Progressive Failure Analysis of Adhesively Bonded Joints in Crash Simulations

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Abstract

The phenomenological description for the mechanical behaviour of ductile, toughened polymers is currently an active field of research in interfacial mechanics, since the recently developed crash-modified adhesives are well suited to bond structural components of automotive bodies reliably. Therefore, constitutive models for the inelastic behaviour of adhesives and substitute elements for the effective modelling of thin layers are needed for the crashworthiness analysis of bonded car structures.

The transition is shown from solid elements with three-dimensional constitutive models to interface elements for the analysis of thin adhesive layers in this contribution. Two different material models for the rate-dependent, ductile mechanical behaviour of toughened adhesives are briefly discussed. The first approach is based on a three-dimensional elastic-plastic continuum model with a rate-dependent yield stress and a failure criterion. The second approach makes use of an interface element with a traction-separation model for ductile materials.

A reliable estimate for the size of the critical step length is provided, if the equations of motion for the substitute element of the adhesive layer are numerically integrated in time by means of explicit methods.

An adequate experimental setup for testing the inelastic behaviour of a thin layer of crash-modified adhesives up to fracture is analyzed with the finite element method by making use of the substitute element for the bonding. The numerical investigations comprise various modes of failure of the adhesive layer under pure and combined loading in normal and shear direction. The results of the simulation are compared to the corresponding data form experimental tests.

1 Introduction

The failure analysis of adhesive bonds in assembled structures requires a fine discretisation with finite elements of the adhesive layer in thickness direction in order to approximate the state of stress exactly enough. For the crash analysis of complete vehicle bodies small finite elements are undesired, since they require a small critical time step for the simulation with explicit methods of the entire structure. Even if only one finite element is used over the thickness of the adhesive layer, the length of the smallest element edge is in the range of 0.05 to 0.2 mm. The resulting critical time step of classical volume elements for the adhesive layer in the explicit integration algorithm of the equations of motion is still too small for the FE-simulation of a complete vehicle in crash scenarios. The crash simulation with solid elements for thin adhesive layers in complete car body models is numerically much too elaborate, if no additional measures, like mass-scaling, are applied to increase the critical time step.

Thus, interface elements with very small or zero thickness are superior for the modelling of adhesive layers. Then, the critical time step is no longer controlled by the Friedrichs-Levy criterion of the solid elements for the adhesive layer but rather by the mass of the neighbouring shell or solid elements, modelling the adjacent steel structures and the stiffness of the bonding. The transition from solid to interface elements is discussed in chapter 2.

The modelling of the brittle material behaviour for adhesive layers was performed with a mixed-mode fracture mechanics approach - see [1]. The constitutive theory was implemented as a user definded material model into the finite element code LS-DYNA [2], [3]. The results of typical benchmark problems for the simulation of the initiation and the growth of delaminations in layered composite structures have been computed - see [1] - with the traction-separation relation of Tvergaard and Hutchinson in the finite element analysis. The failure analysis of adhesively bonded structures is in the line of research to the simulation for delaminating layered shells and addressed in this contribution.

In chapter 3 the theory of rate-dependent elasto-plasticity with failure is briefly introduced for the finite element analysis of toughened adhesives in bonded assemblies of structural components. The constitutive models are tailored towards the implementation into interface elements. The control of the critical time step is discussed next for the time integration with explicit finite difference methods of the equations of motions for interface elements. The load-displacement diagrams of the finite element simulation with the elasto-plastic model are compared to the corresponding experimental results for a characteristic benchmark example at the end of the paper.

2 From Solid to Interface Elements

Instead of an approximation of the three-dimensional stress and strain state by volumetric continuum elements the thin adhesive layer in bonded structures may be discretized with interface elements - see [4], [5] - to describe the effective in-situ behaviour of the adhesive between both adherents. The transition from the full three-dimensional continuum model with solid elements to the interfacial mechanics approach is shown in fig. 1. The solid element has a complete three-dimensional state of stress and strain, whereas the interface element on the right of fig.1 has only deformations normal and tangential to the thin layer. Due to the large stiffness of the adherent steel parts the more compliant polymeric, crash-modified adhesive is strongly restrained in its deformations in the plane of the thin layer. Hence, the adhesive layer may be viewed as being nearly in a state of plane strain in its tangential directions. The strain tensor simplifies to three nonzero components for the restrained state of deformations, as given in the middle of the material model in fig. 1, and is, thus, called the reduced strain tensor.

