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Experimental and numerical study of the response to various impact energy levels for composite sandwich plates with different face thicknesses

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Abstract

Composite sandwich structures find wide application in the aerospace sector thanks to their lightweight characteristics. However, composite structures are highly susceptible to low velocity impact damage and therefore thorough characterization of the impact response and damage process for the used material configurations is necessary. The present study investigates the effect of face-sheet thickness on the impact response and damage mechanisms, experimentally and numerically. A uni-directional, non-crimp fabric is used as reinforcement in the face-sheets, and a closed cell Rohacell 200 Hero polymer foam is used as core material. Low-velocity impact tests are performed in a novel instrumented drop-weight rig that is able to capture the true impact response. A range of impact energies are initially utilized in order to identify when low level damage (LLD), barely visible impact damage (BVID) and visible impact damage (VID) occur. A thorough fractography investigation is performed to characterize the impact damage using both destructive and non-destructive testing. The damage from the impacts in terms of dent depth, peak contact force, deflection and absorbed energy is measured. The results show bilinear responses in dent depth vs. impact energy and absorbed energy vs. impact energy. It is found that the BVID energy works well as an indication for the onset of excessive damage. Fractography reveals that there is a failure mode shift between the LLD and the VID energy levels, and that delaminations predominantly grow along the fiber direction and rotate in a spiral pattern through the thickness, following the laminate ply orientations. Finally, a progressive damage finite element model is developed to simulate both the impact response and the delamination extent, incorporating both intra-laminar and inter-laminar damage modes. The simulation shows good agreement with the experiments.

Keywords: Non-crimp fabric, drop-weight rig, low-velocity impact, fractography, barely visible impact damage, X-ray micro-tomography, foam core

1 Introduction

Sandwich materials are known to provide high stiffness and strength to weight ratios. In aerostructures the face material is generally aluminum or fiber composites and the core material is either a honeycomb structure or a rigid polymer foam. In a sandwich structure, the face sheets primarily carry the bending and in-plane loads, whereas the core material carries the transverse loads and also connects the two face sheets in a way that makes them interact for enhanced global stiffness [1].

Sandwich structures are susceptible to impact damage. The damage is sometimes hard to detect visually due to its localized nature but can still be significant underneath the impacted surface which could reduce the strength of the component significantly [2]. In the aerospace sector several impact scenarios can occur both in service and during maintenance, for example tool drops, runway debris, hail storms or bird strikes. Studies [3,4] show that such low velocity impact (LVI) could cause considerable damage in the core without necessarily showing significant damage on the impacted face-sheet, thus reducing the stiffness, strength and the load carrying capability of the structure. Therefore extensive experimental campaigns have been performed to predict the effect of impact damage in sandwich structures. Some thorough review work by Abrate [5] followed by Chai et al. [6] cover the significant developments in this area.

In composite structures the impact energy is dissipated in the form of fiber breakage, matrix cracking and delamination. For sandwich structures, face-sheet and core debonding along with core crushing [5–8] constitute additional damage modes. The damage mechanisms are complex and related to the fiber and matrix combinations [7,9], ply-stacking sequence [10,11] and face-sheet/core thicknesses [7,10,12,13]. As a direct consequence, the active modes and relevant impact energy levels need to be re-established for a particular sandwich configuration. A number of studies have been performed in order to study the low-velocity impact response and the underlying damage mechanisms of composite sandwich structures [2,7,9,13–17].

Geometrical parameters show significant effects on the impact response. Ozdemir et al. [13] highlighted that the sandwich core thickness significantly affects the impact response by shifting the damage mechanisms. Atas et al. [7] and Caminero et al. [10] studied the effects of face-sheet thickness on the impact response of monolithic laminates and found that fiber fracture and delamination were the primary damage modes. Mohammed et al. [14] studied the effect of ply-stacking sequence on the impact response of foam-based sandwich structures. They found that core shear cracking was the prominent failure when face-sheets with unidirectional reinforcement were used, whereas tensile cracking dominated for cross-ply, angle-ply and quasi-isotropic face-sheets. The study of monolithic laminates by Caminero et al. [10] also showed that quasi-isotropic laminates exhibited lower peak contact force than cross-ply and angle-ply laminates whereas the latter showed greater dent depth. Xia et al. [15] studied the effect of low-velocity impact on various face-sheets composed of carbon, glass, stitched glass and Kevlar fabric, bonded to foam-based core material. They concluded that the sandwich structure with Kevlar face-sheets was optimal, judging from the peak contact force.

Anderson et al. [9] studied the effect of different core materials on the impact response of sandwich composites. Both foam and honeycomb cores were investigated and the honeycomb specimens showed significant damage and higher dent depth compared to the foam specimens, attributed to cell wall buckling. However, both foam and honeycomb specimens showed tearing and localized dents near the impact region. Al-Shamary et al. [16] also studied the impact response using different foam-core configurations. Zenkert et al. [2] and Shipsha and Zenkert [17] studied core crushing damage in the foam material and developed a damage tolerance model incorporating the properties of crushed core in finite element (FE) modeling.

