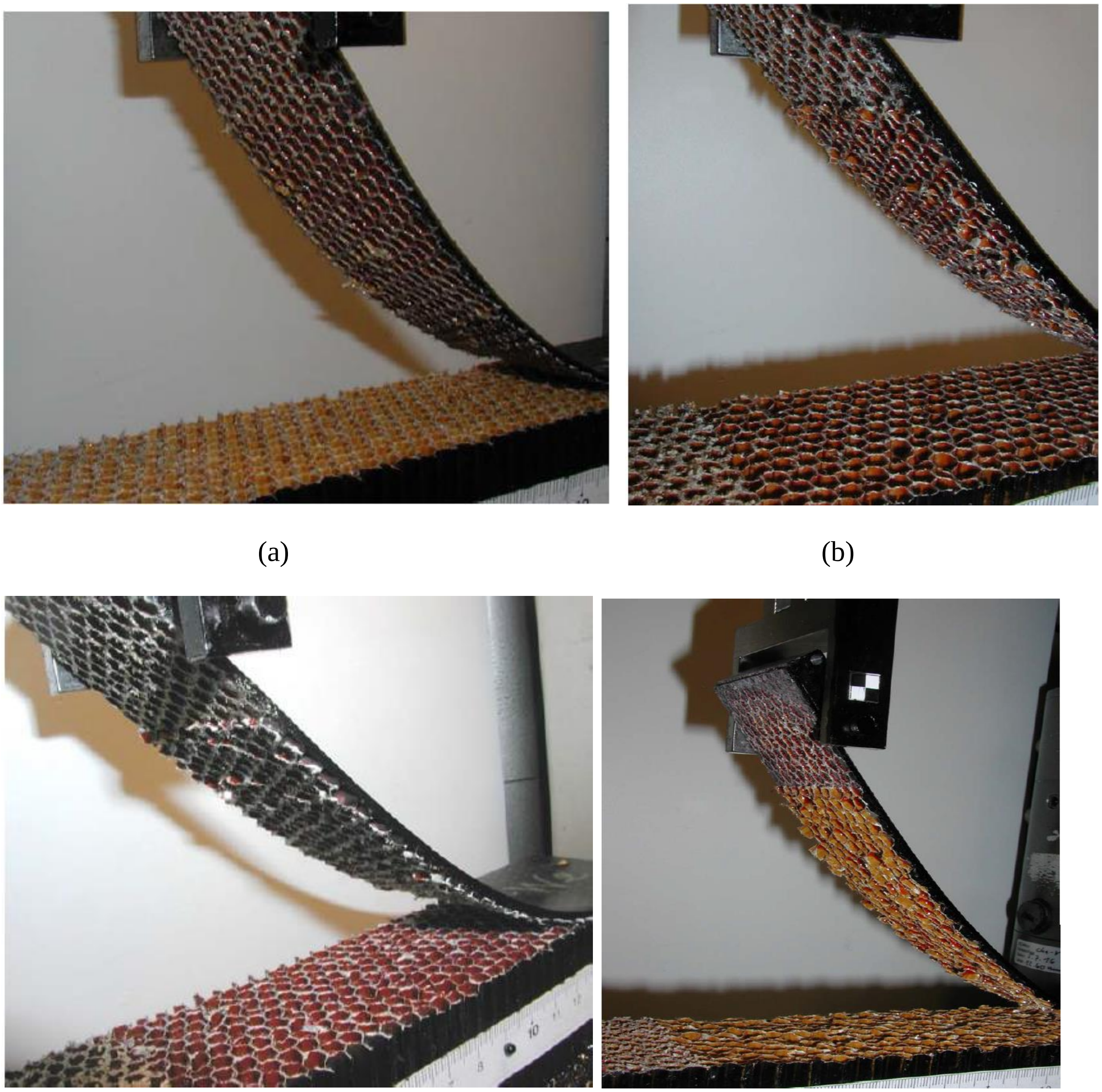
Figure 23 demonstrates the influence of the core density of the disbond process and the resulting peel mode fracture toughness. Three densities, namely 32, 64 and 96 kg/m^3, were compared. In Figure 23 the green color indicates RT, while green column borders specify SCB tests conducted at IMWS test rig, black lines are used for DuPont lab with controlled relative humidity of 60% and red highlights DCB-UBM results provided by DTU.

As expected, the basic tendency is an increasing G_{IC} for higher core density. Within a group of the same material the measured values can fluctuate due to a variation of other material parameters and the test method. It can be seen, that the fracture toughness is slightly lower when the disbond propagates in L direction compared to W direction of the core. Pictures of fracture modes for various core density classes and crack propagation direction are provided in Figure 23.

Furthermore, it appears that the humidity of the material significantly affects the peel mode fracture toughness. All specimen tested at DuPont lab were preconditioned exactly at 60% relative humidity, whereas IMWS and DTU stored the material and tested in a ‘natural’ lab environment which spanned from 20% to 50% RH at room temperature and was close to zero at high temperatures up to 135°C in the climate chamber. As a result of the overall test analysis, the 60% RH preconditioned specimen exhibit an approximately 5 to 20 per cent lower G_{IC} in average. This applies if the basic fracture mode is the same for humid as well as for the dry specimen. Furthermore, the fracture mode itself can be affected by the humidity of the material.

Basic fracture modes observed for the sandwich material under examination can be roughly classified in four modes:

1) Disbond propagation within the core, immediately below the meniscus layer (sub-interface)
2) Disbond turns/kinks towards core material or rather opposite to the face sheet
3) Disbond runs into and propagates in adhesive layer
4) Disbond recurrently switches between adhesion layer and core, accompanied with considerable crack tip ramification



(a) (b)

(c) (d)

Figure 23. Pictures of fracture modes for specimens with h_f = 1.4 mm and h_c = 40 mm, (a) 32 kg/m^3 core (W-direction) (b) 64 kg/m^3 core (W-direction) (c) 96 kg/m^3 core (W-direction) and (d) 32 kg/m^3 core (L-direction).

In principle, the quantitative relation between the strengths and/or the fracture toughnesses of the sandwich components near the interface (adhesion layer, meniscus layer, core) as well as the mode mixity controls the disbond process and the resulting fracture mode. The cracks tends to run along the weakest component of the sandwich assembly.

In some cases disbonding is simultaneously accompanied with additional micro damage of the face sheet, which causes a significant amount of additional energy dissipation related to the disbond process. This was observed for the 96 kg/m^3 core density specimen, see Figure 26. As can be seen in Figure 24 the fracture toughness G_{IC} of these specimens' spans in the range from 1511 up to 2432 J/m^2 (W-orientation), which correspond to a deviation of more than +/- 20%. Although a systematic study of this behavior is not yet completed, the result could be summarized and interpreted as follows:

a) SCB specimen with 'natural' humidity exhibits the highest fracture toughness value.
   - The observed fracture mode is 4), potentially accompanied with micro damage of the face sheet. This causes large amount of energy dissipation to drive the disbond forward. The micro damage may be induced by the small bending radius of the CFRP layer in the vicinity of the disbond front which is caused by the high peel loads necessary to expand the disbond.

b) SCB specimen conditioned at 60% RH shows intermediate G_{IC}.
   - The increased humidity potentially degrades the stiffness and strength of the core paper, which keeps the disbond propagating in a plane below the meniscus, mode 1), as well as reduces the fracture toughness compared to dry core. As observed in a) the face sheet may subjected to sharp bending and energy consuming irreversible CFRP layer degradation.

c) DCB-UBM test method results in lowest fracture toughness within the 96 kg/m^3 core series under examination.
   - In the case of DCB-UBM the face sheets are bonded to 6 mm thick steel doublers which dramatically increase the bending stiffness of the face sheet cantilever beam. This prevents small bending radius of the face sheet and thus micro damage of the face sheet itself. Furthermore, mode mixity is controlled to keep as close as possible to mode-I ($\psi \approx 0°$). Compared to that, the SCB specimens seem to turn to higher phase angle, ψ, or increased mode-II component.

