# Benchmarks for Composite Delamination Using LS-Dyna 971: Low Velocity Impact

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## Summary:

The increasing interest in the implementation of fiber reinforced materials for primary and secondary structures requires a closer look into the performance of these materials under a wide range of structural loads. This paper deals with the application of the commercial solver LS-DYNA to specific modelling procedures and experiments in graphite/epoxy - composite structures with a representation of interlaminar and intralaminar delamination failure. A set of modelling techniques were discussed based on available material and contact definitions in the current version of the explicit solver. Using different approaches, the predicted and experimental results as well as the time history responses in low velocity impact benchmark-models is briefly addressed. Providing an overview of the achieved efficiency with the presented models is part of the effort of improving the realistic simulation of "mesoscale" models of larger composite structures with acceptable computational costs.

## Keywords:

Composite materials, delamination, tiebreak contact, cohesive material

## 1 Introduction

One central issue in designing new composite structures is the characterisation of their mechanical properties and failure mechanisms. The discussion of impact problems contains a large variety of technical issues, which are for themselves a research topic of their own within the field of composite simulation. The characterisation of low velocity impact behaviour and damage tolerance of composite materials still represents a technical challenge for a realistic simulation of barely visible damage building, and for an accurate prediction of strength reduction and damage growth.

Carbon fiber/epoxy materials inherently exhibit a brittle material behaviour. Failure occurs when the linear elastic response reaches the material strength allowables with little or no plasticity. The technical evaluation of crash energy absorption in metallic, polymeric and composite structures has enjoyed a large development through the past years due to the achieved increment of computational efficiency and power. This study deals with the simulation of carbon/epoxy composites under low velocity impact and with the prediction of barely visual delamination damage using the explicit code LS-Dyna.

Within this study one important challenge was to maintain a balance between mesh qualities and computational cost. A reasonable balance is the basis for the simulation of larger models with an acceptable material degradation and delamination growth.

Technical difficulties in the failure evaluation through delamination are discussed among other issues in [1]. The lack of information about the normal stress in the thickness direction of shell elements may lead the analyst to adjust the material parameters in an ad-hoc manner in order to get an acceptable evaluation of the damage. Considering these known limitations and restrictions, the discussion of the current possibilities of LS-DYNA and the new features of the explicit code offered an incentive for this work in cooperation with the Institute of Aircraft Design at the University of Stuttgart (IFB).

Improvements on the explicit code such as improvements on the contact algorithms and their parallelisation, and newly provided user defined material models promise better efficiency. The intention of this study is to compare simulations with available experimental data. New cohesive formulations were used to capture the delamination damage within the models. The restricted applicability for larger structural models, however, remains to be discussed. For evaluation purposes the IFB provided the experimental results of low velocity impact tests, which include the visualization of the delamination areas using non destructive methods.

## 2 Material Characterisation

The material characterization of composite materials involves a wide range of procedures which are used and needed to describe the features of the composition, preparation and mechanical properties of the fiber/matrix compound. Material characterization in the post failure regime, however, still represents a challenge for standardisation and appropriate testing methods. For the elaboration of the test specimens at the IFB a woven carbon/epoxy combination was used.

Where possible, the results of the conducted material test were implemented in the analysis. The remaining parameters were obtained through trial and error comparisons, numerical calibration and maintaining reasonable values as presented in [2].

### 2.2 Material Definitions in LS-DYNA: MAT_54/55

MAT_54 and MAT_55 or MAT_ENHANCED_COMPOSITE_DAMAGE [3] are only valid for thin shell elements. Both material formulations are similar and describe a progressive failure within the limits of strength, strain and time step size. While MAT_54 uses the Chang-Chang matrix failure criterion, MAT_55 uses the Tsai-Wu matrix failure criterion.

According to [1] failure behaviour within this material model can be adjusted to the experimental results in a rather heuristic manner. The use of this material model provided acceptable results considering the experimental evaluation of material tests and taking further assumptions for all failure relations. In a first approach the delamination failure is captured with the suppression of the integration points through the thickness of the shell elements when matrix failure is reached.

### 2.3 Material Definitions in LS-DYNA: MAT_58

An overview of this material was given in [1], where the difficulty of acquiring the experimental data and parameter identification needed for this material model was also discussed. The basis formulation of MAT_58 or MAT_LAMINATED_COMPOSITE_FABRIC is described in [4]. The material behaviour in this formulation is based on three damage parameters. An overview of the failure surfaces referring to the use of this material formulation is also described in [1]. In addition [5] describes the use of this model for crash applications. Some problems and improvements in the implementation of composite damage mechanics in user defined materials are also reported in [6].

