DAMAGE AND IMPACT SIMULATION OF TEXTILE REINFORCED COMPOSITES USING FEA

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SUMMARY: Several studies have pointed out the numerous advantages of using composite materials for impact loaded structures. With carefully tailoring, the composite structures provide a much better response to impact loads than metal components and bring additional advances concerning weight savings and structural stiffness.
Unfortunately, one of the greatest challenges still facing optimised usage of composite materials in impact loaded structures are related to insufficient simulation capabilities. Most of the optimisation performed so far were achieved via expensive and difficult to evaluate experimental tests.
To overcome those difficulties for available commercial explicit FEM codes, new material models have been developed in the last years that account for many of the failure and post-failure behaviour of composite structures under impact loading. These models are mostly based on non-local damage description.
The present paper deals with the study and verification of a non-local damage model, which has recently been implemented in LS-DYNA for solid elements and of its capabilities to predict plate bending impact in composite laminates.

KEYWORDS: composite material models, nonlinear explicit FEM, non-local damage, post-failure response, impact loads

INTRODUCTION

Due to their lower density and high mechanical properties composite materials have turned to be an ideal material for a wide range of applications in several industry fields, ranging from aerospace to civil engineering [1]. In the last decade several experimental work did also show that composite materials do possess also an outstanding energy absorption potential [2-4] and several applications in aircraft and automobile industry have shown the superiority of composite materials to dissipate energy during a impact event when compared to usual monolithic materials.
The applications of composite materials under impact loaded events have become an important issue nowadays and numerous studies have been conducted on an effort to improve its energy dissipation capabilities or to prevent vital load carrying components to be damaged due to out of plane impact events that might lead to reduction in in-plane properties and compromise the load bearing capacity of such structures [5-9].
Unfortunately, one of the greatest challenges still facing optimised usage of composite materials in impact loaded structures are related to insufficient simulation capabilities. Much of the work done to the time to optimise composite components under impact load has been performed via expensive and difficult to evaluate experimental work. Simulation of crash events has played a minor role on this optimisation process on the past and are now gaining more importance as a consequence of the development of material models capable to simulate the complex phenomena happening during a crash event on the material level [10].

The majority of methods previously used for the prediction of impact resistance of composite structures overlook the complex processes of damage development taking place in the material and do consider only a part of the nonlinearities that take place in the material. Neither the peculiarities of damage nucleation and growth, nor the effect of the loading rate, or the effect of this damage on the local and overall stiffness are taken into account in a realistic and coherent manner. Inevitably, such deficiencies of the design methods are reflected in the size of the resulting structures, which are usually over dimensioned and less reliable than they could be [11].
To overcome those difficulties for available commercial explicit FEM codes, new material models have been developed in the last years that account for many of the failure and post-failure behaviour of composite structures under impact loading [10]. These models are mostly based on non-local damage description, what makes it difficult to provide direct input data to the damage controlling variables. The presented paper deals with the study and verification of a non-local damage model, which has recently been implemented in LS-DYNA for solid elements and of its capabilities to predict plate bending impact in composite laminates.
However, the performance of all these models are highly sensitive and strongly depends on the correct experimental determination of the introduced damage parameters. The presented paper emphasises the efforts to calibrate the aforementioned material model via static and high strain rate tests and its capabilities to predict impact damage under plate bending impact event correctly.