As can be concluded from the above results, the choice of the test method can substantially affect the resulting fracture toughness as it potentially influences the fracture mode of the specimen itself. DCB-UBM method, due to stiff face sheet doublers, inherently avoids critical bending deformation and thus inhibit face sheet micro damage. The disbond can be forced, by means of explicit mode mix control, to propagate within the core, even in cases where the SCB tends to change the basic disbond mode. Thus, DCB-UBM potentially can produce a fracture toughness G_C interpretable as a core material parameter. On the other hand, SCB method (in particular without doublers) simulates 'natural' peel mode of the sandwich. The measured fracture toughness G_{IC} here seems to be a 'material system' for the DCB-UBM fracture testing whereas for the SCB specimen, the measured values are more of a 'structural' property. It should be noted that, a slight discrepancy in comparison is present only for the case of 96 kg/m^3 dense core. This may also be attributed to the core material itself and the corresponding failure mode. Unlike the other core cases tested here (32 and 64 kg/m^3), the denser core exhibited a more brittle fracture at the interface for a wide range of mode-mixity conditions [6].

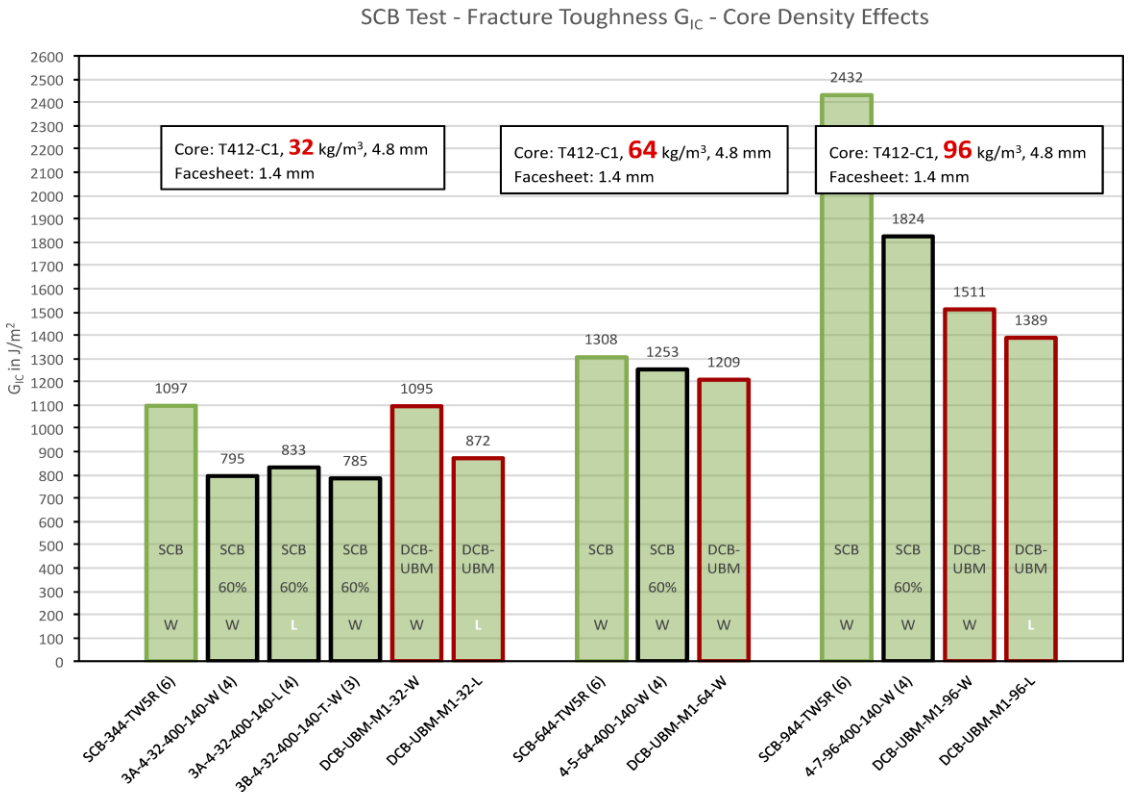


Figure 24. G_{IC} test results: Effect of core density.

3.3.3. Effect of Face Sheet Thickness

The effect of 'natural' or unconstrained deformation of the sandwich subjected to peel loads, compared to a guided deformation with smaller deflection and rotation of the face sheet cantilever beam, was studied by means of core type T412-C1, 32 kg/m^3, 4.8 mm cell diameter, sandwich specimen. Figure 25 summarizes the measured G_{IC} for sandwich with two different face sheet thicknesses. For the 1-layer thin face sheet specimen huge rotation of the face sheet was observed. The sharp local bending near the crack front seems to cause a fracture mode modification accompanied with a micro damage of the CFRP layer, when following the argumentation in 3.3.2. This apparently results in higher G_{IC} (see left two columns). As expected, the specimen with 1-layer face sheet, reinforced with a 1.05 mm GFRP doubler, tends to reproduce the lower G_{IC} values measured for the same material system but with 4-layer face sheet. Additional validation would be possible on the basis of a 1-layer specimen DCB-UBM test. In that case the measured G_{IC} should immediately compare with the 4-layer system, since the global as well as the local deformation is forced to be identical due to steel doublers. Such validation tests are currently not available but may be subject of future investigation.

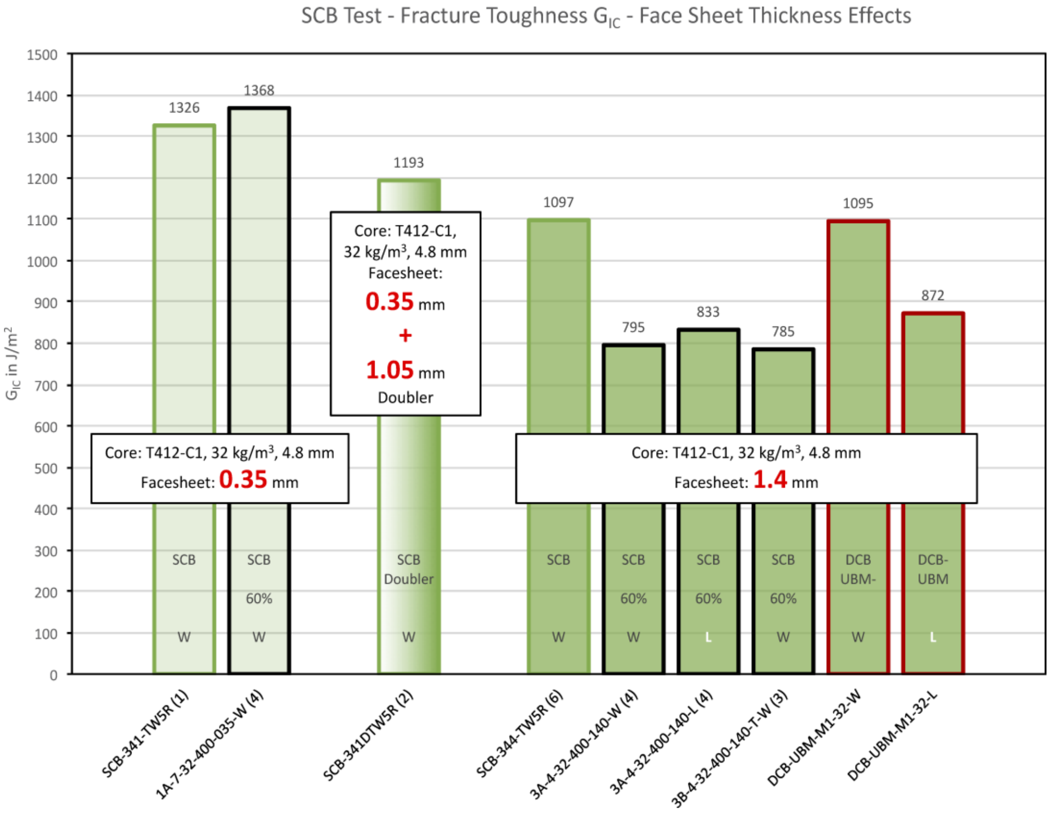


Figure 25. GIC test results: Effect of face sheet thickness.

