DEFORMATION AND FAILURE OF MULTI-LAYERED FIBRE-METAL-LAMINATES SUBJECTED TO HIGHLY-DYNAMIC LOADINGS CONDITIONS

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Abstract

The impact behaviour of fibre-metal-laminates (FMLs), consisting of metal sheets and fibre reinforced composites (FRCs) layers are studied experimentally and numerically in this paper. Two thermoplastic based FMLs have been investigated: an AlMg3-PA6CF60-FML and an AZ31B-PA6CF60-FML. The reference test set-up is a Charpy drop weight experiment with varying parameters like lay-up, drop height and support distance. To achieve sufficient adhesion between the metal and the FRC, a modified thermoplastic Nolax Cox 391 foil is used.
An increasing number layers of metal and FRC results in growing impact energy absorption due to the combination of delamination, crack stopping at interfaces, fibre failure and plastic deformation of the metal. For rising support distances the influence of bending increases, so thick ductile metal cover sheets absorb the energy through plastic deformation.
In an accompanying simulation with the finite element method (FEM) in LS-DYNA, a Johnson-Cook material model was used for the metal components and the Chang-Chang failure criterion for the FRCs. Between the metal and FRC parts cohesive elements were used. Good concordant results between experiment and simulation were achieved for maximum forces and deflections. Another constitutive model which enables capturing the plastic behaviour of the thermoplastic matrix is also compared.

1. Introduction

FMLs consist of thin layers of metal which are stacked with FRC layers in an alternating sequence. The aim is to bring the advantages of each component together. FMLs have low masses, high stiffnesses and strengths, gentle introduction of forces in thickness direction through the metal, as well as better fatigue strength, corrosion resistance and especially a high energy absorption capability [1],[2]. Especially latter property gives a great advantages for applications where impact and crash situations are critical with respect to personal injuries and cost-intensive structure damages. Consequently, metal parts are increasingly replaced by FML components in the aerospace sector. Well-known brand names are Arall, Carall or Glare which consists of aluminum alloy sheet stacked with aramid, carbon or glass fibre reinforced composite layers [1], which are already used in applications like the Airbus A380 [3].

The investigation of the interlaminar properties of FMLs as well as suitable interlaminar modelling approaches with FEM are crucial because the interfaces characerise the failure behaviour (delamination) in a great extent. To achieve good adhesion between the metal and the FRC layers,

there are several methods like surface treatment, a modification of the FRC matrix or the addition of adhesion promoters [3].
The FEM enables a structural analysis with complex loading scenarios without cost intensive prototyping and experiments. Hence, suitable material models and meshing methods have to be investigated to describe the deformation and failure of the FRC layers, metal sheets and especially the interfaces of FMLs. The state of the art is to simulate each component with its own material model to implement the failure criteria of the FRC and plastic deformation characteristics of the metal [4]-[6]. The usage of cohesive elements or contact definitions between the layers is usual to describe the delamination behaviour [7]. For impact loading conditions, the strain rate and temperature dependencies have to be considered.

In the presented study the impact behaviour of various FML configurations are compared to each other and the FRC without proportion of metal by means of a 3-point bending impact test. Moreover, the influence of loading conditions like support distance and impact velocity is studied. Accompanying the experiments, a numerical analysis are performed to simulate the given impact cases with solid elements for each layer and cohesive elements in between.

2. Materials and experimental investigation

Two quadratic metal alloy sheets with an edge length of 295 mm were used for the FMLs, an aluminium (AlMg3) and a magnesium alloy (AZ31B). The thicknesses vary from 0.5 mm to 1 mm for AlMg3 respectively 0.6 mm and 1.2 mm for AZ31B. As FRC material, a carbon fibre reinforced Polyamide 6 was used (Celstran® CFR-TP PA6 CF60-01). This is a unidirectional tape with a fibre volume fraction of 60 %, a nominal area weight of 194 g/m² and a nominal cure ply thickness of 0.13 mm, supplied by Celanese. A modified thermoplastic foil (Nolax Cox 391) was put between the FRC layers and the metal sheets to achieve good adhesion. After the FRC tapes and adhesion foils were cut into the same dimensions as the metal sheets, all components were stacked in a defined sequence (four different FML lay-ups, Table 1) and consolidated in a vacuum assisted press to produce hybrid plates.
Therefore, a temperature of 250°C, a pressure of 5 bar and a press time of 20 min was used to consolidate the FML plates. An additional plate with 28 layers of PA6CF60 was produced in order to compare the structural response to FML specimens. The specimens were separated from the plates by water jet cutting, manually ground and conditioned in standard climate conditions for at least 24 h.