By means of the thickness d_k of the layer it is possible to switch between the reduced strain tensor $\boldsymbol{\varepsilon}$ and the displacement discontinuity vector [[**u**]] across the interface. This fact allows the implementation of arbitrary constitutive models of the complete 3d-continuum theory into interface elements with reduced kinematical degrees of freedom. The constitutive model in the strain driven displacement method of the finite element analysis provides the corresponding stress tensor $\boldsymbol{\sigma}$ as given in fig. 1 with a zero shear stress component in the plane of the adhesive layer.

The interface element with zero thickness only requires a mathematical relation between the traction vector and the separation in normal and tangential direction – described by the displacement discontinuity vector - as its constitutive model. The theory of internal variables for the constitutive modelling of the inelastic material behaviour may be taken over into the theory of interfacial mechanics. The three stress components of the corresponding traction vector **t** on the interface are computed by means of the constitutive relations from the given displacement jumps [[**u**]].

Obviously, the precision for the prediction of the state of stress and strain in the adhesive layer reduces with the transition from the 3d-continuum theory to the interfacial mechanics approach, whereas the numerical efficiency augments, if the solid elements for the adhesive layer are replaced by cohesive zone elements in the numerical simulation with the finite element method of assembled structural components.

The virtual work due to the deformation of the interface elements has to be accounted for in d´Alembert´s principle [6], [7] in order to derive the correct equations of motion.

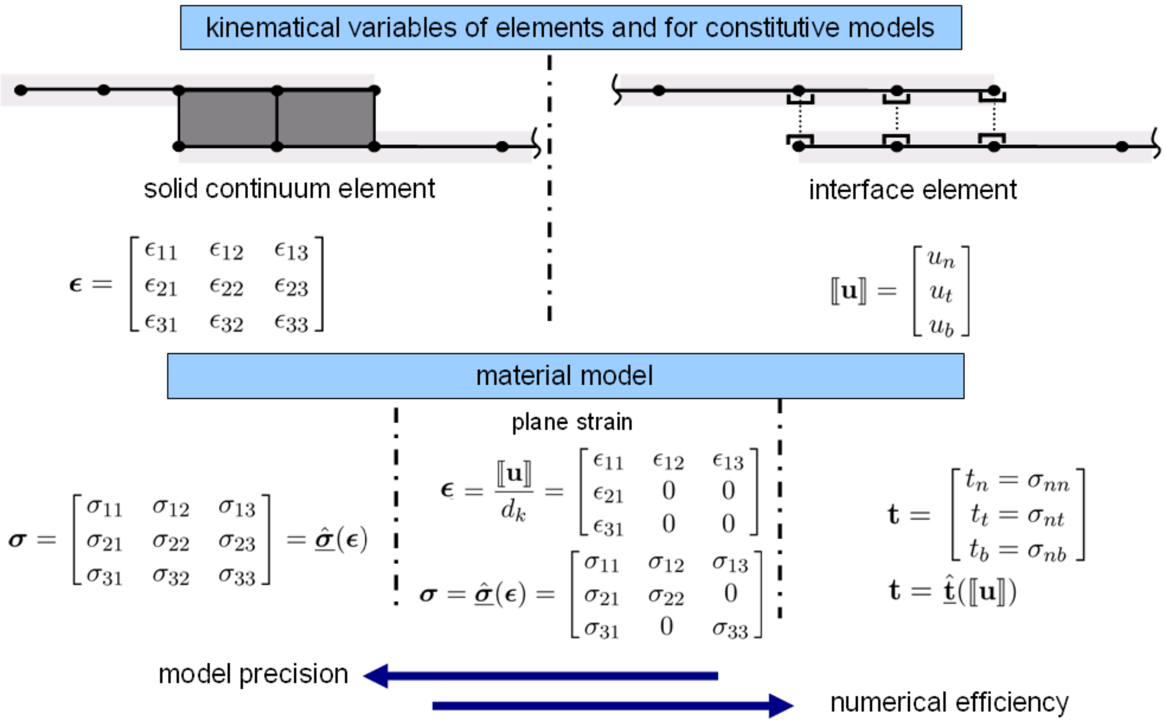

***Fig. 1**: Transition from solid to interface element*

3 Theoretical Background of Constitutive Models for Adhesives

In order to prevent the sudden brittle fracture at low orders of strain, the typical adhesives, made of epoxy resin, are toughened by addmixing particles of elastomeric substances in order to make the duromeric matrix more ductile. These crash modified adhesives become strain rate dependent and withstand large strains as they occur in the bonded joints of car bodies during crash scenarios. Tests on bulk specimens of toughened adhesives show permanent deformations after unloading, if the material is strained beyond a certain limit.