## 3 Modelling Techniques

During the past years the main representation of a composite plate has been discussed in two directions:

- Two dimensional models (conventional shell approach)
- Three dimensional models (conventional solid approach)

Figure 1 shows a conventional modelling approach starting with the detailed description of the stacking sequence through the thickness of the plate for both types of representations.

Fully three dimensional models (see figure 1a) have been commonly used to describe the delamination process in low velocity impacted specimens, because the stress component through the layer thickness is also considered. These models, however, are not suitable for the simulation of structural components. This, however, remains the main target of technical applications with complex geometries and larger dimensions.

New improvements in the explicit code LS-DYNA make it possible to capture interface failure between the sublaminates. An affordable modelling complexity compared to the common three dimensional sublaminate modelling is shown in figure 1b.

Experiences with homogeneous anisotropical modelling (figure 1c) lead to a reasonable performance of solid elements in the low velocity impact simulations. A smeared in-plane anisotropy, through the thickness of the plate, however, influenced the calculated delamination area.

Sublaminates (see figure 2) represent a new approach, which is based on the separation of the stacking sequence in two or more single shell surfaces. Failure within the interfaces can be considered using new contact options such as the ones described in [7] or new additional cohesive element formulations as described in [8] and [9].

The conventional shell approach was the basis for the used models in order to avoid the high computational cost of fully three dimensional models. The decrease of anisotropy caused by the sublaminates and equivalent mechanical properties for groups of layers in the stacking sequence can be used as a countermeasure to avoid long running times.

The following sections describe the use of models with one or multiple single shell surfaces as a first approach to capture delamination failure. In a first phase of abstraction the common modelling approach is presented. This approach describes the composite plate as a single surface of shell elements. The stacking sequence definition is described “through the thickness“ by the material orientation in each integration point.

Taking into account some compromises and restrictions between mesh densities and ply failure mechanisms, the following sections demonstrate also some of the models considering a multiple shell surface approach used for low velocity impact simulations.

## 4 Simulations with LS-DYNA

At first, according to the experimental information in [6] and the published material properties for the UD-layer available in the literature, a set of simulations were conducted. Comparisons were made with the available experimental results reported in [6]. Similar tests were also conducted at the IFB. Comparisons between a two surface approach and experimental data for this configuration were also performed.

### 4.1 Simulation Results, T800/3900-2

Results achieved for MAT_54 using a single shell surface for the laminate with the suppression of integration points after matrix failure are shown in figure 3. The time history response curves for the contact forces (see figure 4) were compared to the experimental data in [6].

### 4.2 Low Velocity Impact Results, woven carbon/epoxy (IFB)

Figure 5 shows a comparison between the experimental set up of a plate under a 20 J impact and the simulation response for the sublaminate formulation with one cohesive zone. For simplification, the simulations describe the impactor and the surrounding boundary conditions of the plate as undeformable material (*MAT_RIGID). The experimental determination of the delaminated areas was performed using ultrasonic non-destructive methods. The separation of the shell surface into two sublaminates with interface failure was based on the MAT_185 formulation and new implementations for the tiebreak contact definitions between the sublaminates.

The cohesive zone according to [8] describes a bilinear model for the traction separation law (see figure 6). Figure 7 shows a comparison between the simulation results for the matrix failure (MAT_54/55) and the experimental results using non-destructive test methods.

Figure 8 shows a comparison between the experimental response of a plate under a 20 J impact and the simulation response for the MAT_54/55 formulation with one tiebreak interface definition between the sublaminates.

## 5 Conclusions

The present models describe the use of alternative modelling techniques for low velocity impact simulations and demonstrate the capability of damage representation through the separation of the laminate properties into sublaminates. Interface damage based on a cohesive material formulation requires, however, an appropriate material validation for the adhesion zone. Though the results made with these plate models were acceptable, the use of just one interface failure definition still required an artificial adjustment of the material parameters. The material response and delamination growth with such models using one or more interfaces offers an alternative for the prediction of delamination in larger structural simulations. Some comparisons with fully three dimensional models and an adequate identification of the relevant material parameters are still needed to further study this kind of modelling in other applications.