Little work is found that brings understanding to the LVI response of foam-based sandwich materials with different face-sheet thickness. Such studies are important for the design of applications where the face-sheet thickness varies and scaling is required based on the available experimental data at hand. In the present study, a detailed experimental and numerical investigation of the effect of face-sheet thickness on the impact response of foam core sandwich materials is performed. Impact energy levels at which transition between damage mechanisms occur are determined. The effect of impact energy and face-sheet thickness on the impact response is studied by means of dent depth, peak contact force, displacement and absorbed energy. Some of the face-sheet thicknesses fall outside the limit where idealized theory due to thin face-sheets and thick core is considered to apply [1]. Both destructive and non-destructive techniques (2D and 3D) are used to characterize the impact damage. A FE model simulating progressive damage is developed to simulate both the impact response and the extent of delamination, incorporating both intra-laminar and inter-laminar damage modes. Finally, the results are compared, discussed and some general conclusions are made.

2 Material and specimen data

In the present study, sandwich panels with relatively thick face-sheets, i.e. in relation to the core, are investigated. Three different face-sheet thicknesses are applied to a core material with constant thickness. Sandwich specimens are manufactured (in-house) using uni-weave carbon fiber non-crimp fabric (NCF), HTS45 E23 Tenax®, with an areal weight of 205 g/m². The face-sheets are symmetric with a quasi-isotropic lay-up $[0/45/90/-45]_n$, where $n = 2, 3 \text{ or } 4$. A Rohacell 200 Hero, Polymethacrylimide (PMI) closed cell foam supplied by Evonic AG, is used as core material. A Huntsman LY556 Araldite epoxy, supplied by ABIC Kemi AB, is used as resin. It is infused, at 40°C, into the fiber reinforcement using a vacuum-assisted infusion process and left to cure at 80°C for 7 hours followed by post-curing at 120°C for another 8 hours. In the end the resin also works as an adhesive between the core and the faces. The final face-sheet thicknesses are 1.6, 2.4 and 3.1 mm, and the nominal thickness of the core material is 9 mm in all tested specimens. The three different sandwich types are in the following referred to as C1(1.6/9/1.6), C2(2.4/9/2.4) and C3(3.1/9/3.1), respectively. The achieved fiber volume fraction is approximately 55 %.

A small portion of the finished plate is cut, polished and inspected in a light microscope for possible presence of voids or dry spots in order to ensure the quality of the plates. Typical

microscopy images of the face-sheets are shown in Figure 1. The mechanical properties of the NCF composite is taken from Bru et al. [18], who performed a comprehensive characterization of the mechanical and fracture properties of the very same NCF/epoxy material system. Some of the required mechanical properties for the present study are presented in Table 1. The mechanical properties of the core material are presented in Table 2, where the compressive modulus is taken from a recent study performed by the authors in [8].

All panels are manufactured to a size of 900 mm x 420 mm, which are then cut into specimens of 150 mm x 100 mm size, following the ASTM standard for LVI testing [19]. The details of the manufacturing and test matrix are provided in Table 3. A total of 25 samples per configuration are used for LVI testing at varying impact energy levels.

Table 1. Material properties of NCF composite face-sheet material, obtained from [18]

Longitudinal modulus [GPa]	E_1	136
Transverse modulus [GPa]	E_2	9.3
In-plane shear modulus [GPa]	G_{12}	4.4
Longitudinal tensile strength [MPa]	X^T	1790
Longitudinal compressive strength [MPa]	X^C	631
Transverse tensile strength [MPa]	Y^T	29
Transverse compressive strength [MPa]	Y^C	130
In-plane shear strength [MPa]	S^L	77
Poisson's ratio [-]	ν_{12}	0.28
Mode-I fracture energy [J/m ²]	G_1^C	150
Mode-II fracture energy [J/m ²]	G_S^C	690
Longitudinal tensile fracture energy [kJ/m ²]	G_{1t}	67
Longitudinal compressive fracture energy [kJ/m ²]	G_{1c}	103
Mode mix ratio [-]	η	2

Table 2. Material properties of Rohacell 200 Hero core material

Density [kg/m ³]	205
Compressive modulus [MPa] ^a	350
Tensile modulus [MPa]	389
Shear modulus [MPa]	109
Compressive strength [MPa]	7.1
Poisson's ratio [-]	0.3

^a From Ref. [8]

Table 3. Test material details

Plate Config.	Face sheet stacking	No. of plies	No. of samples
C1(1.6/9/1.6)	[0/45/90/-45] ₂	8 (x2)	25
C2(2.4/9/2.4)	[0/45/90/-45] ₃	12 (x2)	25
C3(3.1/9/3.1)	[0/45/90/-45] ₄	16 (x2)	25

Figure 1. Microscopy images of face-sheets for three plate configurations (scale $200\ \mu\text{m}$)

3 Experiments

3.1 Low-velocity impact

In a previous study by the authors [20], a novel instrumented drop-weight test rig (DWR)¹ was designed and manufactured in-house, for LVI testing. A photograph of the test rig is shown in Figure 2. It is designed to prevent transfer of unwanted mechanical noise such as vibrations into the load cell that is used to measure the load during the impact event. A novel catch mechanism preventing secondary impact is also implemented in the DWR. A detailed presentation of the design and evaluation of the DWR is presented by Rajput et al. [20]. The load-time response is captured by a Kistler piezoelectric load cell ($\pm 20\ \text{kN}$), attached to an impactor, and the displacement vs. time response and impact velocity are extracted from an optical laser measuring system. The measurements are fed into a data acquisition system for post-processing.