COMPOSITE MATERIAL BEHAVIOUR UNDER HIGHLY DYNAMIC LOAD AND ITS MECHANICAL DESCRIPTION

It is well known that composite structures in the form of laminates or textile composites are extremely susceptible to crack initiation and propagation along their laminar interfaces in various failure modes [5, 6]. In fact, delamination is one of the most prevalent life-limiting crack growth modes in composites as it may cause severe reduction of in-plane strengths and stiffness, potentially leading to catastrophic failure of the whole structure [5-8]. Damage of polymeric composite structures through impact events is perhaps one of the most important condition that limits wide applications of multilayered composite structures. Whilst high-energy impact loading leads to shear plug failure with full penetration or very localised shear/compressive damage which may be visually detectable, low-energy impact can produce extensive sub-surface delamination with little or no detectability. The presence of internal damage was found to cause substantial degradation in important in-plane mechanical properties, mainly strength and stiffness [12, 13].
The type and extent of damage resulting from impact on composites is governed by many different parameters such as: material properties, impactor mass and geometry, impact velocity and composite lay up, with impacting kinetic energy being the most important parameter on the damage response.
Several composite damage models have been developed to deal with failure due to impact loading: failure criteria approaches, fracture mechanics approaches, plasticity approaches and damage mechanics models. The damage mechanics approach provides a method which can determine accurately the full range of deterioration of a composite material, from the virgin material with no damage, to the fully disintegrated material with full damage [6]. In addition, the method has the potential to predict different composite failure modes, and allows an energy dissipation mechanism, due to the formation of microcracks within the composite, to be included in the model. The concept of damage mechanics has focused especially on the degradation of stiffness due to matrix cracking or delamination in a composite. Some damage mechanics based models have also been developed and implemented into well-known finite element codes [9, 13]. These models are the baseline for the actual material model used here

and have been extended to the third dimension to be used within solid elements formulation [10].
In addition to the damage behaviour, it is well known that some composite materials are strongly rate dependent and their strength and stiffness response change quite much under different loading rates.
The majority of the actual material models in commercial FEM explicit codes used to predict damage failure in composite materials, with some few exceptions, do not account for this particular phenomena and underestimate strongly the structure response. The model investigated here accounts for the strain rate effects on strength and stiffness and allows a more realistic prediction of the failure response of composites under impact loads.

MATERIAL MODEL DESCRIPTION

The investigated material model MAT 162 is implemented in the FE-code LS-DYNA for brick elements and encompasses several features to predict progressive and post failure response of composite materials under impact loads as well as strain rate dependence [10]. In the following, a short overview about the mechanical background of the model will be given.

Failure criteria

A stress based failure surface $\boldsymbol{r_j}$ developed within the failure criterion proposed by HASHIN [14] is extended to the three dimensional stress space. Coupling effects between failure modes are also included to handle plain weave composites and a stress based delamination failure criterion was implemented. Three damage functions are formulated to describe fibre failure, one for compression, one for tension/shear and one for crushing under pressure. To take matrix cracking into account, one failure function for in-plane failure and one for delamination are introduced. For unidirectional layers, the failure surface is described by five separate criteria, for bidirectional layers seven criteria are used. To account for degraded strengths, the failure surface shrinks as the material suffer damage or grows with the strain rate growth.

Constitutive Law

The non-local damage approach is based upon the damage model proposed by MATZENMILLER [13] and WILLIAMS [9], respectively, where the elastic moduli are degraded via direction dependent damage factors, which are controlled by an exponential function. The strain rate effects are considered by a scale factor that increases strengths and stiffness according to the loading speed.
To transform the nominal stress $\boldsymbol{ó}$ of an orthotropic layer to the effective stress $\boldsymbol{\tilde{ó}}$, a rank-four damage operator $\boldsymbol{D_i}$ with i ranging from 1 to 6 is introduced. This damage tensor relates the onset and growth of damage to stiffness losses in the material. The compliance relationship for the damaged state then results in

$$\boldsymbol{e} = \boldsymbol{S^0}\boldsymbol{\tilde{ó}} = \boldsymbol{S^0}\boldsymbol{D}\boldsymbol{ó} = \boldsymbol{\tilde{S}}\,\boldsymbol{ó}\ ,$$

where $\boldsymbol{S^0}$ denotes the compliance matrix at the initial state, with

$$\tilde{S}(D)=\begin{bmatrix} \frac{1}{(1-D_1)E_1} & -\frac{n_{21}}{E_2} & -\frac{n_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{n_{12}}{E_1} & \frac{1}{(1-D_2)E_2} & -\frac{n_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{n_{13}}{E_1} & -\frac{n_{23}}{E_2} & \frac{1}{(1-D_3)E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{(1-D_4)G_{12}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{(1-D_5)G_{23}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{(1-D_6)G_{13}} \end{bmatrix}$$