Based on his experimental investigations for toughened adhesives Schlimmer proposed in [8] a rate-independent constitutive model of compressible, non-associated, isotropic elasto-plasticity. The strain rate is additively decomposed into an elastic and a plastic part. The stresses are computed with a linear elasticity assumption from the elastic strains. Linear and exponential isotropic hardening was added in [9] to the material equations for the crash-modified adhesives.

The plasticity model of Schlimmer was upgraded with a rate-dependent yield stress and a failure criterion for the adhesive layer at complete damage according to proposals by Johnson and Cook [10], [11] and Borvik et al [12]. The extended version of the model was implemented into the code LS-DYNA within the framework of the research project "Methodenentwicklung zur Berechnung von höherfesten Stahlklebverbindungen des Fahrzeugbaus unter Crashbelastung" [13]. The complete theory of the continuum model with a few benchmark examples is published in [14].

In addition to the continuum approach above the elasto-plastic interface model with failure and softening of Anand and coworkers [15] was extended to rate-dependency and applied to the analysis of toughened ductile adhesives. This interface model uses a two surface yield condition with two modes of plastic flow. The displacement discontinuity vector is split into an elastic and a plastic part. The flow rule is associated in the mode of yielding due to loading normal to the adhesive layer and non-associated in case of plastic flow due to shear. Combined hardening or softening in both modes of plastic flow is assumed as linear. The rate-dependent elasto-plastic model equations were coded into LS-DYNA as a user defined material model for the application of interface elements - see also [14]. The performance of the interface elements with the elasto-plastic material relations is demonstrated at the benchmark test below, which is outlined in more detail together with other examples in [14].

4 Time Step Control for Explicit Integration of Equations of Motion

The size of the critical time step for the conditionally stable explicit schemes has to be estimated for the numerical time integration of the equations of motion. The inverse of the largest eigenfrequency of the linear system of ordinary differential equations of second order limits the maximum allowable time step, which is slightly reduced and then taken for the step-by-step integration of the nonlinear system of the equations of motion. The largest eigenfrequency of the system is usually not known, since it is practially impossible to solve the associated eigenvalue problem. Therefore, approximate solutions, mainly based on the analysis of the finite element, must be used for a conservative estimate of an efficient time step.

The critical time step for the spatially discretized equations of motion for the complete structure is computed from the largest value $\omega_{\max}$ of the set of maximum eigenfrequencies of all individual finite elements. The maximum eigenvalue of the solid elements is often approximated by the bar wave velocity c and the smallest distance Δl of two arbitrary nodes within the element. The critical time step Δt is then given in accordance with the Friederichs-Levy criterion as:

$$\Delta t = \frac{\Delta l}{c}$$

If only one solid element over the thickness d_k is used for the spatial modelling of thin adhesive layers, the smallest distance Δl between adjacent nodes is equal to d_k. For this the criterion above leads to an inefficiently small critical time step, since the length of any edge in the finite elements must be at least 5 mm for the crash ananlysis of complete vehicle bodies to guarantee a reasonable run time in practice. Therefore, we resort to another estimate for the critical size of the time step.

The interface element with zero thickness between the adherent steel components provides only stiffness to the finite element model of the complete assembly of structural components. The distributed springs, symbolizing the stiffness of an eight node interface element, connect the mass of the top and bottom plane in fig. 2.