Table 1. Symmetric lay-ups of the pressed plates

1	[0.5 mm **AlMg3** resp. 0.6 mm **AZ31B**/2x 0.13 mm **PA6CF60**]$_{2S}$
2	[0.5 mm **AlMg3** resp. 0.6 mm **AZ31B**/2x 0.13 mm **PA6CF60**]$_{4S}$
3	[1 mm **AlMg3** resp. 1.2 mm **AZ31B**/4x 0.13 mm **PA6CF60**]$_{2S}$
4	[1 mm **AlMg3** resp. 1.2 mm **AZ31B**/4x 0.13 mm **PA6CF60**]$_{S}$
5	[28x 0.13 mm **PA6CF60**]
	0.1 mm **Nolax Cox 391** between each metal-PA6CF60-interface

A drop weight tower with Charpy wedge impactor geometry and supports, according to DIN EN ISO 13802, was used (Figure 1). Two different support distances (24 mm and 60 mm) and drop heights (400 mm and 1000 mm) were chosen for the tests to investigate the ratio of shearing and bending as well as the strain rate dependency. According to the drop heights the impact velocities of around 2.80 m/s respectively 4.43 m/s result. The specimens have a width of 15 ± 0.3 mm. The lengths vary with the support distances and the thicknesses with the lay-ups. The experimental programme is shown in Table 2.