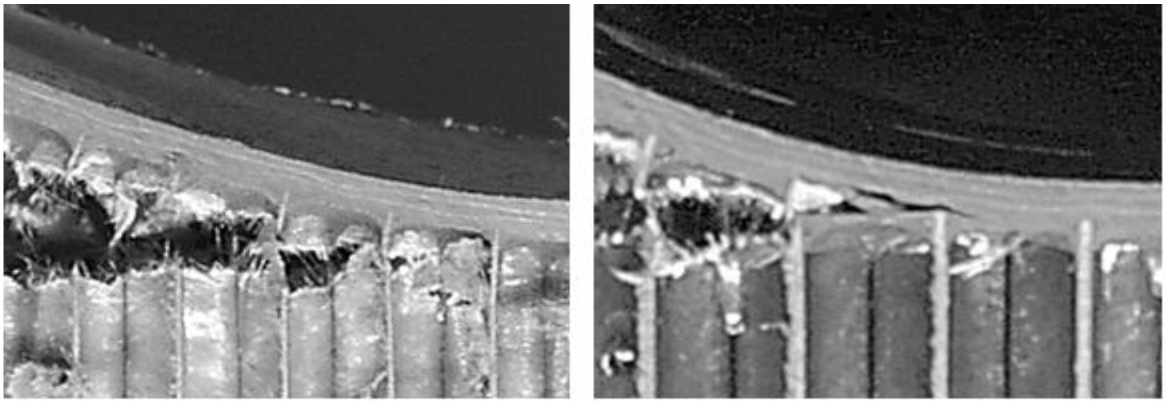


Figure 26. Disbond fracture characteristics. (Left): Disbond below meniscus layer. (Right): Disbond branches into adhesion layer.

3.3.4. SCB Fatigue Test

A fatigue test procedure based on SCB method was developed by Airbus. To keep the test rig as well as the process control simple and robust, the G was not required to keep strictly constant during crack propagation. For small crack extension Δa of about 10 mm the variation in G was seen to be negligible. The process is described in more detail in [3].

A set of pilot tests were carried out at room temperature on the baseline sandwich material with 32 kg/m^3 NOMEX® core, 4.8 mm cell width, 4-layer face sheet. A variation of wave form, load control and frequency was applied. Figure 27 shows a representative Δa/ΔN versus G curve. As can be seen from the graph, not negligible crack propagation was observed even for very small loads, what can be seen as one of the most important outcome of this initial study. The test was started at a load level of $G/G_{IC,\ static} = 0.7$ and stopped at 29 J/m^2.

Disbond propagation under fatigue loads need to be addressed in future programs. The labs have established and validated different methods of data recording, crack length measurement as well as specimen preparation, specimen clamping or bonding and load introduction variants (see Chapter 2 and [4]). Based on the results of DoSS SCB series a range of valid test options could be formulated which enable labs to fulfill the requirements of the prospective ASTM test standard and take into account at the same time specific industry needs. For a detailed description of materials, test conditions, test performance, data reduction and results see technical reports [4], [6].

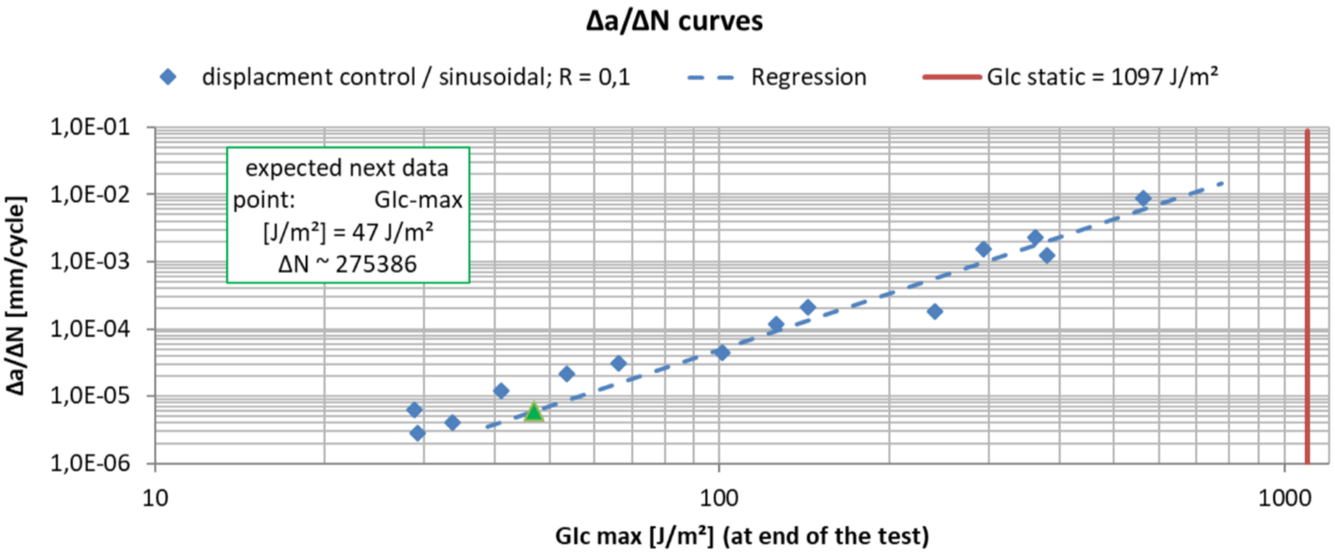


Figure 27. SCB fatigue test results.

4. Industrial application of the SCB Test

The SCB "peel" test is currently considered by aerospace industry value chain for many applications including non-structural sandwich structures and interior applications. Till date, the SCB test protocol has from experience, demonstrated good repeatability and reproducibility. In addition to Fracture Toughness G_{1c} data, other output including maximum load, fracture mode, load as a function of load position curve, and provide valuable information for composite structure design but also processing, quality control and inspection of constituents.

5. Standardization of the DCB-UBM test method for future industrial use

The DCB-UBM test method is currently not a standardized test methods. Nonetheless the DCB-UBM test method currently represents the most effective test method to achieve a wide range of mixed mode fracture toughness measurements for sandwich face/core interfaces, as well as general interface toughness properties for laminates as well as general cohesive interfaces. A number of DCB-UBM test rigs of varying design and capabilities exist across currently mainly Europe, within both industry and university laboratories (LM Wind Power, DTU – 2 labs, Aalborg University, EPFL, etc.).

Recently an initiative to initiate a process to define a uniform test procedure guideline for the DCB-UBM has been identified by the ESIS Technical Committee 4 (TC4). The activity is planned to include both round robin testing as well as definition of recommendations for rig design, test procedures, etc.

and all documented in an ESIS TC4 test guideline. The guideline can later be used as a basis for a definition of an ISO standard for the DCB-UBM test method. The work on the ESIS TC4 test guideline is planned initiate in 2018 based on a working group consisting of a range of interested partners.

6. Fracture Mechanics Approach for the analysis of Honeycomb Sandwiches

The disbond at the face/core interface is treated under the ambit of Linear Elastic Fracture Mechanics (LEFM) and is bolstered on the bi-material fracture mechanics [10]–[16]. Essentially, the crack growth can happen in three possible ways: 1) crack may propagate along or close to the face/core interface, 2) propagate by kinking into the face sheet or 3) dive into the core and propagate through core. In order to assess the structural integrity of sandwich composite, face sheet/core disbond strength must be determined. The fracture resistance or critical strain energy release rate (referred to as fracture toughness) should be taken into consideration during the design phase. Typically the quality of face sheet/core disbond strength is estimated using a climbing drum peel test (CDP) [17]. However, the CDP method only yields a qualitative assessment of the interface. Various test methods exist in the literature which are capable of measuring interface fracture toughness [18]–[28]. Most of the test methods measure the load required to propagate an incremental crack length, *da*, and utilizes a suitable data reduction technique to obtain fracture toughness from the measured load and compliance of the specimen.

The crack propagation along face/core interface in a sandwich composite is mixed-mode in nature due to the high elastic mismatch across the interface. Therefore, the applied remoted loadings are typically resolved into interface tension and shear stresses which create mixed-mode I, II and III components. Under the ambit of LEFM, crack propagates when the interface energy-release rate exceeds a critical fracture toughness value. In the case of bi-material interface, the fracture toughness is a function of mode-mixity [11]. Therefore fracture tests are conducted at various mixed-mode I/II, II/III or I/III ratios to create a map of fracture toughness vs. mode-mixity for a given sandwich interface. In addition, the energy release rate can also be obtained numerically using various methods such as: virtual crack closure technique (VCCT) [29]–[31] or crack surface displacement extrapolation method (CSDE) [32]. These methods have been widely used to compute energy-release rate as well as to determine the mixed-mode condition from both continuum (2D) and solid (3D) finite element analyses.