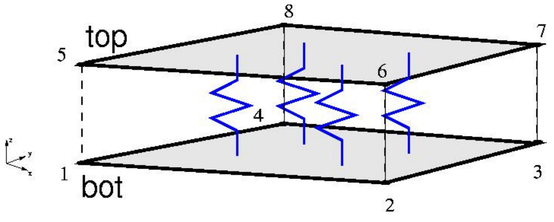

***Fig. 2**: Interface element symbolized by distributed springs*

Both planes may consist of shell elements, describing the adjoining sheet metal or the surfaces of solid elements, used for the modelling of more bulky structural parts. The mass of both surfaces mainly comes from the bonded steel components and to a little extend from the adhesive layer. Fig. 3 shows a node with mass m_1 in the top plane and the neighboring node with mass m_2 in the bottom surface, connected by a discrete spring with stiffness k, which is computed by numerical quadrature at the integration points of the interface element. The parameter k equals the product of the shear or normal stiffness times a quarter of the element area in case of an eight node interface element.

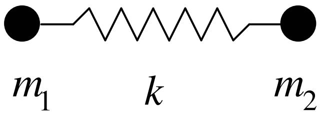

***Fig. 3**: Spring-mass system*

It has to be remarked that the interface element provides no stiffness in membrane direction and may be used only in combination with other structural elements. The critical time step for the spring-mass system is given by:

$$\Delta t = 2\sqrt{\frac{m_1 m_2}{m_1 + m_2}\frac{1}{k}} \tag{1.1}$$

Note that the thickness d_k of the adhesive layer does not enter the estimate of the critical time step in the last equation for the interface element in connection with the nodal mass of the adherent steel components. It may be shown that the critical time step of the solid elements for the steel parts is not further limited by this estimate for the interface elements.

5 Numerical Example

The „Laboratorium für Werkstoff- und Fügetechnik" at the University of Paderborn developed an experimental setup to investigate the mechanical behaviour of adhesively bonded joints - see [16]. The purpose of the test is to characterize the behaviour of bonding techniques under different mechanical stress conditions. Two U-shaped components are joined together with an adhesive similar to a flange in an automotive application – see fig. 4, upper left sketch. The test specimen can be pulled apart with different clamping devices under various angles of loading with respect to the normal on the adhesive layer – see fig. 4, lower left drawing. Four different load angles are chosen with 0° for pure shear loading, 90° for normal loading and two load angles with 30° and 60° for combined loading. The loading is applied in terms of prescribed nodal velocities on the far ends of the U-shaped profiles. In order to investigate the influence of rate-dependency, the analysis and the experimental testing has been performed for two loading velocities with v = 1 m/sec and v = 2.5 m/sec.

In the numerical analysis only the symmetrical half of the specimen is analyzed as shown in the figure below on the right. Since the validation of the substitute element was primarily intended, both the adhesive layer and the adherent steel parts are meshed fairly fine with interface and solid elements in the region of the bonding. However, outside of this area the steel parts in the clamping devices are modelled as rigid bodies, where the loading in terms of prescribed nodal velocities is applied. Special attention has to be given to the filling at the outer edge of the adhesive layer around the corner of the steel parts. Due to the increased thickness the strains in the filling are smaller and local failure takes place later. The retarded failure of the thick adhesive layer shows up as a long plateau with a low level at the end of the load-displacement diagrams of the continuum model after the peak force is passed.

Each load case has been investigated with both constitutive models mentioned above for the adhesive. The material parameters are identified from the data of experimental tests at bonded tubes with a fairly homogeneous state of stress in the adhesive layer under tension and torsion. These test data are given by Schlimmer in [8]. The physical meaning and the numerical values of the constitutive parameters used in the analysis are published in [14].