Figure 2. Drop-weight impact test rig

¹ Granted patent (SE-1751589-1)

In the present study, the DWR setup consists of a hemispherical 16 mm diameter steel impactor attached to an impactor giving a total impact mass of 3.04 kg. Specimens are fixed and centered over a 125 mm x 75 mm opening in a rigid substrate plate. Movement of the specimen is restricted using four rubber clamps mounted on each side of the base plate as suggested by the ASTM D7136 test standard [19].

3.2 Impact energy levels

According to aircraft airworthiness requirements, a component having either barely visible impact damage (BVID) or visible impact damage (VID) should be damage tolerant enough to be airworthy and fly without jeopardizing the safety [21,22].

Usually BVID represents impact events such as e.g. a tool drop during service or impact from debris on the runway during aircraft takeoff and landing. According to an ISO standard [23] BVID is defined as a residual indentation dent depth of 0.3 mm after impact. In the present study low level damage (LLD) and VID are defined as having residual dent depths of approximately half (0.15 mm) and double (0.6 mm) that of a BVID dent depth, respectively.

In order to identify the energy levels corresponding to LLD, BVID and VID for the three different plate configurations, an initial pilot scan is performed by impacting the different panels from varying drop heights. For all these tests the impactor mass is unaltered. 3 to 5 samples per energy level are used to get an estimate of the impact damage and check for uncertainties or variability in the test setup. The impact energy levels range from 4 - 25 J, i.e. impact velocities of 1.6 to 4 m/s.

The dent depth is measured right after the impact test, using a digital dial caliper supplied by Mitutoyo Corp. The dial gauge is moved along the impacted surface in order to estimate the impact dent depth, using an un-damaged surface as reference.

3.3 Inspection and characterization of damage

A thorough damage characterization of impacted specimens is performed using state of the art non-destructive (NDT) and destructive (DT) test methods. After the LLD, BVID and VID energy levels are identified, the damage from the different energy levels is inspected for all three face-sheet thicknesses.

3.3.1 Ultrasonic inspection

In order to explore the impact damage through the thickness, ultrasonic scanning is performed using through-transmission ultrasonic (TTU) and pulse-echo (PE) inspection techniques. PE only provides the extent of damage in the (closest) face-sheet, which predominately consists of delaminations. TTU provides information on the total damage area but does not separate face-sheet damage from core damage. It is thus unable to capture core damage if it does not extend beyond the face-sheet damage. A schematic of the two inspection methods is presented in Figure 3 where the red area indicates delaminations in the impacted face-sheet and the white lenticular shape in the core material indicates core damage and/or face-core de-bonding. Both measurement techniques have an error of ± 2 mm, which potentially means a maximum total

difference in width of 4 mm between the two methods. Thus, the reading from the TTU can only confidently be regarded as core damage at locations where the TTU measurement indicates 4 mm larger damage than the PE measurement. A total of four impacted specimens and one reference specimen are inspected for each configuration.

Figure 3. Illustration of TTU and PE inspection methods

3.3.2 X-ray micro-tomography

In order to examine the microstructure of the impacted specimens, X-ray micro-tomography (XMT) is used [24,25]. During an XMT scan, a large number of x-ray projection images are captured at equal angles as the sample makes one full rotation. Based on the projection data, the full 3D-microstructure of the sample is reconstructed using a tomographic software. From the acquired 3D data it is possible to make a quantitative characterization of the internal features such as delaminations, voids, cracks, grains, fibers etc., and calculate quantities such as porosity, volume fraction of fibers and grain size distribution, using 3D image analysis [26].

In the present study, the composite sandwich specimens were scanned using a Zeiss Xradia 510 Versa X-ray Micro-tomography system, see Figure 4. The imaging system provides flexibility with high resolution (down to $<0.7 \mu\text{m}$ spatial resolution and $<70 \text{ nm}$ achievable voxel) and high contrast capabilities.

Figure 4. The experimental setup for the scanning of the impacted sample, using a Zeiss Xradia 510 Versa micro-tomography system.

The specimen configuration with the thickest face-sheet i.e. C3(3.1/9/3.1) and with impact damage at VID energy level is used for the investigation of delamination pattern in this inspection method. A circular cut-out around the damaged area, 50 mm in diameter, is scanned with a resolution of 47.55 μm . A total scan of 1601 projections were acquired with an exposure time of 4 seconds, which resulted in a total scan time of approximately 3 hours. A 3D visualization and quantitative analysis of the microstructure was obtained using a Dragonfly Pro software (ORS).

3.3.3 Fractography

Destructive inspection testing is also performed in order to better study the damage inside the impacted specimens. Test are carried out by sectioning the impacted specimen using a diamond coated blade saw. The sectioning is performed by cutting the impacted specimen in various directions with respect to the face-sheet ply orientations, i.e. in the 0, 45, 90 and -45 degree directions as illustrated in Figure 5, where different sectioning planes are highlighted. By doing so, the failure morphologies in all four ply orientations can be studied. Two small samples (S1 and S2) with in-plane size of 20x20 mm are cut out, polished and inspected under an optical microscope. For a sample denoted S1, damage along the 0 and 90 degree fiber orientations are studied, whereas for the S2 sample, damage mechanism under 45 and -45 degree orientations are investigated.

Figure 5. Sectioning planes of impacted specimen along various ply orientations

4 Numerical simulation

An approach for simulating low-velocity impact response is presented. An explicit finite element model is developed for both composite face-sheets and foam-core in Abaqus/CAE [27]. The face-sheets are modeled for simulating both intra-laminar and inter-laminar failure behavior whereas the foam core model includes core crushing behavior.