Attention is brought to the aspect of mode separation which is performed numerically in VCCT and CSDE methods. The crack tip stress solution oscillates near the tip which is introduced due by the elastic mismatch at the interface. This oscillatory behavior is aggravated when the mismatch across the interface is huge as is the case with a sandwich face/core interface. Invariably, the numerical oscillations will corrupt the mode-separation and will lead to erroneous results. However, the oscillation is restricted to very close to the crack tip. CSDE method circumvents this oscillation by extrapolating both energy-release rate and mode-mixity to the crack tip from the K-dominant zone [32]. The VCCT have been modified to better handle the oscillatory behavior by extending the number of nodal pairs ahead and behind the crack tip [33] or by modifying the element length to avoid the region of oscillation [31]. An analysis round-robin has been kick started under the banner of CMH-17, wherein VCCT and CSDE methods will be compared for several bi-material interfaces. The mode-mixity will be benchmarked with analytical expressions, which exist for moment loaded disbonded sandwich specimens [34], [35].

For mode-separation, a 2D continuum model is utilized by both DTU and Fraunhofer in conjunction with CSDE and VCCT techniques, which are implemented are separate post-processing subroutines. Commercial code, ANSYS® [36] is used at DTU, whilst ABAQUS® [37] is used at Fraunhofer IMWS. In both models, face sheet and core are considered as homogenous. Prior to the actual discussion on details regarding the finite element model, it must be mentioned that DTU utilizes finite element (FE) model of the sandwich DCB-UBM specimen along with the CSDE method to determine mode-mixity and to verify energy-release rate computation. Whereas, Fraunhofer uses FE-model of sandwich SCB specimen to investigate the SCB test procedure with regard to test conditions and handling error tolerance under typical testing lab operation to ensure reproducibility and robustness of the test method.

6.1. Finite element fracture modeling approach in DTU

An example of the 2D-FE-model of the DCB-UBM sandwich specimen is shown in Figure 28. A similar 3D model is also presented in Figure 29. The CSDE method requires highly densified crack tip mesh which can be noted in both 2D and 3D models in Figures 28 and 29. However, it should be noted that only 2D model is employed to estimate mode-mixity at various moment ratio, $MR = M_1/M_2$, see Figure 28. A detailed account of the DCB-UBM FE-model and implementation can be found in [9].

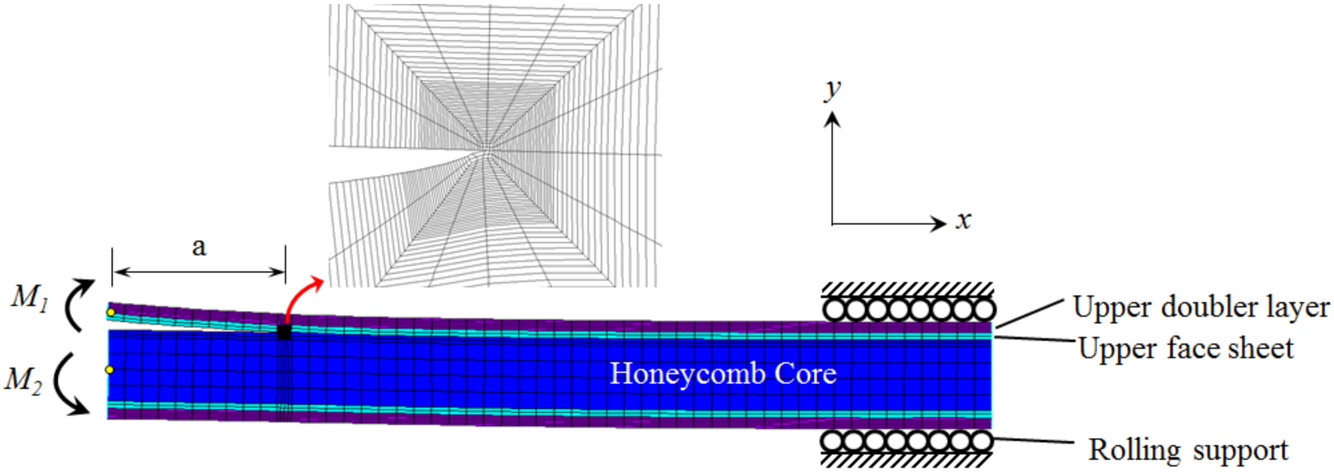


Figure 28. 2D FE-model of reinforced DCB-UBM sandwich specimen built using ANSYS® at DTU.

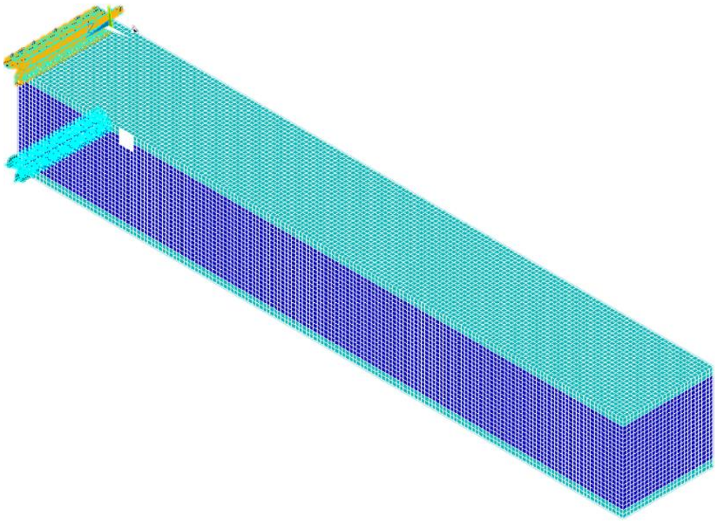


Figure 29. 3D FE-model of DCB-UBM specimen modeled in ANSYS®.

Iso-parametric Plane 182 and Plane 183 elements were used in the 2D model with 4-node Plane 182 elements used in the crack tip region only to capture large strains. Similarly, in the 3D model, Solid 185 elements were used in the crack tip region alone, whereas higher order Solid 186 elements were used in rest of the model. The face sheet is modeled as orthotropic and properties were obtained at Fraunhofer IMWS. Two face sheet thicknesses were considered in the DoSS project: a singly ply plain weave CFRP with a thickness of 0.35 mm and a 4-ply configuration of the same material type with a total thickness of 1.4 mm. Standard tests were performed on both face sheet types to obtain in-plane tensile properties [38]. The out of plane tensile modulus was obtained using a micro-mechanical model. A detailed description of the face sheet properties can be found in [4].

6.2. Finite element fracture modeling approach in Fraunhofer IMWS

The commercial code ABAQUS® in conjunction with the VCCT method is utilized at Fraunhofer IMWS. The 3D model is made of 20-node brick, reduced formulation C3D20R elements for both face sheet and core. The FE-model of a typical sandwich SCB specimen is shown in Figure 30. The VCCT is implemented as a separate post-processing sub-routine. Two approaches in modeling the face sheet were considered for the thicker 4-ply face sheet. In the first approach, the face sheet properties are considered to be homogenous and in the second method, individual ply is modeled. For the thinner face sheet consisting of 1-ply the properties obtained from the tensile testing is provided as input. Special attention must be taken in modeling of sandwich composite with honeycomb core, which is explained in detail in a later section.

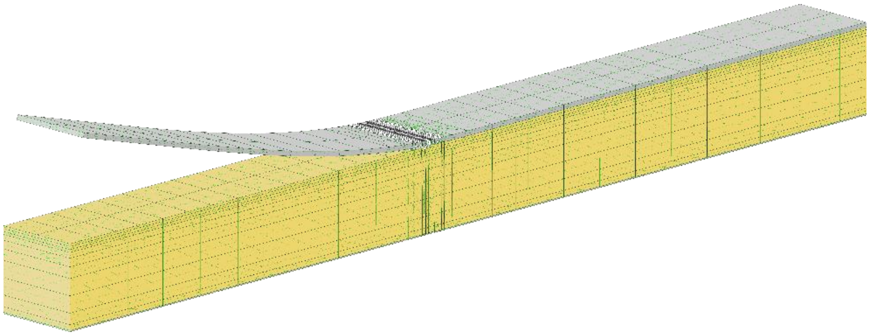


Figure 30. 3D FE-model of SCB sandwich specimen built in ABAQUS®.