Damage evolution law and coupling of the damage modes

The damage growth law used in the model is fairly general formulation that was originally used for the problem of uniaxial tension on a unidirectional laminate [9]. The evolution laws are described via an exponential function that is only driven by one independent parameter m for every individual failure mode j

$$D_i = 1-\exp\left(\frac{1}{m}\left(1-r_j^m\right)\right)$$

where r_j denotes the damage threshold in the individual failure mode j. The coupling of the damage modes, more precisely the effect of damage in one specific direction on the elastic properties in other directions, is provided by a damage rule of the form

$$\dot{D}_i = \sum_j \dot{f}_j q_{ij}$$

where the scalar functions $\dot{f}_j$ control the amount of damage [13]. The coupling of the damage mode j and the damage variable i, dependent on whether the layer is an unidirectional or bidirectional layer, is described by a vector-valued function q_{ij}.

Strain rate dependent material properties

The stiffness and the strengths of composite materials are known to be strain rate dependent. Strain rate effects are modelled via an scalar factor that scales up or down the strengths and stiffness according to the relation between these properties and the strain rate growth [11].
The equations used to relate stiffness changes due to load rate are direction dependent while the strengths relation is controlled by a single parameter that influences all orthotropic strengths equally once the strain rate changes.
The relationship between strain rate and stiffness and strengths takes the form of the functions below:

$$\{C_{\dot{e}}\} = \{C_{ref}\}\left(1+C_1 \ln\frac{\{\dot{e}\}}{\dot{e}_0}\right) \qquad \{R_{\dot{e}}\} = \{R_{ref}\}\left(1+C_2 \ln\frac{\{\dot{e}\}}{\dot{e}_0}\right).$$

EXPERIMETAL INVESTIGATION

For the calibration of realistic simulation models for fibre and textile reinforced lightweight structures under dynamic loading, such as crash or impact loads, basic experimental investigations of these composites were performed in the Dept. of Engineering Science at Oxford and are required to gain a deeper knowledge about their dynamic material behaviour and failure mechanisms [15].

Static tests

To calibrate the material model, several uniaxial tensile and compressive tests were conducted with [0/90/90/0] multi-layered flat bed knitted fabric specimens under static loading conditions [16]. The obtained stress-strain curves were used to calibrate the material model response in the corresponding numerical model. Subsequently, the reduced elastic properties of the $[0/90]_s$ composites could be compared with the reduced moduli predicted by the numerical model. Based on the experimental crack density studies on such composites, conclusions regarding the determination of damage parameters of more complex composites could be drawn [16].

High speed tensile tests

High-speed tensile tests were carried out on glass fibre reinforced specimen with a fabric reinforcement structure [2, 11, 15]. The strain rates were varied from 0.0004 1/s (quasi-static test) up to 40 1/s (highly dynamic test). The associated stress strain diagrams of the single tensile tests were obtained and used to calibrate strain rate dependency in the model. The resulting stress strain response indicates a strong strain rate dependence of strengths and stiffness.

Impact tests

Finally to verify the numerical results from the impact simulation several experimental plate bending impact tests have been carried out at several impact velocities ranging from 4m/s up to 10 m/s [15]. The plate bending impact tests were performed with a Hopkinson device (Fig. 1) at the Dept. of Engineering Science in Oxford.