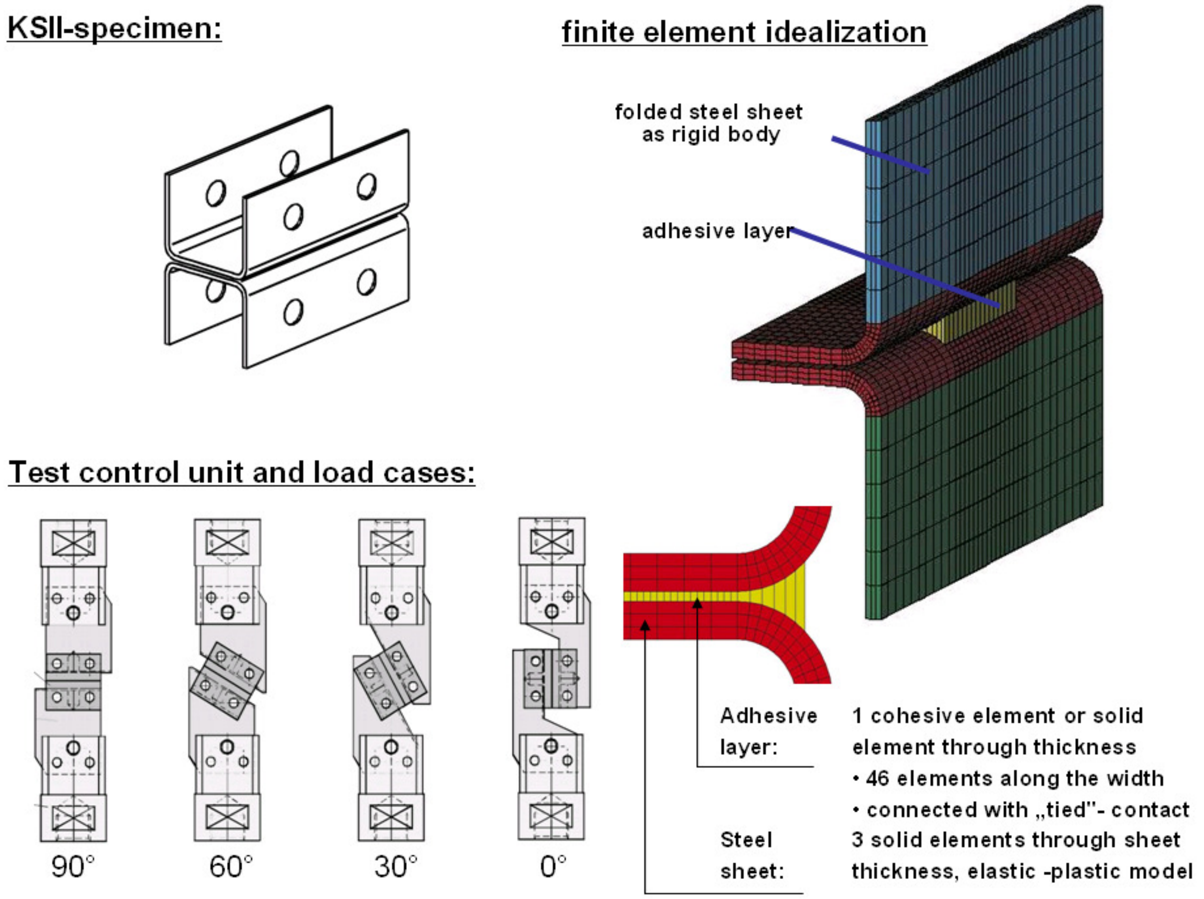

***Fig. 4**: KS-II test specimen with different control units for load angles and finite element mesh*

The results of the analysis are plotted as the total internal force in load direction versus the local displacement in figs. 5 to 8 and compared to the measured data from the experiments, performed at the “Laboratorium für Werkstoff- und Fügetechnik” at the University of Paderborn within the framework of the joint research project indicated in [13]. The local displacements in the experiment are computed as the difference of the displacements vectors for two marked points on the clamped legs of the upper and lower U-shaped steel parts. In the finite element analysis the local displacement is defined as the discontinuity between the displacements of the rigid bodies for parts of the upper and lower steel component. The force in load direction on the ordinate of the diagrams is calculated in the theoretical investigation from the stresses in the adhesive layer by summing them over the entire area. In the tests it is currently not possible to measure the force in the adhesive layer. Therefore, a measurement cell is put into the top of the upper clamping device. Due to the inertia effects of the mass for the parts between the adhesive layer and the measurement cell, the measured forces differ from the total internal force transferred through the joint between the lower and upper steel component. It is difficult to estimate the deviation of the internal force in the measurement device from the resultant on the cut through the adhesive layer. Despite the unknown error we compare the measured force to the calculated stress resultant in the joint and plot both forces over the local displacements in the diagrams of figs. 5 to 8.

The force-displacement curves of the simulations for the two velocities are given for the KS-II specimen under the load angles of 0° and 30° in fig. 5, where the corresponding test data are also added. The diagrams from the tests with the two different loading velocities show significant differences for the force-displacement relations in both cases and reveal rate-dependency. However, the simulated results for the force-displacement diagrams are very close and show hardly any influence of the strain rates. The peak loads of the experiments and the numerical analysis are in the same order of magnitude.