4.1 Face-sheet progressive damage model – intra-laminar failure

The face-sheets are modeled at lamina level with linear elastic material properties for the undamaged material, coupled with Hashin's damage initiation criterion for predicting the onset of degradation at a material point [28,29]. The physically based criterion represents the actual

behavior during fracture. Hashin proposed four different damage initiation criteria for each failure mode, summarized as follows:

1. *Fiber tension* ($\sigma_{11} \geq 0$)

$$\left(\frac{\sigma_{11}}{X^T}\right)^2 + \alpha \left(\frac{\sigma_{12}}{S^L}\right)^2 = 1 \quad (1)$$

2. *Fiber compression* ($\sigma_{11} < 0$)

$$\left(\frac{\sigma_{11}}{X^c}\right)^2 = 1 \quad (2)$$

3. *Matrix tension* ($\sigma_{22} \geq 0$)

$$\left(\frac{\sigma_{22}}{Y^T}\right)^2 + \left(\frac{\sigma_{12}}{S^L}\right)^2 = 1 \quad (3)$$

4. *Matrix compression* ($\sigma_{22} < 0$)

$$\left(\frac{\sigma_{22}}{2S^T}\right)^2 + \left[\left(\frac{Y^c}{2S^T}\right)^2 - 1\right] \left(\frac{\sigma_{22}}{Y^c}\right) + \left(\frac{\sigma_{12}}{S^L}\right)^2 = 1 \quad (4)$$

Here σ_{ij} is the effective stress tensor, X^T and X^c are the longitudinal tensile and compressive strengths in the fiber direction, respectively. Y^T and Y^c are the transverse tensile and compressive strengths in the matrix direction, S^L and S^T is the longitudinal and transverse shear strengths and α defines the contribution of shear stress in the fiber tension criterion.

When the failure index in any of the damage initiation criteria equals 1, a degradation of the material is activated through a damage evolution law proposed by Camanho and Davila [30]. Damage evolution is modeled by effectively reducing a damage variable that controls the stiffness of the finite element. The reduced stress vector is related to the strain by a damage stiffness matrix given by:

$$\sigma_r = C_d \epsilon,$$

where

$$C_d = \frac{1}{D} \begin{bmatrix} (1-d_f)E_1 & (1-d_f)(1-d_m)\nu_{21}E_1 & 0 \\ (1-d_f)(1-d_m)\nu_{12}E_2 & (1-d_m)E_2 & 0 \\ 0 & 0 & D(1-d_s)G_{12} \end{bmatrix} \quad (5)$$

with $D = 1 - (1-d_f)(1-d_m)\nu_{12}\nu_{21}$ and d_f , d_m and d_s reflecting the current level of fiber, matrix and shear damage.

4.2 Face-sheet progressive damage model – inter-laminar failure

In order to model the inter-laminar damage, i.e. delamination between plies, a cohesive damage model is incorporated. For the initiation of damage in the cohesive surface, a quadratic stress criterion is used, given as:

$$\left[\frac{\langle t_1 \rangle}{\sigma_1} \right]^2 + \left[\frac{t_2}{\sigma_2} \right]^2 + \left[\frac{t_3}{\sigma_3} \right]^2 = 1 \quad (6)$$

Where t_i and σ_i represent the tractions and strengths in mode 1, mode 2 and mode 3, respectively. The Macaulay brackets $\langle \rangle$ indicates that the damage can't be initiated by a pure compressive stress.

In order to accurately model the cohesive behavior, a sufficient number of elements are required within a cohesive zone length l_{cz} , to ensure the correct dissipation of energy. Turon et al. [31] proposed an analytical expression to calculate the cohesive zone length l_{cz} , as:

$$l_{cz} = ME \frac{G_c}{(\tau^o)^2} \quad (7)$$

Where E is the Young's modulus, G_c is the critical energy release rate, τ^o is the maximum interface strength and M is a parameter close to unity as proposed by Hillerborg et al. [32]. Turon et al. [31] suggested that at least two elements should be present within the cohesive zone and if the size of the elements become too small the length of the cohesive zone can be increased by changing the interface strength. In the proposed model the calculated cohesive zone length l_{cz} is 1 mm with an interface strength of 35 MPa.

For the cohesive model, the damage evolution is defined by the Benzeggagh-Kenane criterion [33] which assumes that the first and second shear fracture energies are identical and given as:

$$G_C = G_I^C + (G_S^C - G_I^C) \left[\frac{G_S}{G_I + G_S} \right]^\eta \quad (8)$$

where G_C is the critical fracture energy, G_I^C is the mode I fracture energy, G_S^C is the shear mode fracture energy, $G_S = G_2 + G_3$ and η is the cohesive property parameter related to the mode-mixity ratio.

4.3 Foam-core progressive damage model

The foam-core material exhibits a crushable hardening response in the plastic region [8] and a crushable foam material model available in Abaqus/CAE is used for modeling such behavior. The elastic core response is modeled using elastic properties of the foam material, i.e. compressive modulus and poison's ratio. After the yield stress the cells in the foam material start crushing without further increase in stress until the foam is crushed and the densification region is reached, near the end of the compression regime. A uni-axial compression curve of the Rohacell 200 Hero foam material is presented by authors in [8] where the plastic region is

used as input to the crushable foam hardening model in Abaqus. The crushable foam model is first calibrated by numerically simulating the uni-axial compression response of pure foam material alone.