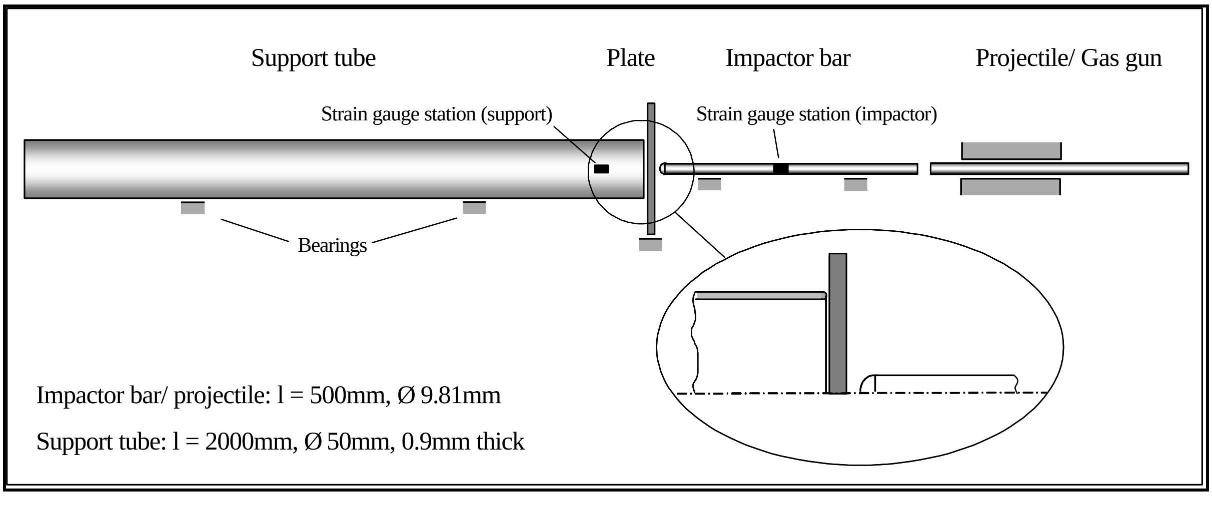

Fig.1: Hopkinson device

The resulting experimental, obtained energy curves from the impacting tests were then used to verify the validity of the calibrated material model. A detailed explanation about the experiments conducted and the corresponding material data obtained can be seen in [16].

NUMERICAL INVESTIGATION

Since MAT162 is a relatively new model, several single element tests have been conducted with the intent to evaluate the effectiveness of the several features the material subroutine includes. The single element tests results show a good correlation with the expected behaviour. The model features, namely direction dependent failure criteria, damage parameters and strain rate control parameters, did work well and have shown their reliability to predict the behaviour in one element. The parameters to control numerical instabilities in explicit calculations did also perform well.
Non-local damage models can just be calibrated via curve fitting with the experimental tests, several FE models were built to simulate the uniaxially loaded specimens that were tested in tension.
The damage and development in a quasi-static tensile tested specimen is depicted in Fig. 2.

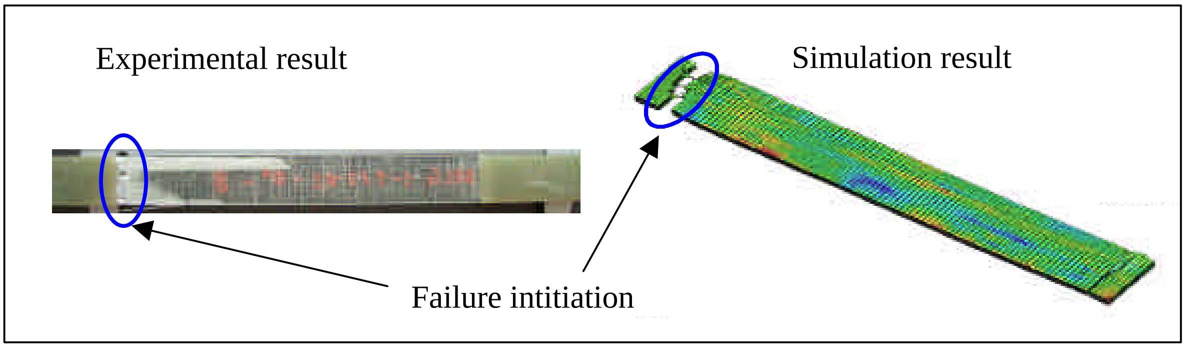

Fig.2: Fracture patterns of an uniaxial tensile test and the simulation, respectively

The static data [16] were used to fulfil the linear elastic portion of the material model, namely static moduli , static strength and Poisson's ratios. In addition, a number of tensile high speed tests have been performed and further calibration was conducted to obtain the strain rate dependency effect in the material [11, 15]. An example of these curves is depicted in Fig. 3 for the high speed tensile test with 1m/s with the corresponding calibrated simulation curve.