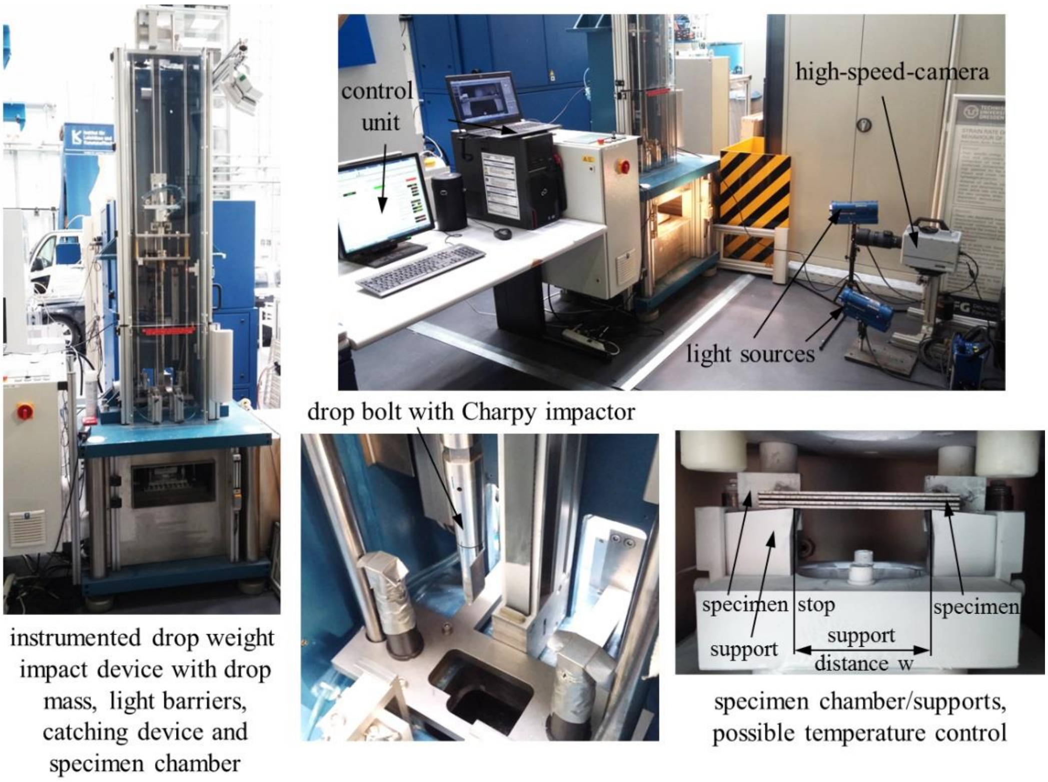


Figure 1. Drop weight impact test rig

Table 2. Experimental programme

Material	Lay-up	h_D in mm/ m_D in kg	d in mm	l in mm	h in mm (AlMg3/AZ31B)	nr. per hybrid material
AlMg3-PA6CF60-FML and AZ31B-PA6CF60-FML	1	400/10	24	54	3.58/3.95 ± 0.06	5
			60	90	3.52/3.90 ± 0.06	5
		1000/10	24	54	3.70/4.04 ± 0.04	6
			60	90	3.60/4.00 ± 0.06	5
	2	400/20	60	90	7.25/7.95 ± 0.05	7
		1000/20			7.35/8.08 ± 0.06	7
	3	400/20	60	90	6.56/7.32 ± 0.09	7
		1000/20			6.64/7.38 ± 0.07	7
	4	400/10	24	54	3.22/3.61 ± 0.04	5
			60	90	3.18/3.58 ± 0.04	5
		1000/10	24	54	3.29/3.66 ± 0.03	6
			60	90	3.25/3.65 ± 0.05	5
					Total	70 x2
PA6CF60	5	400/10	24	54	3,66 ± 0.06	5
			60	90	3,65 ± 0.02	5
		1000/10	24	54	3,74 ± 0.02	6
			60	90	3,69 ± 0.03	5
					Total	21

h_D: drop height, m_D: drop mass, d: support distance, l: nominal specimen length,
h: specimen thickness, n: number of specimens

3. Numerical investigations

The Charpy impact on the AlMg3-PA6CF60-FML specimens is simulated using explicit FE solver LS-DYNA because of the highly nonlinear deformation and failure. Every single layer of the specimens is meshed with solid hexahedral elements to consider stress conditions in thickness direction and for better mesh connections. To avoid instabilities and reduce calculation time solid elements with one point integrations are used (ELFORM 1). For the metal sheets, the deformation and failure model of Johnson and Cook is used, which is implemented as MAT_015_JOHNSON_COOK. This model considers plastic hardening, strain rate and temperature dependency as well as multiaxial stress conditions [8]. The following equations (1, 2) show the fundamental stress and strain behaviour with von Mises stress σ_{eq}, hydrostatic stress σ_m, effective plastic strain ε_p, failure strain ε_f, reference strain rate $\dot{\varepsilon_0}$ and temperature T. The values for deformation parameters A, B, n, C, m and failure parameters D_1, D_2, D_3, D_4, D_5 were applied from [9],[10] for AlMg3.

Deformation: $$\sigma_{eq} = (A + B \cdot \varepsilon_p^n) \cdot \left(1 + C \cdot ln\frac{\dot{\varepsilon_p}}{\dot{\varepsilon_0}}\right) \cdot \left(1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right) \quad (1)$$

Failure: $$\varepsilon^f = \left(D_1 + D_2 \cdot \exp\left(D_3 \cdot \frac{\sigma_m}{\sigma_{eq}}\right)\right) \cdot \left(1 + D_4 \cdot \ln\frac{\dot{\varepsilon_p}}{\dot{\varepsilon_0}}\right) \cdot \left(1 + D_5 \cdot \frac{T - T_{room}}{T_{melt} - T_{room}}\right) \quad (2)$$

For the FRC layers, the material model MAT_054_ENHANCED_COMPOSITE_DAMAGE is used. It relies on the well known stress based Chang-Chang failure criterion for the prediction of the onset of damage [11],[12]. This considers different failure modes like fibre and matrix tensile or compression failure, as well as their interactions. Furthermore, it includes definable failure strains, damages, minimum time steps and strain rate dependent strengths.