4.4 Finite element model

An explicit finite element LVI model is developed in Abaqus/CAE for all three plate configurations. The face-sheets are modeled with continuum shell elements (SC8R) using one element through the ply thickness. The core is modeled with 3D stress elements (C3D8R). The top face-sheet (impact side) is modeled with an individual stack of plies in order to insert cohesive surfaces between each ply, each ply having a thickness of around 0.2 mm. A hemispherical impactor is modeled with discrete rigid elements. A composite lay-up tool is used to define the orientation of the fibers in each ply where the face-sheet elastic properties are defined as lamina.

A general contact condition is defined between the impactor and the top face-sheet. The interaction between each ply is defined using the cohesive surface option in Abaqus, where the quadratic traction criterion is used for damage initiation and the Benzeggagh-Kenane criterion is employed for damage evolution. All relevant material properties used in the FE model are presented in Table 1 and Table 2. The mesh is refined near the impact area with a minimum element size of 0.5 mm. Boundary conditions are applied to simulate the experimental test setup by restricting all nodes resting on the rectangular edge underneath the specimen from vertical translation, in order to represent the opening (125 mm x 75 mm) in the support table. All degrees of freedom of the impactor are constrained except the vertical translation. The initial velocity in the vertical direction before impact is prescribed. The mass of the impactor (3.04 kg) is defined on the reference point located at the center of gravity of the impactor. For all three plate configurations, the identified impact energy levels for LLD, BVID and VID are simulated. A meshed finite element model is shown in Figure 6.

Figure 6. Finite element LVI model

5 Results and discussion

In this section, experimental and numerical results are presented and discussed for the low-velocity impact response on the three different face-sheet configurations. Firstly, the experimental results are presented showing the effect of face-sheet thickness on the impact response parameters, i.e. dent depth, absorbed energy, peak contact force and displacement, along with the failure modes for the identified energy levels i.e. LLD, BVID and VID. Secondly, results from the FE simulations is presented and discussed, where the impact response and delamination extent is compared with the corresponding experimental results.

5.1 Experimental results

The detailed parameters obtained from the impact test results are presented in Table 4 and the effect of different parameters are discussed separately in the following sections.

Table 4 Low velocity impact test results

Plate configuration/ Identified energy levels	Impact energy [J]	Impact velocity [m/s]	Dent depth [mm]	Peak load [kN]	Max deflection [mm]	Absorbed energy [J]
C1(1.6/9/1.6)						
LLD	4.10 ± 0.1	1.64 ± 0.02	0.17 ± 0.04	3.67 ± 0.04	2.33 ± 0.13	1.52 ± 0.07
	5.16 ± 0.2	1.84 ± 0.04	0.23 ± 0.02	4.32 ± 0.11	2.61 ± 0.01	2.00 ± 0.45
BVID	6.90 ± 0.2	2.13 ± 0.03	0.31 ± 0.05	4.54 ± 0.28	2.96 ± 0.48	2.97 ± 0.47
	8.07 ± 0.2	2.30 ± 0.03	0.45 ± 0.06	5.01 ± 0.42	3.10 ± 0.15	3.99 ± 1.20
VID	9.00 ± 0.3	2.42 ± 0.04	0.54 ± 0.06	4.85 ± 0.23	3.25 ± 0.31	4.76 ± 0.77
C2(2.4/9/2.4)						
LLD	5.31 ± 0.1	1.87 ± 0.02	0.14 ± 0.02	4.65 ± 0.56	2.33 ± 0.11	1.91 ± 0.18
	8.32 ± 0.3	2.34 ± 0.04	0.22 ± 0.05	-	-	-
BVID	11.1 ± 0.4	2.70 ± 0.03	0.28 ± 0.04	6.96 ± 0.11	3.29 ± 0.21	3.71 ± 0.22
	13.0 ± 0.3	2.92 ± 0.04	0.43 ± 0.04	-	-	-
VID	14.2 ± 0.2	3.06 ± 0.03	0.55 ± 0.03	7.22 ± 0.60	3.79 ± 0.14	7.75 ± 0.57
C3(3.1/9/3.1)						
LLD	8.17 ± 0.5	2.32 ± 0.07	0.17 ± 0.04	6.27 ± 0.05	2.49 ± 0.05	2.76 ± 0.44
	13.2 ± 0.4	2.95 ± 0.04	0.22 ± 0.04	7.80 ± 0.09	3.29 ± 0.11	4.31 ± 0.14
BVID	18.1 ± 0.5	3.43 ± 0.05	0.27 ± 0.05	9.40 ± 0.28	3.70 ± 0.07	6.59 ± 1.11
	21.0 ± 0.3	3.72 ± 0.03	0.36 ± 0.07	10.3 ± 0.35	4.03 ± 0.11	8.20 ± 1.67
VID	23.0 ± 0.9	3.89 ± 0.08	0.63 ± 0.06	9.71 ± 0.36	4.28 ± 0.23	12.8 ± 0.80

5.1.1 Dent depth versus impact energy

Figure 7 shows the dent depth versus impact energy for all three plate configurations where the identified LLD, BVID and VID energy levels are highlighted based on the definitions presented above. Apart from the identified energy levels, a bilinear relationship between the dent depths and the impact energy is also noted, consistent for every face-sheet thickness as indicated by dotted lines in Figure 7.