The performance of the calculated damage with these interface failure mechanisms remains to be discussed for load cases where the post failure regime has an influence on the structural response (i.e. compression after impact experiments). Mapping the damage of low velocity impact simulations to such a second test procedure could reveal the performance of the different modelling approaches using the output from the history variables for each constitutive law. This topic also remains in the scope for further work using the presented mesoscale modelling for larger structures.

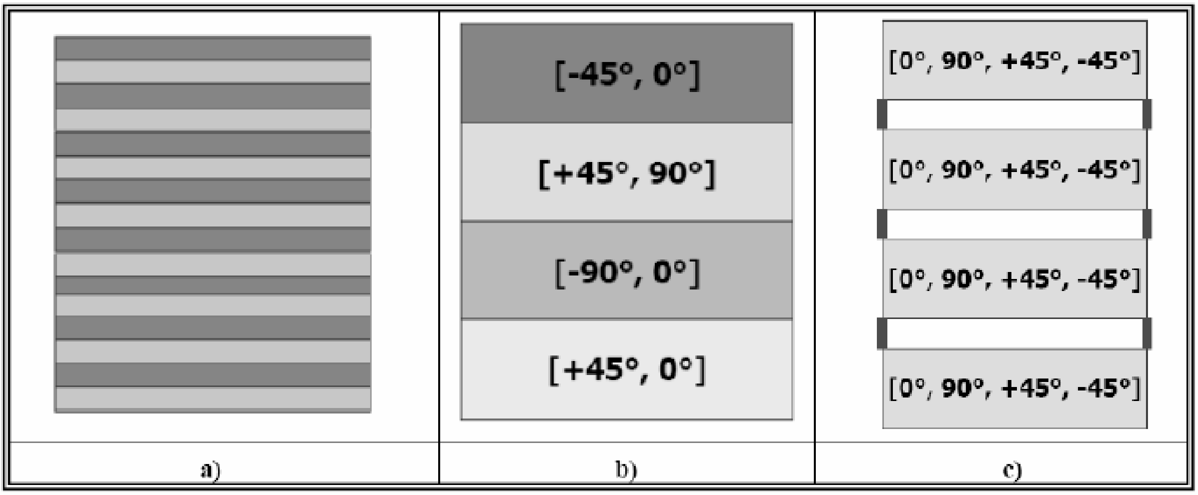


*Fig. 1. Modelling approach for laminated composites: a) Fully three dimensional modelling, b) Sublaminate formulation within the stacking sequence, c) Homogeneous anisotropical definition*

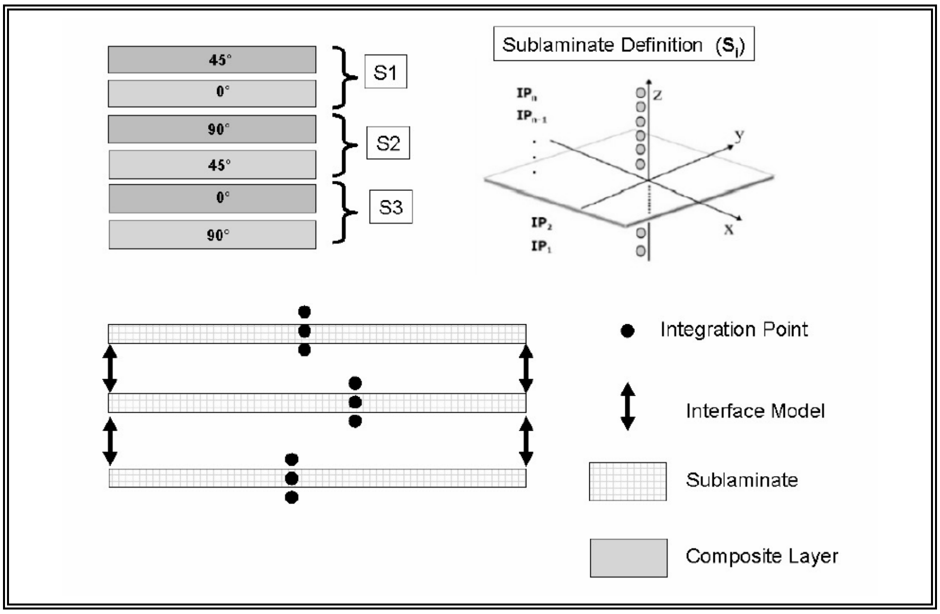


*Fig. 2. Stacking sequence separation with models for interface failure: Models for lamina and interfaces allowing delamination*