In addition, one experimental configuration was modelled using a plasticity based constitutive model, which was developed for multi-layered flat-bed weft-knitted fabrics [13]. The constitutive model homogenises the behaviour of fibre and matrix to simulate the composite. The matrix is represented by a strain rate dependent isotropic elastoplastic constitutive model based on the approach proposed by Goldberg [14], while a 1D transversally isotropic model is used for representing the carbon fibres. A damage mechanics approach is used to model fracture. The constitutive model (MAT_COMPACT) was implemented as user defined material model into LS-DYNA.

The layers of adhesion promoter between the metal and the FRC are modelled with cohesive elements. No cohesive elements are attached between the FRC plies because there was not any delamination but between the metal sheets and the composite plies. MAT_138_COHESIVE_MIXED_MODE distinguishes between normal (Mode 1) and shear loading conditions (Mode 2) which are superimposed to a resulting load and strength characteristic in the mixed mode [7],[15]. This allows the simulation of the delamination behaviour of specimens. The main parameters to describe material model are the strengths and energy release rates for each mode respectively direction, which were determined through preliminary experimental tests (DCB, ELS, MMB, tensile and interlaminar shear) and numerical calibration of the *F*-*s*-curves. The critical energy release rate is 1.0 kJ/m² for Mode 1 and 2.4 kJ/m² for Mode 2 respectively. The through thickness tensile strength is 12.3 and the interlaminar shear strength 45.0 MPa .

Additional one-way contact definitions between all layers prevent their penetration after cohesive element failure. Impactor and supports are modelled as thin shell elements and rigid material to reduce the calculating time. The defined impactor mass and velocity are the same as in the experiments with 10 kg and 4.43 m/s. Figure 2 shows the FEM-model for the drop weight impact test and an FML specimen with lay-up 1 and a support distance of 24 mm.