Figure 7. Impact energy vs. dent depth

For all three plate configurations, the knee of bilinear lines is present close to the BVID energy level i.e. corresponding to a dent depth of 0.3 mm. It thus appears that the BVID energy level, at least for the studied material configuration, also works as an indicator for the onset of more excessive damage. At higher energy levels the dent depth will increase more with increasing impact energy. It should be noted that the energy levels needed to create the same dent depth vary substantially between the three different plate configurations, as it depends on the face-sheet thickness.

5.1.2 Contact force versus impact energy

The force vs. time impact response for the studied impact events, i.e. all configurations and energy levels, are plotted in Figure 8. Only one curve per energy level is shown. It can be seen that the response is nearly elastic for LLD and BVID energy levels, whereas significant damage is observed for the VID case, seen as a sharp load drop near the peak contact force. It can also be seen that the duration of the impact decreases with increasing face-sheet thickness for all three plate configurations. That is most likely due to the higher bending stiffness of the specimens with thicker face-sheets. There is also a vague hump visible at the initial phase of the impact events which is believed to coincide with the onset of core crushing. It looks more pronounced for the LLD energy levels but that is likely a flick of the eye since the relative magnitude of the force decay is higher at the lower impact energy levels.

Figure 8. Force vs. time impact response for the identified energy levels

Figure 9. Peak contact load vs. impact energy

How the peak contact load varies with the impact energy is plotted in Figure 9. The maximum peak load increases virtually linearly with the impact energy up to the BVID level and then appears to level out. This is believed to be due to excessive fiber damage in the face-sheet once the BVID energy has been exceeded, which will be discussed more in a later section. The trend is consistent for all three plate configurations although the asymptotic peak load level increases with the face-sheet thickness. Obviously the thicker face-sheets provide higher impact resistance than the thinner ones.

5.1.3 Plate deflection versus impact energy

Force vs. displacement impact responses are shown in Figure 10, where the displacement results are obtained directly from the optical laser measuring device. The laser beam is able to measure the position of the impactor during the whole impact event and the plots thus show both the loading and unloading during impact. Again core crushing is visible as slight humps near the start of the loading curves.

Figure 11 shows the peak displacement of the impacted specimen as a function of the impact energy. The peak displacement for the three impact levels increases with the face-sheet thickness. For each plate configuration, the peak displacement appears to increase linearly with the impact energy.

Figure 10. Force vs. displacement response for the different face-sheet thicknesses and energy levels

Figure 11. Peak displacement vs. impact energy

5.1.4 Effect of face-sheet thickness on the absorbed energy

The area under the force vs. displacement curve represents the energy being transferred to (on-loading) and from (off-loading) the specimen during the impact event. Some of this energy is absorbed as various extents of fiber breakage, matrix damage, delamination and core crushing in case of sandwich specimen. The impact energy vs. time is shown in Figure 12, for all three plate configurations and one curve per energy level. It is believed that relatively little energy dissipates during impact due to the design of the DWR; the impactor is not in contact with anything else than the specimen during the impact event and although some slippage may occur between the specimen and the substrate plate and grippers, it is likely not associated with significant energy dissipation. The finally absorbed energy should then be relatively well represented by the (asymptotic) level at the end of the respective energy vs. time curve. It increases with the face-sheet thickness and impact energy levels, i.e. with the severity of the impact damage, signifying that more energy is absorbed when more failure mechanisms are activated. Although the force vs. time responses for the BVID specimens in Figure 8 do not show significant load drops, considerably more energy is absorbed by these specimens than for the LLD specimens, shown in Figure 12. That might indicate that the BVID energy level triggers more failure modes than the LLD level. In addition, the energy absorption increases with increasing face-sheet thickness and is highest for the VID energy level and the C3 specimens. This is again related to much more energy being needed to achieve VID for specimens with thick face-sheets.

The peak absorbed energy as function of impact energy is plotted for all specimens in Figure 13. In all three plate configurations, the absorbed energy shows a bilinear trend, similarly to what was observed for the dent depth (see Figure 7). It appears that more severe damage, associated with more absorbed energy, occurs beyond a certain impact energy. This shift seems to happen at about the BVID level for all configurations in the study.

Figure 12. Energy vs. time impact response for the identified energy levels

Figure 13. Absorbed energy vs. impact energy

5.1.5 Effect of face-sheet bending stiffness

Rather than studying how the LLD, BVID and VID energy levels vary with the face-sheet thickness, the face-sheet bending stiffness appears to be a more relevant measure. In Figure 14 the impact energy for the different damage levels is plotted versus the bending stiffness. The face-sheet bending stiffness per unit width for the three different face-sheet thicknesses is calculated from

$$D_f = \frac{E_f t_f^3}{12} \quad (9)$$

where E_f is the face-sheet elastic modulus and t_f is the face-sheet thickness. The impact energy required for LLD, BVID and VID vary virtually linearly with the face-sheet bending stiffness. It is interesting to note that if D_f would approach zero, all three curves would fall (through extrapolation) to different non-zero impact energy values. This “residual” energy is attributed to the energy being absorbed by the core material, which increases with the damage levels since they are associated with different dent depths.

Figure 14. Relations between the face-sheet bending stiffness and the impact energy for LLD, BVID and VID energy levels

5.2 Damage characterisation

Damage extent both in terms of the in-plane damage size from TTU and PE inspections are presented in Table 5. TTU images for the BVID energy level are shown in Figure 15, where the damage extent is highlighted in red.