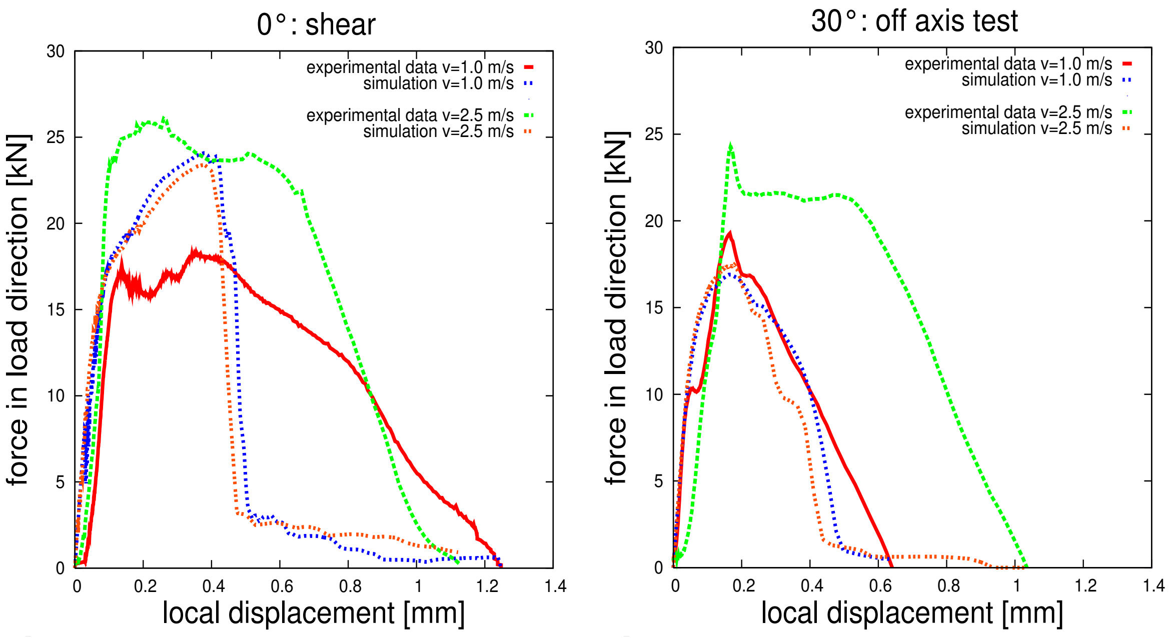

Fig. 5: *Simulation results of continuum model and experimental data for shear loading (0°) and combined loading (30°)*

The mechanical behaviour of the KS-II specimen under combined loading with an angle of 60° with respect to the direction of the adhesive layer and under normal loading, i.e. for an angle of 90°, is given in fig. 6 from the finite element analysis with the continuum model and from the experimental investigations. The theoretical solution and the test data are in fairly good agreement.