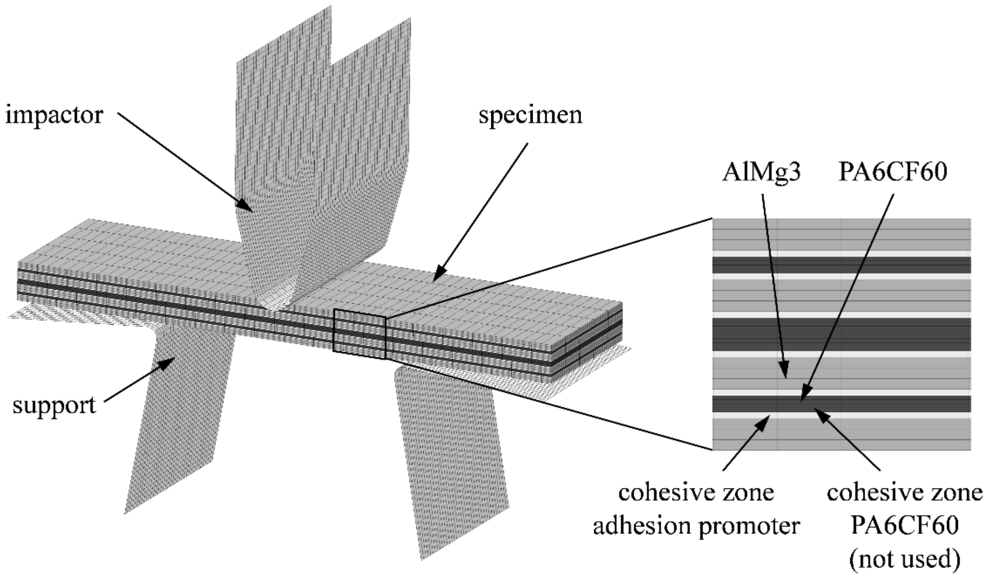


Figure 2. FEM-model of the drop weight impact test for lay-up 1

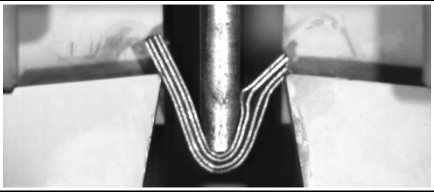
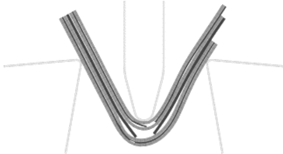
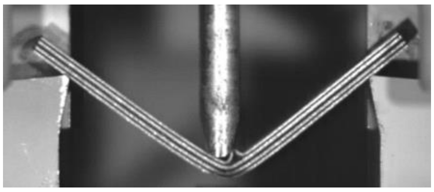
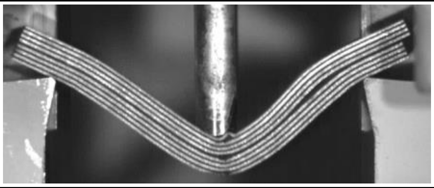
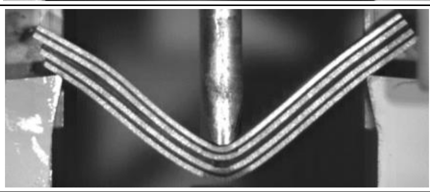
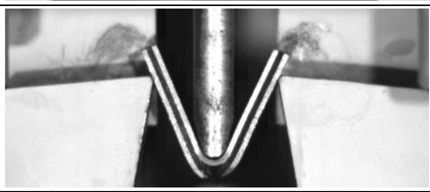
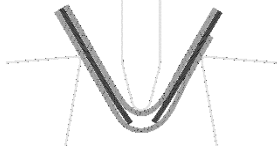
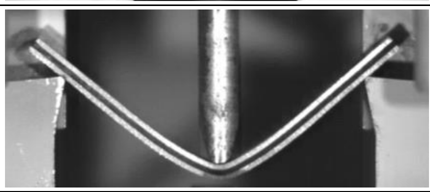
4. Results and discussion

4.1. Failure behaviour of the AlMg3-PA6CF60-FML specimens in experiment and simulation

Table 3 compares high-speed-camera images for the AlMg3-PA6CF60-FML specimens from the experiments to the simulation results. For the lay-ups with a high shear stress influence, the first delamination is initiated in the mid-plane of the specimens between the metal and the FRC by maximum shear stresses. The upper delaminated plies bulge which is caused by bending compressive stresses. There is no delamination between the FRC interfaces because of the higher interlaminar properties in contrast to the metal-FRC-interface. That is why no shear induced delaminations are observable for lay-up 4 (no metal-FRC-interfaces in the middle of the specimens and low bending stiffness because of metal cover sheets). Only some delaminations induced by peeling stresses occur at the bottom of the specimens. Lay-up 1 with a support distance of 60 mm does also not show any delamination behaviour because of the dominating bending compressive and tension failure.

For lay-up 2 and 3 the higher specimen thicknesses increase the influence of shear in contrast to bending stresses and deflections despite a support distance of 60 mm. Thus, the first main damages are delaminations, again. In addition to the delaminations, a compressive failure of the FRC can be detected at the upper plies of the specimens. At least the specimens fail with a tensile failure of the lower FRC plies and slight cracks or failure of the metal layers.
The AlMg3-PA6CF60-FMLs behave more ductile than AZ31B-PA6CF60-FMLs, have higher elongations at break and more remaining in-plane load bearing capability without brittle fracture behaviour. Less metal layers are failed after impact.

Table 3. Impact failure behaviour comparison of the AlMg3-PA6CF60-FMLs in experiment and simulation, drop height 1000 mm

Lay-up/ support distance	Experiment	Simulation
1/ 24 mm		
1/ 60 mm		 MAT_054  MAT_COMPACT
2/ 60 mm		No sufficient numerical stability, aborted calculation due to negative volumes in elements
3/ 60 mm		
4/ 24 mm		
4/ 60 mm		

The simulation results do not show a failure of the lower metal sheet unlike experimental investigations. The failure mode predicted by MAT_COMPACT does not match the experiment. The simulation showed large scale delamination, which were not present in the experiments. This indicates an underprediction of damage in the composite, which in turn results in large scale delamination failure. Better results for the plastic deformation and failure behaviour of the metal sheets can be achieved with additional tests of the used alloy and a numerical calibration of the parameters in the Johnson-Cook-model.