Table 5. Damage extent from TTU and PE inspection

Plate Configuration	TTU extent			PE extent		
	Length [mm]	Width [mm]	Area [mm ²]	Length [mm]	Width [mm]	Area [mm ²]
C1(1.6/9/1.6)						
LLD	22±1.0	21±2.6	324±29	21±2.1	19±2.1	303±53
BVID	26±1.5	24±1.8	524±93	22±2.2	22±4.3	382±75
VID	27±1.3	27±2.9	571±53	24±3.4	23±3.1	437±106
C2(2.4/9/2.4)						
LLD	26±0.5	27±1.3	420±43	27±1.0	27±2.2	303±54
BVID	34±1.3	35±0.5	755±52	34±3.6	35±3.1	667±124
VID	33±1.5	34±2.4	777±50	33±1.0	34±1.7	603±124
C3(3.1/9/3.1)						
LLD	22±0.8	21±1.7	458±51	20±1.0	19±2.8	572±31
BVID	30±1.4	30±2.2	949±29	29±3.4	27±2.8	920±184
VID	31±1.0	29±0.5	856±67	31±2.2	27±3.8	868±49

Regardless of the damage size, the total damage extent for all three plate configurations is quite circular in shape. The damage size from both the TTU and PE inspections are plotted in Figure 16, for the three identified impact energy levels. The damaged area measured by TTU is larger than those from PE for the C1 configuration while the two methods show more similar damage areas for the C2 and C3 configurations. In fact, for the thickest configuration (C3) the TTU results overlay the PE results except for the LLD level, which is slightly off. As mentioned earlier the TTU inspection only captures the maximum extent of the damage, including both core and face-sheet damage, whereas PE inspection only captures the damage

extent in the face-sheet. Thus if the area measured by TTU exceeds that from PE there is wider damage in the core material than in the face-sheets. That is primarily the case when the impacted face-sheet is thin. More of the energy is then transferred to the core material and dissipates in the form of core crushing and face-sheet-core de-bonding. For the cases with thicker face-sheets the damage becomes more confined in the face-sheets with more energy dissipation in the form of delaminations between the plies that grow and overshadow the core damage.

Figure 15. C-scan view from TTU inspection after impact at BVID energy level (total damage extent is shown in red)

Figure 16. Damage extent area from NDT inspection for the identified energy levels

The damage area increases between the LLD and BVID levels but seems to level out without much further growth between the BVID and VID levels. As mentioned in previous sections other significant transitions in the impact response are observed and approximately coinciding with the BVID level, for example shifts in dent depth and absorbed energy.

Optical microscopy images of LLD, BVID and VID samples for all three plate configurations are shown in Figure 17, where the samples are cut along the 0° ply orientation, i.e. section A-A in Figure 5. Only half of the sectioned image from the point of impact is shown. It can be seen that the main failure mechanism for LLD specimens is delamination, where the number of delaminations increases with the face-sheet thickness. For BVID specimens, the main failure mechanism is delamination with multiple transverse shear cracks. Some core crushing and face-core de-bonding can also be seen for configurations C2 and C3. This is again because it takes more energy to create the same dent depth in the thicker samples. That will in turn lead to more energy dissipation through core crushing and face-core de-bonding, resulting in a wider damage area, as seen in Figure 16. A relatively wide delamination crack is seen for the

C2 sample with BVID (Figure 17) but it is believed to be due to natural variation in the crack patterns and flex-back mechanisms after impact.

Figure 17. Microscopy images of LLD, BVID and VID impact damages (half of section A-A in Figure 5). 1: Transverse shear crack, 2: delamination, 3: fiber breakage, 4: core damage, 5: Face-core de-bonding

For VID, several types of damage are observed. In addition to delamination and transverse shear cracks, significant fiber breakage and core crushing can be seen. The damage extent doesn't grow much in-plane but the number of delamination increases through the thickness, indicating a shift of cracks extending primarily planar to more in-depth. That is likely related to the leveling out of the delamination extent observed for VID in Figure 16. The sudden shift in dent depth and absorbed energy in Figure 7 and Figure 13 are also likely due to more extensive fiber fracture causing greater indentation for relatively lower increase in impact energy. The peak contact force (Figure 9) then also levels out after BVID. The excessive fiber breakage is also visible in the load vs. time response (Figure 8) and the energy absorption curves (Figure 13).

A thorough investigation is performed in order to study the delamination growth and pattern through the thickness. For this purpose di-sectioning is performed in various directions with respect to the face-sheet ply orientations i.e. in the 0° , 45° , 90° and -45° directions, as illustrated in Figure 5. 3D illustrations of microscopy images from sections S1 and S2 are presented in Figure 18 for the VID energy level of the C3 configuration. It can be seen that delaminations predominately grow parallel with the fiber orientation in each respective ply. One delamination crack is highlighted in red for each of the S1 and S2 cases in Figure 18. Fiber breakage is also visible underneath the impact but further out there are virtually only delaminations. The same trend is seen for all three plate configurations, irrespective of their face-sheet thickness and the impact energy.