6.2.1 Honeycomb core: Problem of near tip element distortion

Honeycomb cores are inherently orthotropic in nature with varying tensile and shear properties. In the technical data sheets provided by the suppliers, only properties such as out of plane compressive modulus, shear moduli along L and W direction are provided [39], [40]. To improve computational efficacy, it is preferred that core be modeled as homogenous. In the earlier FE-models involving homogenized honeycomb core, several approximations were made for in-plane properties which included the unknown values to be kept very small [41], [42]. One such parameter that was assumed to be small due to a lack of experimental data was the transverse Poisson’s ratio, which led to massive element distortion near the crack tip, as shown in Figure 31 and 32a. These near tip element distortion will render the mode-mixity tools such as VCCT and CSDE unreliable as they rely on the crack tip deformation characteristics. However, analytical model available in the literature estimated that Poisson’s ratio should be equal ~1 [43]. An attempt by Fraunhofer IMWS showed that by approximating the Poisson’s ratio close to the recommended value from the analytical method, the crack tip stabilizes. This behavior is illustrated in Figure 31 for a constant element size where the distortion is observed to be less for increasing Poisson’s ratio. It should be noted that *y*-axis is taken in out-of-plane in Figure 31.

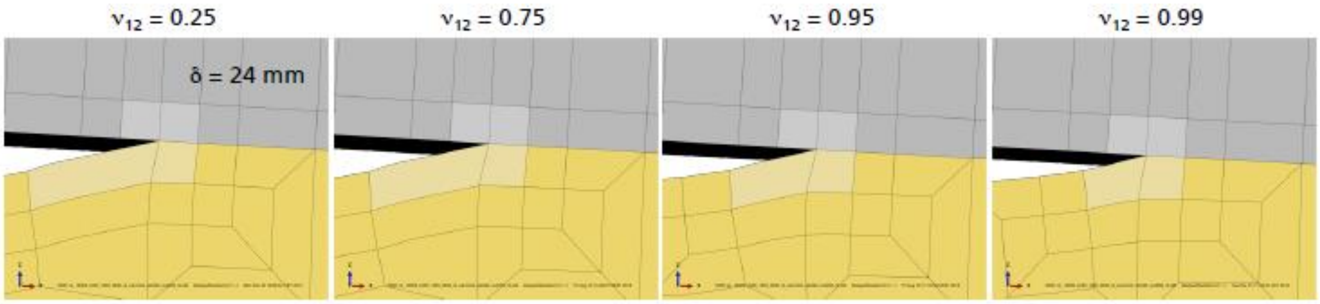
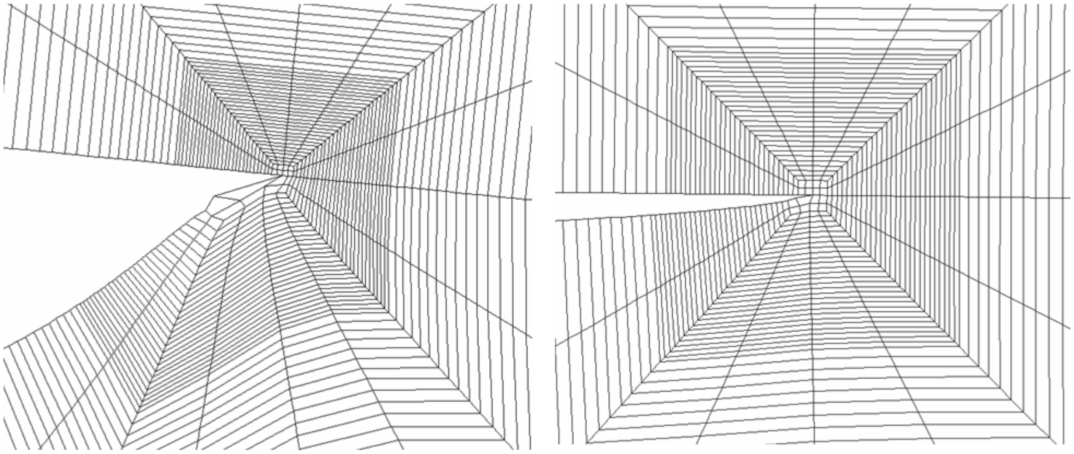


Figure 31. Effect of near tip element distortion on Poisson's ratio (same element length scale).

6.2.2. Core homogenization approach

From early analyses, it was demonstrated that by considering transverse Poisson’s ratio close to 1 will lead to stabilization of crack tip. In other attempts at DTU, it was also found that the in-plane moduli also play a key role in near tip element distortion. It was concluded that in order to homogenize the core effectively in the FE-model accurate material properties need to be provided as input. Extensive work on measurement of core and core paper properties of the sandwich specimens considered in the DoSS project was performed at TU Dresden [44]. The experimentally estimated core properties presented in [44] qualitatively agrees with the analytical approach provided in [43]. Employing the homogenized core properties also circumvented the issue of excessive crack distortion as shown in Figure 32. Therefore, throughout the analysis within the DoSS project, the homogenized core properties were taken from [44]. The experimental methods outlined in [44] requires specially designed fixtures to measure core moduli and Poisson’s ratio. Thus, the analytical approach can also be substituted for simpler analyses and for complex 3-D simulations the measured core material data is preferable.



(a) (b)

Figure 32. Crack tip element distortion before and after core homogenization approach using inputs from TU Dresden.

6.3. SCB Parametric analysis and discussion

The sandwich FE-model along with the CSDE method was employed to analyze whether the mode-mixity condition remain within the mode I regime for the various specimens considered in the DoSS project. The CSDE method utilizes the relative crack flank displacements to compute the phase angle [deg] as:

$$\psi = \tan^{-1}\left(\frac{\delta_x}{\delta_y}\right) \tag{1}$$

Where δ_x and δ_y are the relative sliding and opening displacements at the crack tip (see Figure 28). The mode-mixity expressed using the phase angle, ψ, was obtained for several crack lengths by applying a unit load (see Figure 6). The phase angle (ψ) can be briefly described as the ratio of relative sliding to that of normal openings at the crack tip. Mode I conditions are assumed to exist within the range: $-10° \leq \psi \leq 10°$. Plots of phase angle (ψ) vs. crack length for the different core density classes are provided in Figure 33 for the case of 40 mm thick core. Two face sheet thickness for 32 kg/m^3 dense core is also provided in the plot. It is noticed that for all the sandwich cases considered here, the crack propagates in mode I regime. The mode-mixity phase angle (ψ) also indicates the propensity of crack to advance at various crack lengths. For the denser core (ψ), negative phase angle values are observed indicating that the crack has a tendency to grow toward face sheet. Whereas for lighter core (ψ), a positive value in phase angle is observed which indicates the tendency of the crack to kink into the core.

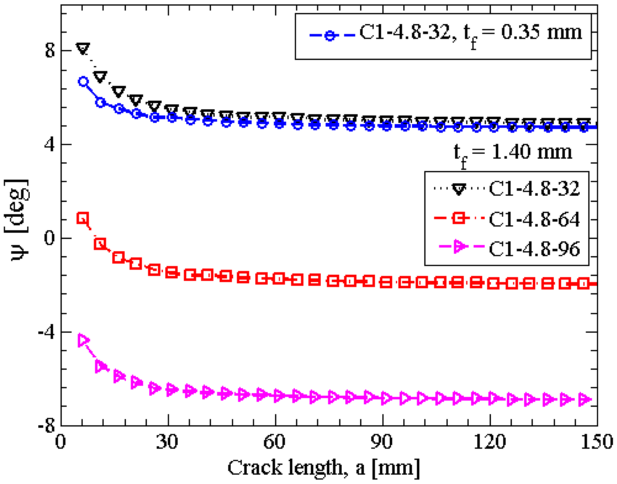


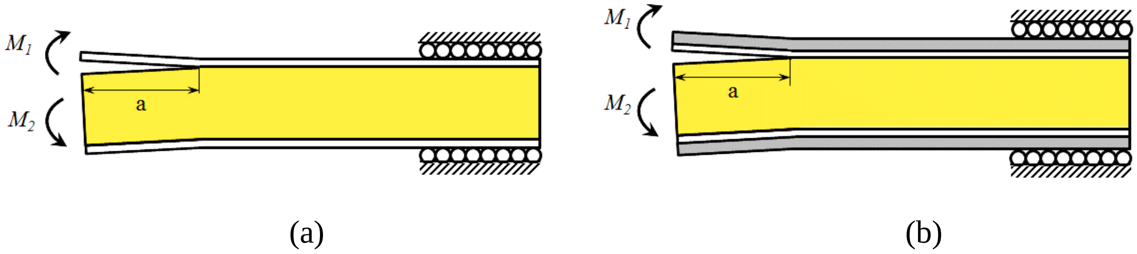
Figure 33. Mode-mixity phase angle (ψ) vs. crack length for the SCB sandwich specimens.