4.2. *F-s*-curves of impacted FML specimens in experiment and simulation

Figure 3 compares the *F-s*-curves from the experiment and the simulation for AlMg3-PA6CF60-FMLs with lay-up 1 and 4 at a drop height of 1000 mm. The *F-s*-curves of specimens which were tested with a lower drop height do not show a significant difference but a lower maximum force and deflection. For MAT_054, the simulated *F-s*-curves show a good correspondence to the experiments, especially in maximum force and deflection. Better results were achieved for the support distance of 60 mm than for 24 mm because of less delamination initiation which influences the deformation behaviour of adjacent elements.

The overall shape of the *F-s* curve predicted by MAT_COMPACT also matches the experiment while the force levels seem too low. The reason for this, as discussed already above, is the presence of large scale delaminations, which were not present in the experiments.

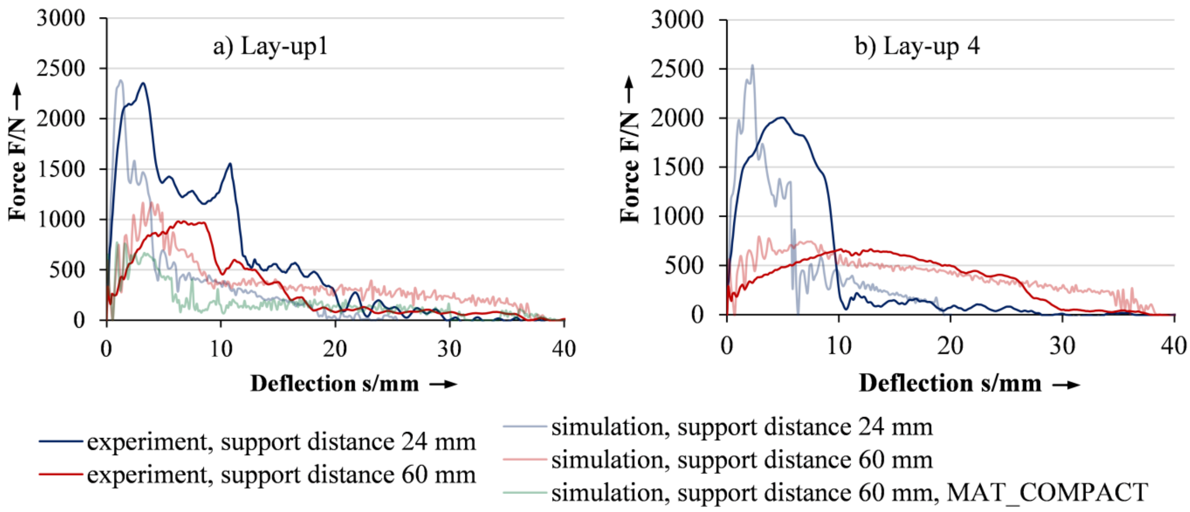


Figure 3. Comparison of *F-s*-curves of the AlMg3-PA6CF60-FMLs in experiment and simulation for lay-up 1 (a) and 4 (b), drop height 1000 mm

5. Conclusions

The impact behaviour of FML specimens were studied using Charpy drop weight tests. The influence of parameters like lay-up, metal component, support distance and impact velocity by means of *F-s*-curves and high-speed-camera records on the deformation and failure behaviour was investigated. The common occurrence of different failure mechanisms like fibre failure, cracks in the matrix or the metal, crack stopping at interfaces as well as plastic deformation favours a more pseudo-ductile response, especially in combination with delaminations. On the one hand, multi-layered FMLs show a gentle deformation and failure behaviour at short support distances. On the other hand, higher influence of plastic deformation by bending stresses due to thicker metal cover sheets favours the failure behaviour at long support distances.

The given impact scenario has been simulated in LS-DYNA under usage of hexahedral elements with material descriptions according to Johnson-Cook for the metal sheets, a Chang-Chang-criterion for the FRC layers and cohesive elements for the metal-FRC-interface. Generally, there is good agreement for maximum forces and deflections between experiments and simulations. One additional approach for the composite layers has been investigated with MAT_COMPACT. This modelling approach using plasticity for the thermoplastic matrix does not seem appropriate for this material. Originally, the material was developed for multi-layered flat-bed weft-knitted fabrics, which have resin rich areas. This is not the case for the FMLs investigated here.

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