Results from the XMT investigation of C3 configuration with VID is presented in Figure 19a, where the impacted face-sheet can be seen with delaminations highlighted in red. The delaminations were extracted separately using a Matlab subroutine and a 3D image post-processing software (ORS). The extracted delamination pattern is exported to Matlab as a 3D mesh for further post-processing, in order to enable better illustration of the through thickness variation between different plies, by using a discrete color map, as shown in Figure 19b. Due to the local indentation the delamination cracks are not flat, i.e. not fully aligned with the XY plane. It can be seen in Figure 19b that the delamination cracks are reasonably symmetric around the impact location and primarily extend along the local fiber orientation. The delamination pattern through the thickness, thus resembles a counter clockwise spiral which is better visualized in the animation provided in appendix A.

Figure 18. Illustration of optical microscopy image in 3D – VID energy level of C3(3.1/9/3.1) specimen

Figure 19. (a) X-ray micro-tomography cross-section image of an impacted C3 specimen (delaminations highlighted in red), (b) Delamination pattern showing the extent of delaminations in different ply interfaces, highlighted with different colors.

5.3 Numerical results

The results from the numerical simulations are here presented and compared to the experimental results, for all three plate configurations. Finite element simulations are carried out to simulate the impact response and damage extent. The impact response is compared in terms of force vs. time and force vs. displacement plots, whereas the delamination extent is compared in terms of total delamination area.

5.3.1 Impact response

The numerical impact analysis is performed for the three different impact energy levels, i.e. LLD, BVID and VID, for all three plate configurations. The respective impact energy is achieved by varying the velocity of the impactor in the numerical analysis, corresponding to the impact velocities used in the experiments (Table 4). Figure 20 shows a comparison between the numerical and experimental force vs. time impact response. In general the numerical impact response is in good agreement with the experiments, especially for the peak contact load and time. The model also shows core crushing in good agreement with the experiments. For lower impact energy levels i.e. LLD and BVID, the impact response is elastic both in the simulations and the experiments, whereas for the VID energy level damage is initiated at peak contact load, again in good agreement, and the numerical model also captures the subsequent load drop relatively well.

Figure 20. Comparison of experimental and numerical force vs. time response for the different configurations and impact energy levels

Figure 21 shows a comparison between the numerical and experimental force vs. displacement responses for the given energy levels. In general there is good agreement, especially for the maximum deflection at peak contact force. For LLD specimens, the entire loading-unloading cycles agree well. For the BVID and VID cases the responses differ more, especially during unloading and for the configurations with thicker face-sheets.

Figure 21. Comparison of experimental and simulated force vs. displacement response for the different configurations and energy levels

Figure 22 shows the absorbed energy from simulations and experiments, for the different specimen configurations and energy levels. The absorbed energy mainly comes from creation of fracture surface due to intra-laminar and inter-laminar damage. In general there is good agreement between the experimental and numerical results with exception for the specimens with thick face-sheets at BVID energy levels. For BVID the simulations predict significantly higher absorbed energy compared to the experiments. That is also evident in the force vs. displacement response, during unloading (Figure 21), where more damage is predicted in the BVID simulations than seen in the experiments, leading to higher energy absorption. It can further be noted that for cases where the simulations show lower load-drop after the peak load than seen in the experiments, the remaining unloading is also more rapid than in the experiments, and vice versa. One could possibly improve the accuracy in the simulations by incorporating more advanced 3D damage growth laws, using physically based criteria.

Figure 22. Simulated and experimental absorbed energy for the different configurations and energy levels

5.3.2 Inter-laminar damage

In addition to the impact response, the inter-laminar damage extent, i.e. delaminations, is also modeled and compared with the experimental results. Figure 23 shows the total delamination area for the different cases. The numerical model predicts the delamination extent quite well and it also captures the shift in the response between the LLD and VID energy levels. In other words the apparent asymptotic damage extent levels at higher impact energies are also found in the simulations.

Figure 23. Delamination extent from simulations and experiments, for the different configurations and energy levels

6 Conclusions

The identified energy levels corresponding to BVID, i.e. 0.3 mm remaining indentation, appear to coincide relatively well with onset of more excessive damage, consistently for all three face-sheet thicknesses in the study. The peak impact force also levels out when the impact energy is increased from BVID to VID levels, again for all three configurations. That is associated with a shift in damage mechanisms, shown both by fractography after experiments and by numerical simulations.

The fractographic investigation revealed that energy is absorbed in the form of multiple delaminations, transverse cracks, fiber damage and core crushing. Where the two later failure mechanisms are more pronounced for the higher (VID) impact energy levels. The delamination extent increases in size fairly linearly between the LLD and BVID energy levels

but arrests at higher energy levels, at which damage starts to grow more in the thickness direction of the face-sheets and cause more fiber breakage and multiple delaminations rather than wider ones. Both destructive (fractography) and NDT (X-ray micro-tomography) inspections show that the delaminations primarily grow along the fiber direction resulting in a spiral pattern, coinciding with the ply stacking sequence through the thickness.

A finite element model including progressive damage mechanisms is used to compute the impact response and resulting damage extent for different configurations. The numerical model predicts the impact response well and provides reasonably good representations of several damage mechanisms, e.g. core crushing and fiber damage at peak contact load. The extent of delaminations and failure mode shifts for the different configurations are also well captured by the numerical simulations. Therefore it is concluded that numerical models can be used for parametric studies and could possibly be further extended to simulate the post impact residual strength for damage tolerance assessment.

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8 Appendix A. Delamination pattern animation

An animation file for the delamination pattern through thickness can be viewed online from journal website.

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