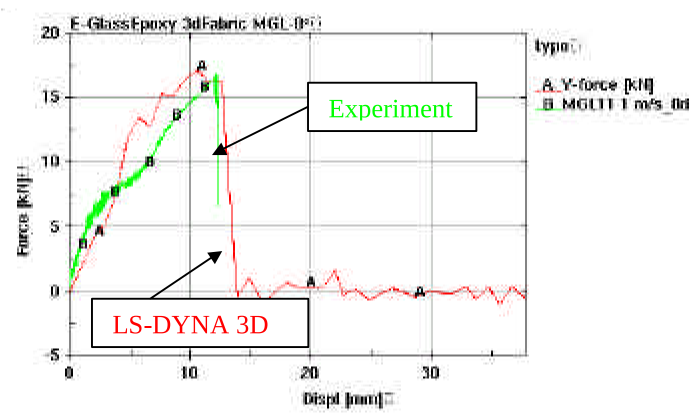

Fig.3: Uniaxial high speed tensile test data and respective simulation data

Finally, various numerical simulations of plate bending impact tests at different speeds were performed (Fig. 4) and the calibrated material input was used to simulate the composite response under impact load. The measured energy curve was then compared to the one obtained from the experiment.

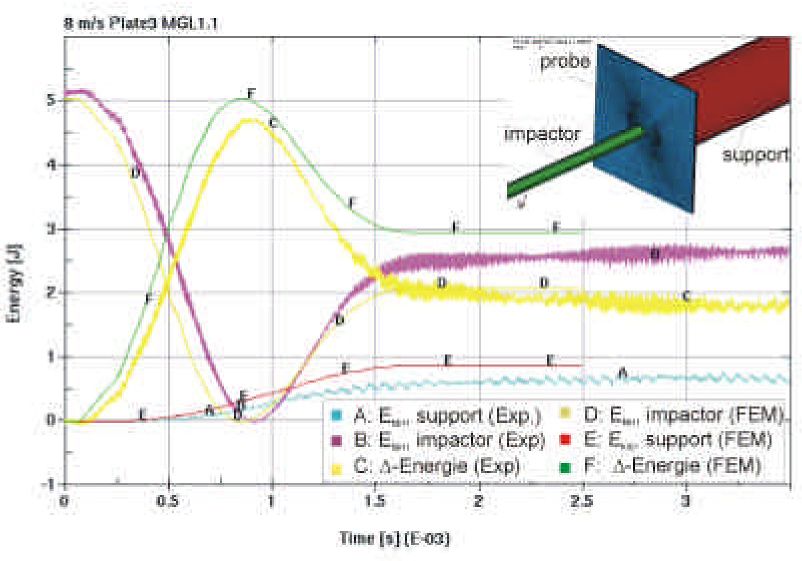

Fig.4: Comparison of the numerical and experimental energy balance (v= 8 m/s)

The differences seen between the green curve (numerical data) and the yellow curve (experimental data) observed in Fig. 4 arise due to the differences on the elastic energy taken by the support and the tube, that were made of elastic steel in the experimental analysis, while in the simulation they were treated, for the sake of faster computation, as rigid bodies. The plate overall damage field can be seen in Fig. 5, were each damage mode is depicted separately as well.