The mode-mixity analysis presented in this section focuses on DoSS specimens. An exhaustive parametric analysis based on mode-mixity was conducted in collaboration with NASA Langley Research Center, Hampton and the results of this work is under review prior to journal submission.

6.4. Closed form expressions for mode-mixity and energy-release rate

For a bi-material interface subjected to generalized loading conditions such as in-plane loads and moments, closed form expressions for energy-release rate and mode-mixity exist [11], [12]. The phase angle in such cases, in particular is expressed in terms of a scalar quantity ω, which is independent of loading and depend only on the externally loads. The ω values can be tabulated for standard specimen geometries and elastic mismatch values across the interface [12]. The tabulated values serve as an aid to compute mode-mixity phase angle (ψ) and energy-release rate using the algebraic expressions. The analysis was extended to disbonded sandwich specimen (see Figure 34a), which is a typical tri-material [34].

Most often, the aerospace grade sandwich specimens comprise of thin face sheets, which lead to excessive rotation when subjected to moments using the DCB-UBM test set-up. Moreover, it becomes cumbersome to apply moments to such specimens without the possibility of any attachment for gripping. To prevent excessive rotation of the crack flanks and to keep the analysis with LEFM, stiff layers are attached to both sides of the specimen, see Figure 34b. The reinforcement layers, referred to as “doublers” also make it easy to mount the specimen on test rigs similar to the one described in section 2.4. The algebraic expressions derived in [34] was recently extended to specimens reinforced with doubler layers in [35]. Therefore, unlike the SCB sandwich specimen, closed form expressions to compute energy-release rate and mode-mixity phase angle (ψ) exist for disbonded DCB-UBM sandwich specimen. It must be noted that the addition of stiff doubler layers does not affect the fracture phenomenon at the crack tip. The doubler merely enables application of moments onto the specimen edges in a test rig [45]. The mode-mixity condition in a DCB-UBM specimen is affected by the ratio of the moment, MR. Therefore by controlling the moment ratio, MR, in a test fracture characterization can be performed at varying mode-mixity conditions.



(a) (b)

Figure 34. Sandwich DCB-UBM specimen (a) un-reinforced (b) reinforced with stiff layers.

7. Sandwich Panel Manufacturing

Airbus Helicopter & Commercial (Fixed Wing) supported the DoSS project with sandwich test panels. For all standard tests in the frame of the DoSS project the Airbus Standard Sandwich Panel are used. Those sandwich panels were produced with 125°C curing material system, different face sheet thickness and honeycomb core density classes and core height. To reflect EASA specific questions about Helicopter applications Airbus Helicopter supplied a 180°C curing material system with specific face Sheet and honeycomb core sandwich panel. With-in the ambit of the DoSS project sandwich test panels a broad range of aerospace application are covered.

7.1. Airbus Standard Sandwich Panel (125°C curing & different face sheet & core configuration)

The Airbus Standard Sandwich Panel (size 2300x1050mm) uses a 125°C curing system material with a 2bar autoclave cycle and one shoot curing (co-curing). In total 9 large panels are produced, which are used in the DoSS project and beyond.

The key panel data are the following:

- Face Sheet thickness of 1.4 mm, except one panel with only one ply
  - A CFRP fabric prepreg (Hexcel fabric 926 and epoxy resin 913) and an AF163 adhesive film is selected.
  - Cured thickness of the CFRP fabric prepreg is 0.35 mm
  - Adhesive film (AF163) forms only the meniscus layer and has no contribution to face sheet thickness.
- Honeycomb core
  - Supplier Schütz, Cormaster C1
  - Selected types [32/ 4.8 / 56] , [64/ 4.8 / 81] and [96/ 4.8 / 105] [density, kg/m³/cell size, mm / paper thickness, µm]
  - Core thickness 40 mm, except one panel with 10 mm core thickness
  - For Disbond Panel Propagation Test (GAG cycle and/or In-Plane Compression) only 32kg/m³ density considered and the Teflon insert is in the tool side.

A typical sandwich panel is shown in Figure 35. The details about the Standard Sandwich Panel are presented in the Appendix of [6].

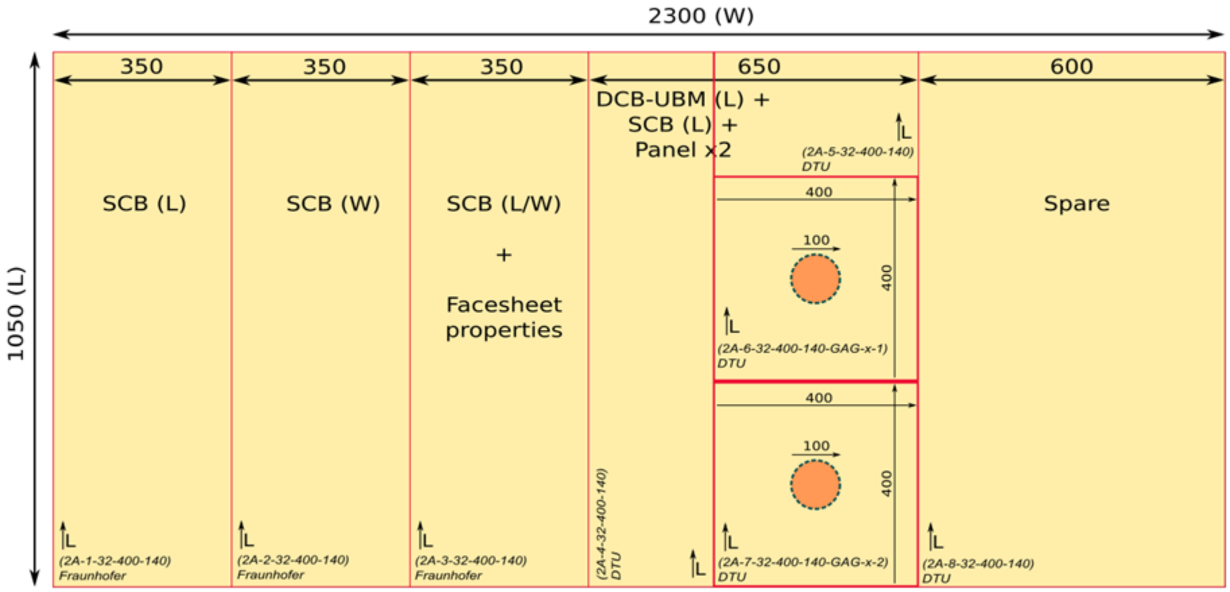
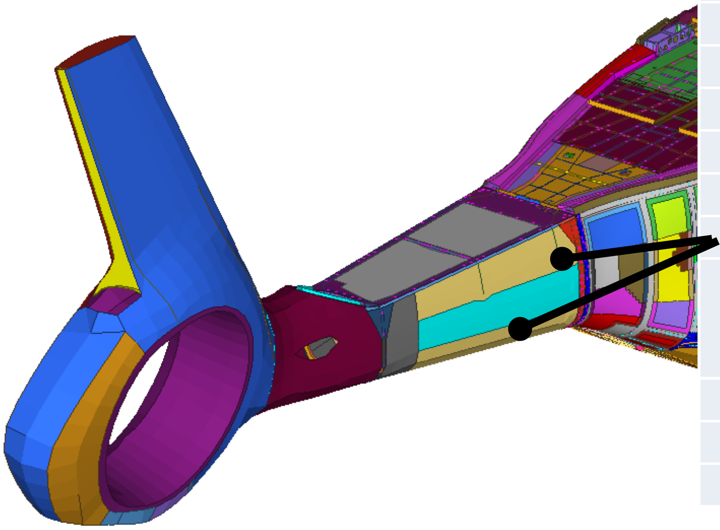


Figure 35. Airbus Standard Sandwich Panel [6].