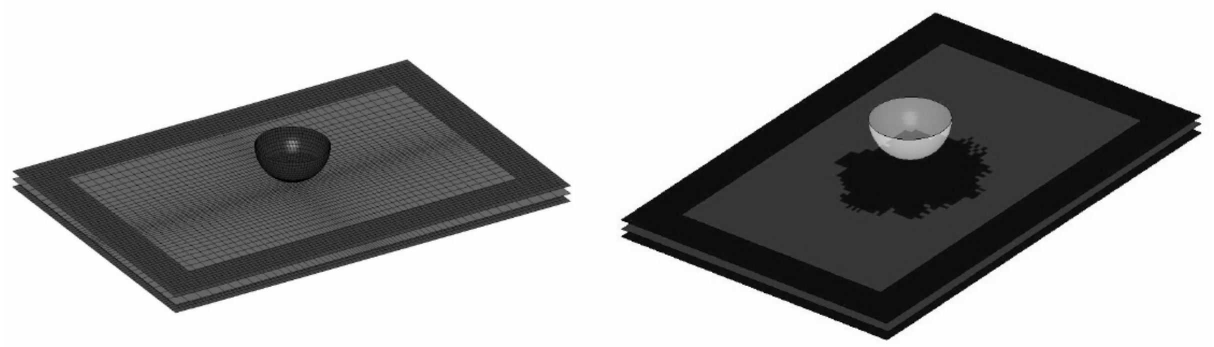


*Fig. 3: Model and delamination results with MAT_54 after numerical calibration (T800H/3900-2, 34,5J with MAT54)*