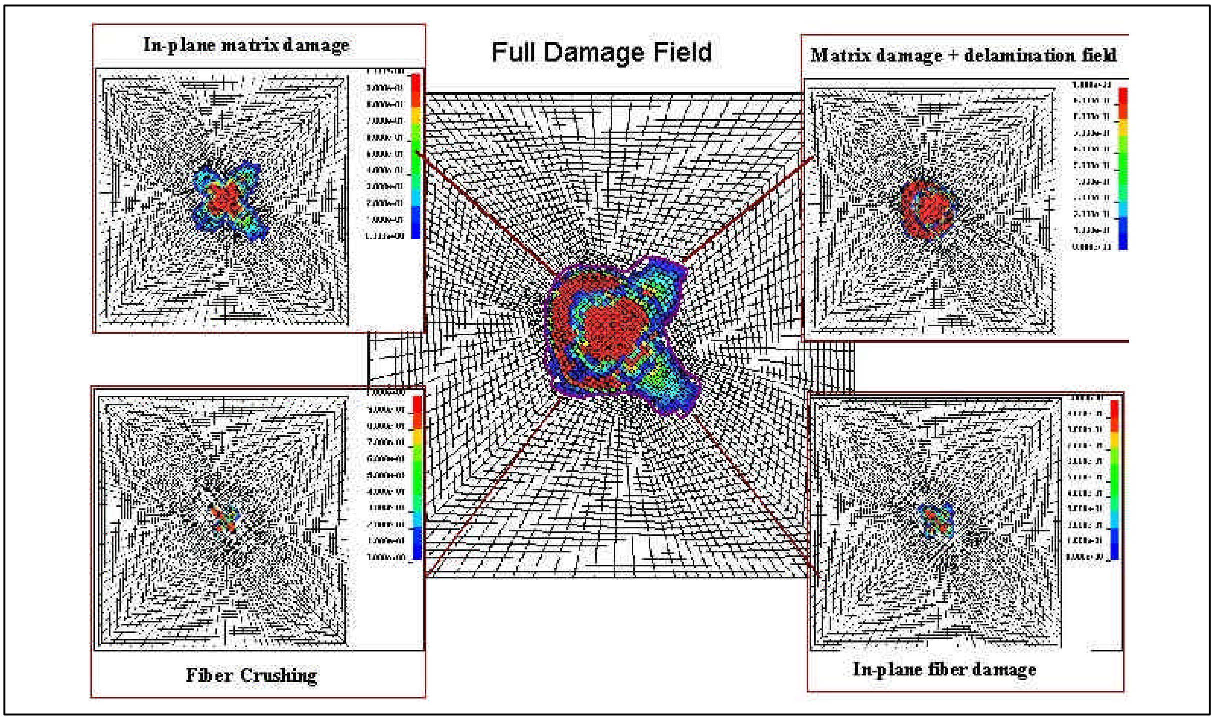

Fig. 5: Total damage field and the damage field due to specific failure modes

Comparing the damage field results with the impacted specimens one might see a good agreement of he damaged area, as it is shown in Fig. 6.