7.2.Helicopter Sandwich Configuration (180°C curing & specific face sheet)

The layup, material and processes for the panel provided by Airbus helicopters are representative for the H160 helicopter tail boom. From this PSE, the sandwich area with the thinness layup has been chosen, which is the most critical configuration considering local buckling as a consequence of a failed bond. For the tail boom, as for most of the H160 CFRP parts, Hexcel prepreg with M18/1 resin is used. The layup of the working skin is UD dominant as the predominant loading condition of the tail boom is bending. In the sandwich areas, a Schütz 48kg/m^3 core according to LN29967 with a cell width of 3.2 has been used. The L axis of the core is orientated along 0° direction of the UDs. To ensure a proper bonding between core and cover sheets, a FM 300.35 adhesive film from Cytec is applied. Figure 36 shows the H160 tail boom as well as the layup used in the specimen.



	Material	**Ori.**	**T [mm]**
1	Fabric M18/1 (G939)	0°	0.225
2	UD M18/1 (G947)	0°	0.163
3	UD M18/1 (G947)	0°	0.163
4	UD M18/1 (G947)	0°	0.163
5	Fabric M18/1 (G939)	45°	0.225
	FM300.35 (Cytec)	-	-
6	Honeycomb, LN 29967 A4 (48kg/m^3 3,2mm cell width)	L	12
	FM300.35 (Cytec)	-	-
7	Gewebe M18/1 (G939)	45°	0.225
8	Gewebe M18/1 (G939)	0°	0.225

Figure 36. H160 Tail boom and representative layup ply thickness valid for 55% FVC.

The specimen has been manufactured according to the serial cycle for M18/1 sandwich parts at the LMP (Laboratory for materials and processes) at the airbus helicopter site in Donauwörth. Figure 37 shows the specimen plate before the curing in the autoclave. The preparation of the specimen for testing (cutting, application of the initial crack, application of the piano hinge) has been done at the Fraunhofer IMWS in Halle.

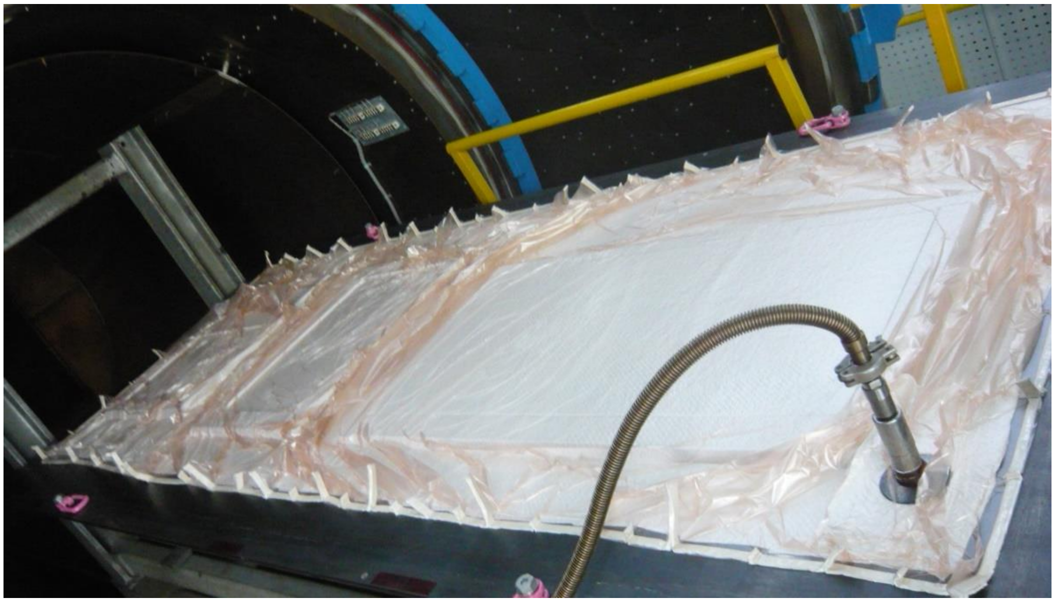


Figure 37. Airbus Helicopters DOSS panel together with other specimen in front of autoclave.

8. Conclusions of DoSS Project

In the DoSS project, comprehensive analysis of honeycomb core test coupons namely, SCB and DCB-UBM were carried out. On that note, the problem of excessive crack tip distortions encountered in finite element modeling was addressed in a systematic way. Transverse Poisson's ratio was shown to stabilize the crack tip distortions. Analytical as well as experimental methodologies were found to solve the problem, rendering the fracture analysis results from finite element simulations reliable.

Comparison of fracture toughness test results (mode I condition) was seen to be consistent in room, elevated and sub-zero temperatures. The consistent data demonstrated that the production process could heavily influence the fracture toughness values based on the operational environment. Production processes for honeycomb core sandwich composites are susceptible in influencing the performance of the sandwiches. For instance, it was shown that in the temperature controlled SCB coupon tests, the crack propagation path depended varied with the production process. The current investigation signifies the environmental factors such as humidity and temperature have on the interface fracture toughness values of the sandwich composites. Therefore, for testing for real applications, steps must be taken to ensure that other environmental factors and not just temperature are regulated. The labs have established and validated different methods of data recording, crack length measurement as well as specimen preparation, specimen clamping or bonding and load introduction variants (see Chapter 2 and [4]). Based on the results of DoSS SCB series a range of valid test options could be formulated which enable labs to fulfill the requirements of the prospective ASTM test standard and take into account at the same time specific industry needs.

The tests performed in the DoSS project with various labs also demonstrated the feasibility to perform fracture characterization of both thin and thick skinned sandwich configurations intended for typical fixed-wing and rotorcraft applications. Moreover, by observing the crack path, whether it lies close to the face sheet or not, it is determined that effect of meniscus layer has an important role to play. Comparison of SCB and DCB-UBM coupon test results in particular, demonstrated that the interface fracture toughness is a material property. To extend the veracity of the argument: steel doubler layers were employed in the DCB-UBM and face/core interface crack propagation was achieved, made possible by controlling the mode-mixity conditions. Nonetheless, if failure happens in the core and not at the interface, then interface fracture toughness can no longer be referred to as a material property. Thus, the challenge is to utilize the toughness values obtained using coupon tests to be incorporated in the design phase and also replicate the same failure mode at a component level. The measured and the presented fracture toughness here, provides a first idea of the range in which the fracture toughness lie for a specific honeycomb core density. In the sandwich design, the selected materials at the interface (face/core/adhesive), production process parameters (humidity, autoclave, etc.) and in-service environmental effects (temperature, humidity etc.) can significantly affect fracture toughness. Therefore, it is recommended that the sandwich part designer must account for all these factors by testing and evaluation covering all environmental factors.

The honeycomb core sandwich coupons tested under the ambit of DoSS was in-line with those specimens used in the rotorcraft industry. The conclusions from this project is applicable for the generality of the honeycomb core sandwich constructions (including fixed wing and rotor craft applications). Simplified engineering approach combined with analytical or numerical evaluations further validates with experiments will be included in the next phase. An outline of the general outlook was provided in the preliminary section containing overview of the DoSS project. The work packages defined in the outline pave way for the future aspects which may be executed in collaboration with a major rotor craft or fixed wing manufacturer.

References

[1] Transportation Safety Board of Canada, “Loss of Rudder in Flight,” Minister of Public Works and Government Services, Canada, 2007.

[2] E. H. Glaessgen, J. R. Reeder, D. W. Sleight, J. T. Wang, I. S. Raju, and C. E. Harris, “Debonding Failure of Sandwich-Composite Cryogenic Fuel Tank with Internal Core Pressure,” *J. Spacecr. Rockets*, vol. 42, no. 4, pp. 613–627, Jul. 2005.

[3] Y. Albertone, “SCB - ASTM Round Robin DuPont Results.” EASA/FAA Disbond Woskhop, Cologne, 2016.

[4] R. Schäuble, M. Goldstein, and M. Petersilge, “SCB Fracture Toughness Tests on Honeycomb Sandwich Material - Technical Report,” Internal report IMWS V793/2017, Halle, 2017.

[5] S. Fimmen, “Mode I Fracture Toughness Tests on Sandwich Structures under constant amplitude fatigue loading,” Bremen, 2017.

[6] V. Saseendran and C. Berggreen, “Honeycomb Sandwich Face/Core Fracture Toughness Measurements using the DCB-UBM Test Method – DoSS Project,” Kgs. Lyngby, 2017.