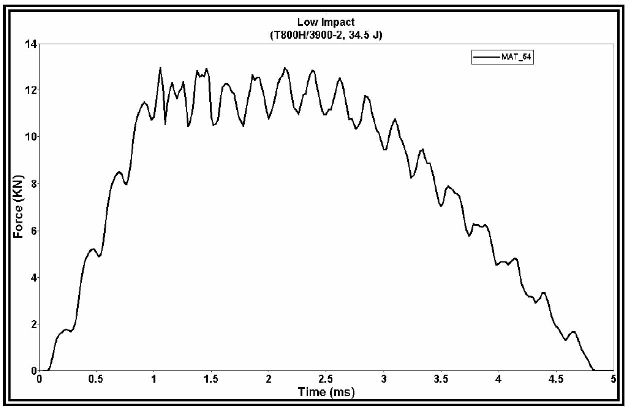


*Fig. 4. Impact force time history, T800H/3900-2, 34,5J with MAT54*

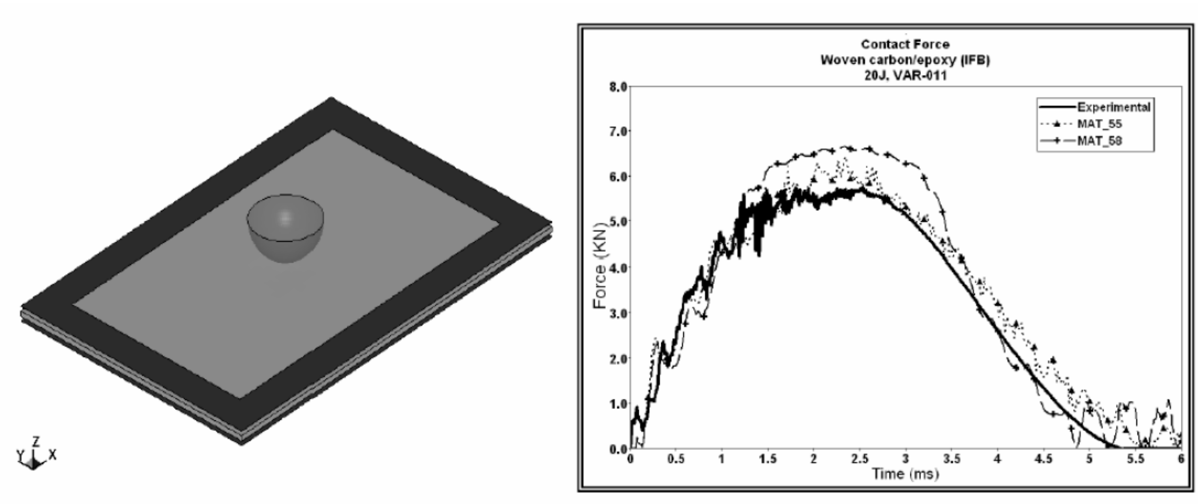
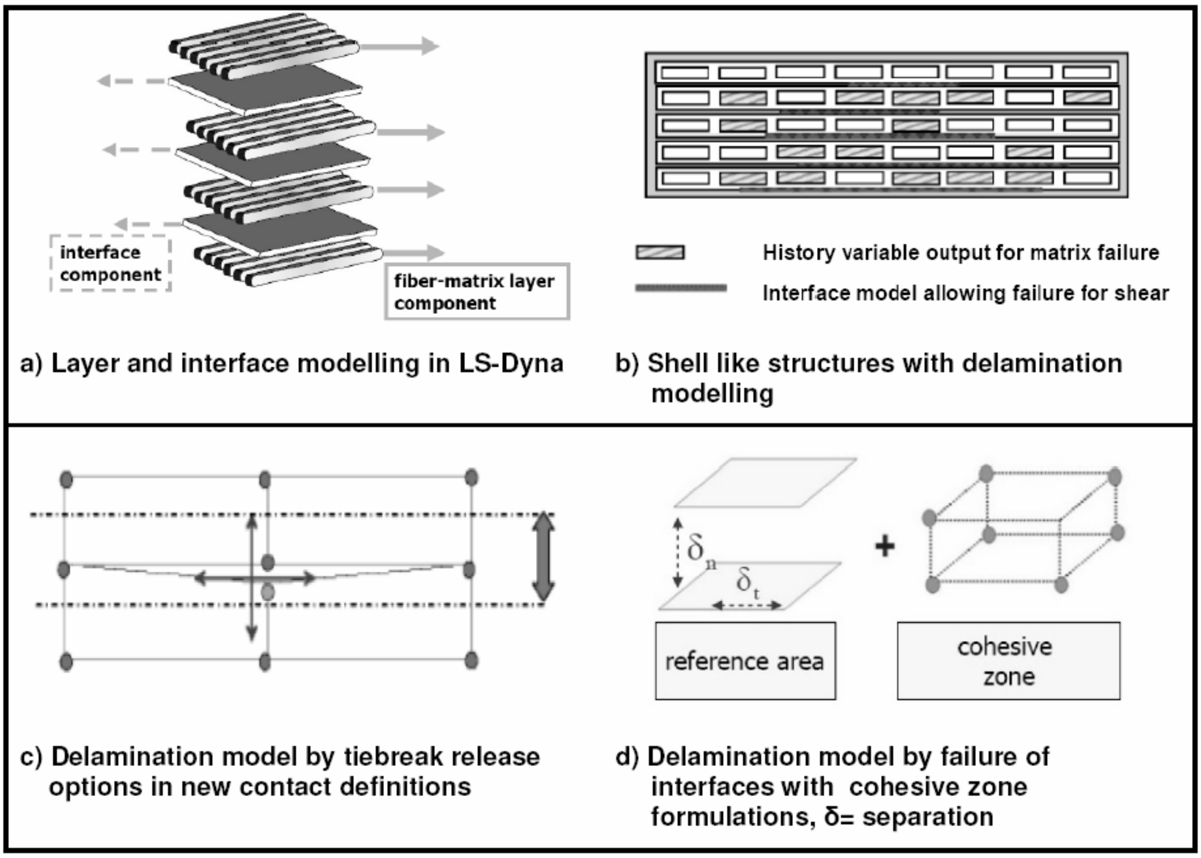


*Fig. 5. Two shell surface modelling: Contact force analysis with MAT54/55 and MAT58 compared to experiment*



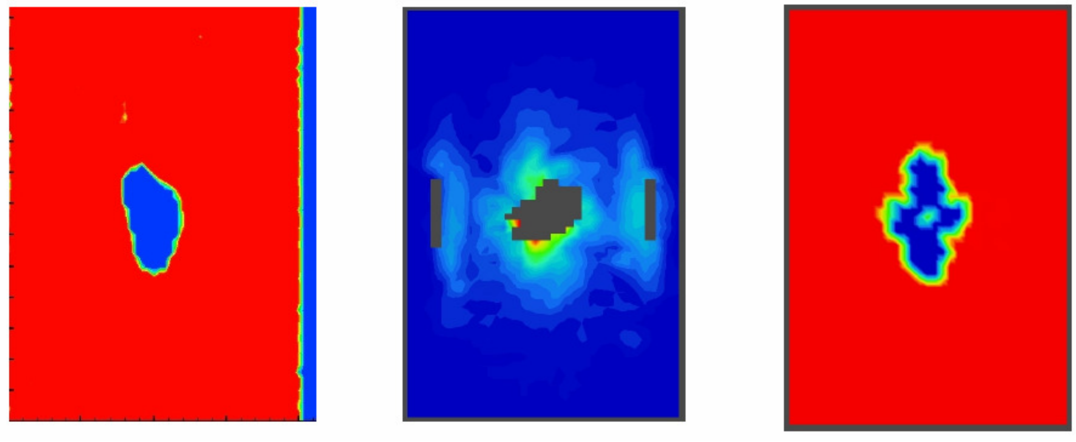
a) Layer and interface modelling in LS-Dyna