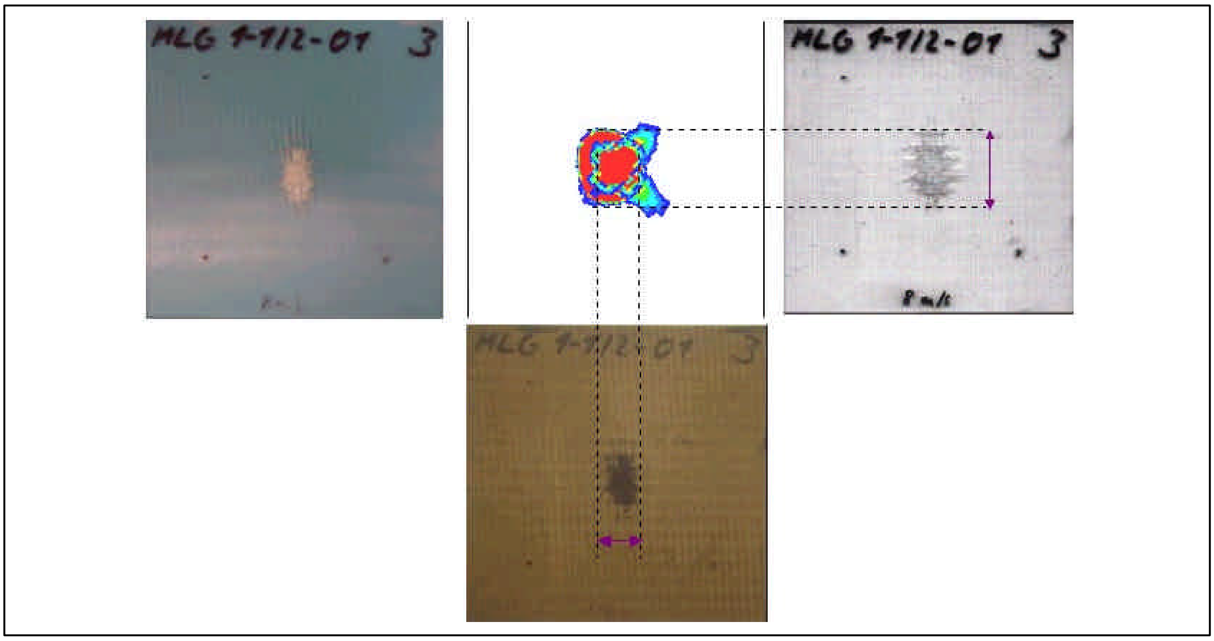

Fig. 6: Comparison of the total damage field calculated with LS-DYNA (middle) and the experimental measured damage fields under impact loading

Finally, Fig. 7 depicts the displacement measured at the plate center with a strain gauge plotted against the numerical obtained displacement at the same location.

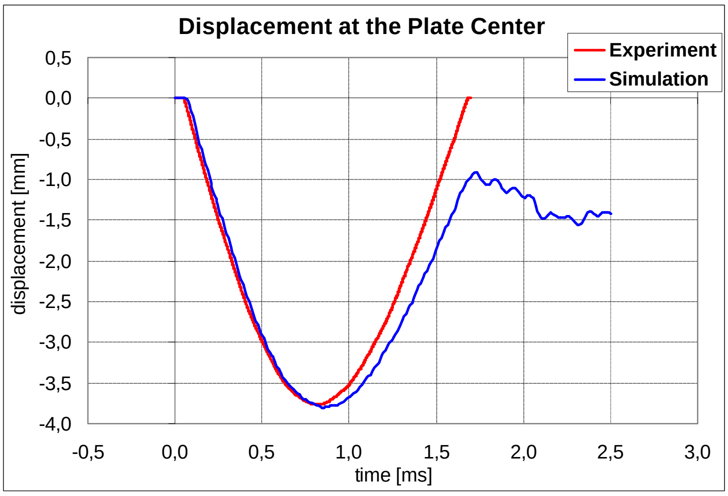

Fig. 7: Comparison of the plate displacement over time for the simulation and the experiment

COMMENTS ON THE RESULTS

Comparing the numerical LS-DYNA 3D results with the obtained experimental data, for the plate bending impact, a good correlation concerning the energy absorption, the failure region and the displacement field can be found. The material model seems to couple very well with the requirements of a crash simulation and shows very good robustness avoiding several common numerical instabilities usually seen in other material models for solid elements in LSDYNA 3D.

The several possibilities offered by the model allow a realistic simulation, with several parameters being taken into account and allowing a better description of the real material response. An additional feature from the material 162 that turns to be advantageous compared

to shell like models, consists on the treatment of cases were delamination plays an important role. The use of solid elements with the third direction shear and normal stress terms allows the use of a failure criterion to judge delamination without any additional contact algorithm, what leads to savings on computational efforts.
On the other hand there exist still issues on the material modelling that require improvements, dependent on the kind of loading the structure might be subjected to. The use of a single parameter to control the strain rate dependence of all the strengths does not seem to be a very efficient choice, since in orthotropic materials the differences among directions plays a very important role. The damage evolution law might also require some modification, especially in the case of treating textile reinforced composites, as it might be seen in [17].

CONCLUSIONS

An new advanced material model recently implemented in LS-DYNA3D for solid elements was investigated concerning its capabilities to predict impact behaviour of composites under low impact velocity. After several unaxial simulations to calibrate the material model input for damage response, the material cards were used to verify the model accuracy under a plate bending impact simulation. A comparison with experimental investigation of the plate provides the required results to evaluate accuracy of the model and shows good agreements with the measured kinetic energy.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of this research by Deutsche Forschungsgemeinschaft DFG within the SPP 1123 at Technische Universität Dresden and the support obtained from the department of Engineering Science of the Oxford University to conduct the impact experiments.

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