[7] 3M, “Scotch-Weld ^{TM} Epoxy Adhesives DP460 Off-White and DP460NS,” St. Paul, MN, 2017.

[8] “Preliminary Round Robin SCB Test Procedure - ASTM Preliminary Standard.” 2015.

[9] V. Saseendran and C. Berggreen, “DCB-UBM Fracture Toughness Results for Disbond of Sandwich Structures – DoSS Project,” Kgs. Lyngby, 2017.

[10] Z. Suo, “Delamination Specimens for Orthotropic Materials,” *J. Appl. Mech.*, vol. 57, no. 3, p. 627, Sep. 1990.

[11] J. W. Hutchinson and S. Zhigang, “Mixed Mode Cracking in Layered Materials,” vol. 29, pp. 63–191, Jan. 1991.

[12] Z. Suo and J. W. Hutchinson, “Interface crack between two elastic layers,” *Int. J. Fract.*, vol. 43, no. 1, pp. 1–18, May 1990.

[13] S. Zhigang and J. W. Hutchinson, “Sandwich test specimens for measuring interface crack toughness,” *Mater. Sci. Eng. A*, vol. 107, pp. 135–143, Jan. 1989.

[14] K. M. Liechti and E. C. Hanson, “Nonlinear effects in mixed-mode interfacial delaminations,” *Int. J. Fract.*, vol. 36, no. 3, pp. 199–217.

[15] P. G. Charalambides, J. Lund, A. G. Evans, and R. M. McMeeking, “A Test Specimen for Determining the Fracture Resistance of Bimaterial Interfaces,” *J. Appl. Mech.*, vol. 56, no. 1, p. 77, Mar. 1989.

[16] J. W. Hutchinson, M. E. Mear, and J. R. Rice, “Crack Paralleling an Interface Between Dissimilar Materials,” *J. Appl. Mech.*, vol. 54, no. 4, p. 828, Dec. 1987.

[17] American Society for Testing and Materials, "Standard Test Method for Climbing Drum Peel for Adhesives," ASTM Standard D1781-98, In: ASTM Annual Book of Standards, Vol. 15.06, ASTM, 2006.

[18] S. Prasad and L. A. Carlsson, "Debonding and crack kinking in foam core sandwich beams—I. Analysis of fracture specimens," *Eng. Fract. Mech.*, vol. 47, no. 6, pp. 813–824, Apr. 1994.

[19] S. Prasad and L. A. Carlsson, "Debonding and crack kinking in foam core sandwich beams—II. Experimental investigation," *Eng. Fract. Mech.*, vol. 47, no. 6, pp. 825–841, Apr. 1994.

[20] L. A. Carlsson, "On the Design of the Cracked Sandwich Beam (CSB) Specimen," *J. Reinf. Plast. Compos.*, vol. 10, no. 4, pp. 434–444, 1991.

[21] S. Smith and K. Shivakumar, "Modified Mode-I cracked sandwich beam (CSB) fracture test," in *19th AIAA Applied Aerodynamics Conference*, 2001.

[22] W. J. Cantwell and P. Davies, "A test technique for assessing core-skin adhesion in composite sandwich structures," *J. Mater. Sci. Lett.*, vol. 13, no. 3, pp. 203–205, 1994.

[23] W. J. Cantwell, G. Broster, and P. Davies, "The Influence of Water Immersion on Skin-Core Debonding in GFRP-Balsa Sandwich Structures," *J. Reinf. Plast. Compos.*, vol. 15, no. 11, pp. 1161–1172, Nov. 1996.

[24] W. J. Cantwell, R. Scudamore, J. Ratcliffe, and P. Davies, "Interfacial fracture in sandwich laminates," *Compos. Sci. Technol.*, vol. 59, no. 14, pp. 2079–2085, Nov. 1999.

[25] W. J. Cantwell and P. Davies, "A study of skin-core adhesion in glass fibre reinforced sandwich materials," *Appl. Compos. Mater.*, vol. 3, no. 6, pp. 407–420, 1996.

[26] B. F. Sørensen, K. Jørgensen, T. K. Jacobsen, and R. C. Østergaard, "DCB-specimen loaded with uneven bending moments," *Int. J. Fract.*, vol. 141, no. 1–2, pp. 163–176, 2006.

[27] X. Li and L. A. Carlsson, "The Tilted Sandwich Debond (TSD) Specimen for Face/Core Interface Fracture Characterization," *J. Sandw. Struct. Mater.*, vol. 1, no. 1, pp. 60–75, Jan. 1999.

[28] A. Quispitupa, C. Berggreen, and L. A. Carlsson, "Design Analysis of the Mixed Mode Bending Sandwich Specimen," *J. Sandw. Struct. Mater.*, vol. 12, no. 2, pp. 253–272, 2010.

[29] E. F. Rybicki and M. F. Kanninen, "A finite element calculation of stress intensity factors by a modified crack closure integral," *Eng. Fract. Mech.*, vol. 9, no. 4, pp. 931–938, Jan. 1977.

[30] I. S. Raju, "Calculation of strain-energy release rates with higher order and singular finite elements," *Eng. Fract. Mech.*, vol. 28, no. 3, pp. 251–274, Jan. 1987.

[31] R. Krueger, "Virtual crack closure technique: History, approach, and applications," *Appl. Mech. Rev.*, vol. 57, no. 2, p. 109, Mar. 2004.

[32] C. Berggreen, B. C. Simonsen, and K. K. Borum, "Experimental and Numerical Study of

Interface Crack Propagation in Foam-cored Sandwich Beams," *J. Compos. Mater.*, vol. 41, no. 4, pp. 493–520, 2007.

[33] C. Berggreen, "Damage Tolerance of Debonded Sandwich Structures," Technical University of Denmark, 2004.

[34] G. a. Kardomateas, C. Berggreen, and L. a. Carlsson, "Energy-Release Rate and Mode Mixity of Face/Core Debonds in Sandwich Beams," *AIAA J.*, vol. 51, no. 4, pp. 885–892, Apr. 2013.

[35] V. Saseendran, C. Berggreen, and L. A. Carlsson, "Fracture Mechanics Analysis of Reinforced DCB Sandwich Debond Specimen Loaded by Moments," *AIAA J.*, no. DOI: 10.2514/1.J056039, 2017.

[36] "ANSYS® Mechanical User's Guide." ANSYS, Inc., Canonsburg, PA, 2015.

[37] "ABAQUS®/CAE User's Guide." Dassault Systems, Vélizy-Villacoublay, France, 2015.

[38] ASTM-D3039/D3039M-08, "Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials." ASTM International, West Conshohocken, PA, 2014.

[39] SCHÜTZ GmbH & Co., "Cormaster C1 Technical Data," 2016.

[40] Schütz GmbH & Co., "Cormaster N636 Preliminary Technical Data," 2016.

[41] M. Rinker, J. G. Ratcliffe, A. . O. Daniel, and R. Krueger, "Characterizing Facesheet/Core Disbonding in Honeycomb Core Sandwich Structure," NASA Technical Report NASA/CR-2013-217959, Hampton, VA, 2013.

[42] Z. M. Chen, R. Krueger, and M. Rinker, "Face Sheet/Core Disbond Growth in Honeycomb Sandwich Panels Subjected to Ground-Air-Ground Pressurization and In-Plane Loading," in *NAFEMS World Congress*, 2015.

[43] L. J. Gibson and M. F. Ashby, *Cellular Solids: Structure and Properties*. Cambridge University Press, 1999.

[44] F. Hähnel, A. Bugiel, and K. Wolf, "Determination of macroscopic properties of different aramid paper based honeycomb cores," Technische Universität Dresden, Chair of Aircraft Engineering, Internal report ILR/LFT-IR17-19, Dresden, 2017.

[45] V. Saseendran, C. Berggreen, and L. A. Carlsson, "Fracture Testing of Honeycomb Core Sandwich Composites Using the DCB-UBM Test," in *Proceedings of the 20th International Conference on Composite Materials (ICCM-20)*, 2015, no. July, pp. 1–6.

Intentionally left blank

Intentionally left blank

European Aviation Safety Agency
Safety Intelligence & Performance Department

Postal address
Postfach 10 12 53
50452 Cologne
Germany

Visiting address
Konrad-Adenauer-Ufer 3
50668 Cologne
Germany

Tel. +49 221 89990-000
Fax +49 221 89990-999
Mail info@easa.europa.eu
Web www.easa.europa.eu