b) Shell like structures with delamination modelling

c) Delamination model by tiebreak release options in new contact definitions

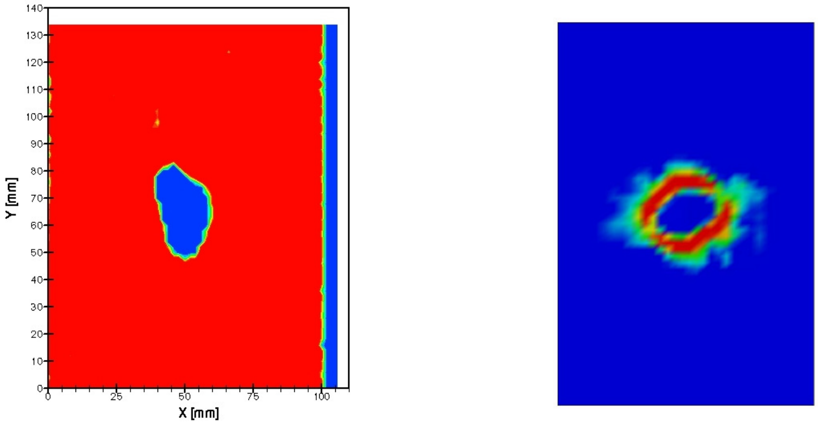
d) Delamination model by failure of interfaces with cohesive zone formulations, δ= separation

*Fig. 6. Stacking sequence allowing separation with different models for interface failure*



a) b) c)

*Fig. 7. 20 J impact: a) Experimental results; b) simulation results; matrix failure in a two shell surface model with one cohesive zone (MAT_185), c) simulation results for shear failure (MAT 55)*



a) b)

*Fig. 8. 20 J impact: a) Experimental results; b) Simulation results; Matrix failure with MAT55 and a two shell surface model with one tiebreak definition*

## 6 References

[1] Schweizerhof K., Weimar, K. Münz, Th., Rottner, Th., Crashworthiness Analysis with Enhanced Composite Material Models in LS-DYNA- Merits and Limits, LS-DYNA Conference, Detroit, Michigan, 1998.

[2] Delaware Composites Design Encyclopedia, Technomic Publishing Company, Inc., Lancaster, Pennsylvania, 1990

[3] Livermore Software Technology Corporation, LS DYNA Version 971, Keyword User's Manual

[4] Matzenmiller, A., Lubliner, J. Taylor, R. L., A constitutive model for anisotropic damage in fiber-composites, Mechanics of Materials (20), 125-152 (1995)

[5] Botkin, M., Johnson, N., Zywicz E., Simunovic S., Crashworthiness Simulation of Composite Automotive Structures, 13th Annual Engineering Society of Detroit Advanced Composites Technology Conference and Exposition, Detroit, Michigan, 1998

[6] Williams, K. V., Vaziri, R., Floyd, A. M., Poursatip, A., Simulation of Damage Progression in Laminated Composite Plates using LS-DYNA, 5th International LS-DYNA Conference, Southfield, Michigan, Sept. 21-22, 1998

[7] Borg, R., Simulation of Delamination Initiation and Growth in Fiber Composite Laminates, Department of Mechanical Engineering, Dissertations No. 776, Lingköping Studies in Science and Technology, Lingköping, 2002.

[8] Gerlach, S., Fioka M., Matzenmiller A., Modelling and Analysis of Adhesively Bonded Joints with Interface Elements for Crash Analysis, 4th LS-DYNA Anwenderforum, Bamberg, 2005

[9] Davila, C. G., Camanho, P. P., Decohesion Elements using Two and Three-Parameter Mixed-Mode Criteria, American Helicopter Society Conference, Williamsburg, VA, 29. 10-1. 11, 2001