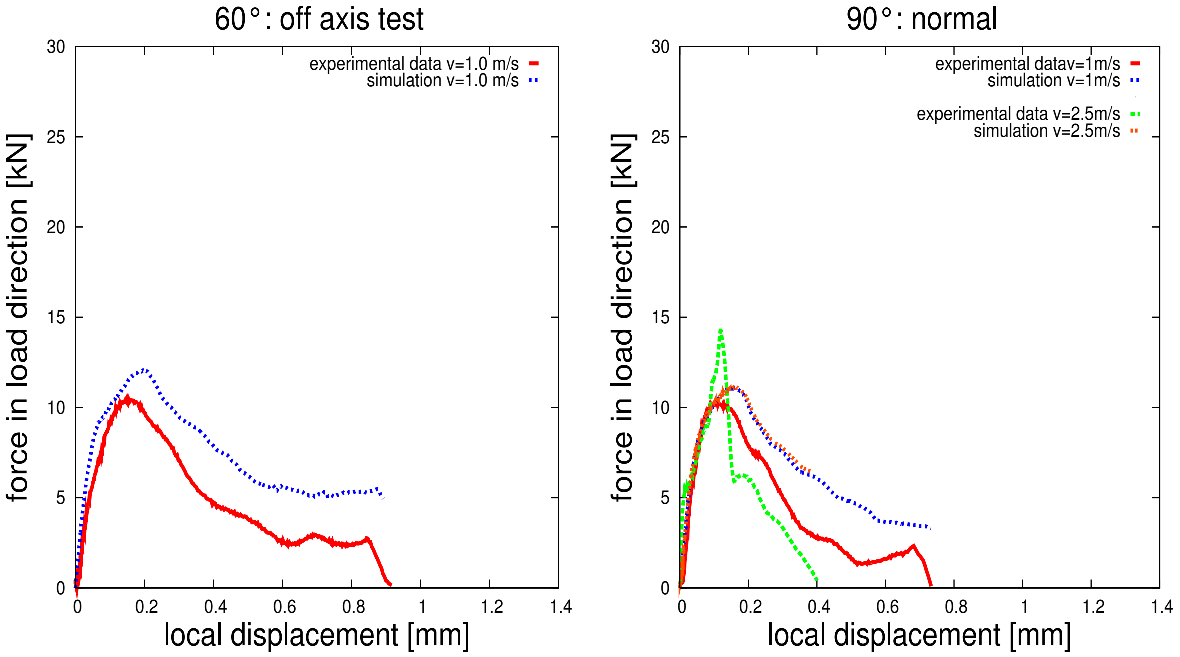

Fig. 6: *Simulation results of continuum model and experimental data for combined loading (60°) and normal loading (90°)*

The results from the numerical analysis for the interface model with the extended version of the traction-separation equation of Anand et al. are graphically represented in figs. 7 and 8 for the four loading angles and the velocity of v = 1m/sec for the separation of the two steel parts. The experimental data for the measured force from above are added to the load-displacement curves.

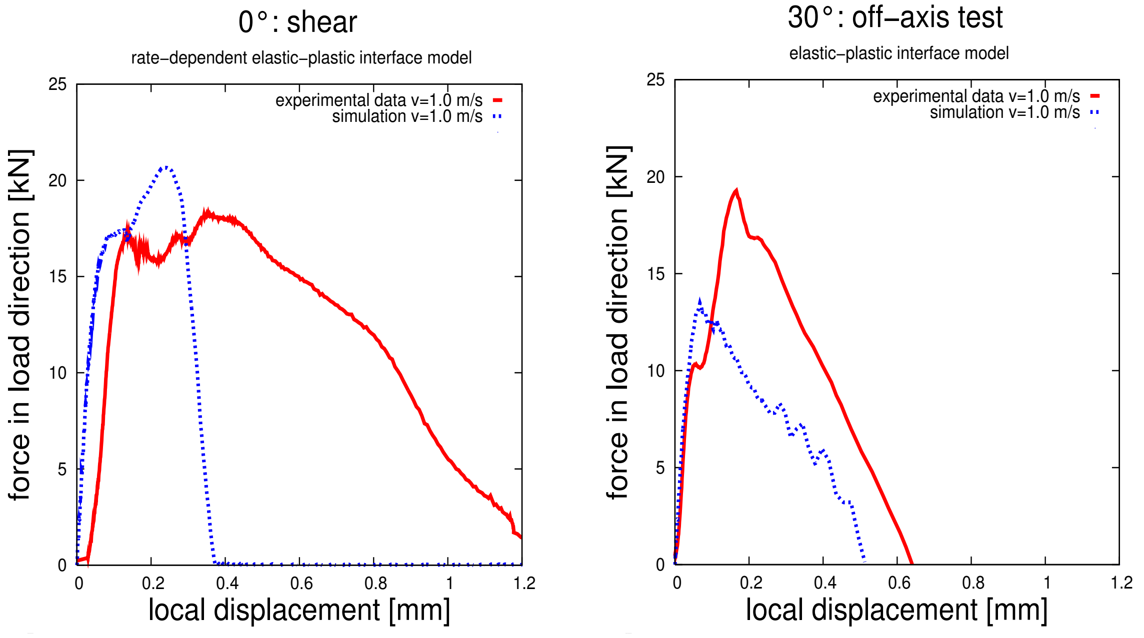

Fig. 7: *Simulation results of interface model and experimental data for shear loading (0°) and combined loading (30°)*

In the case of shear loading the ultimate forces in the experiment and in the simulation agree well, but complete failure is detected at a much smaller relative displacement in the analysis with the traction-separation model than in the test. For the case of combined loading the maximum forces differ more than in the diagrams for shear loading, however, the post critical parts of the force-displacement curves agree better.

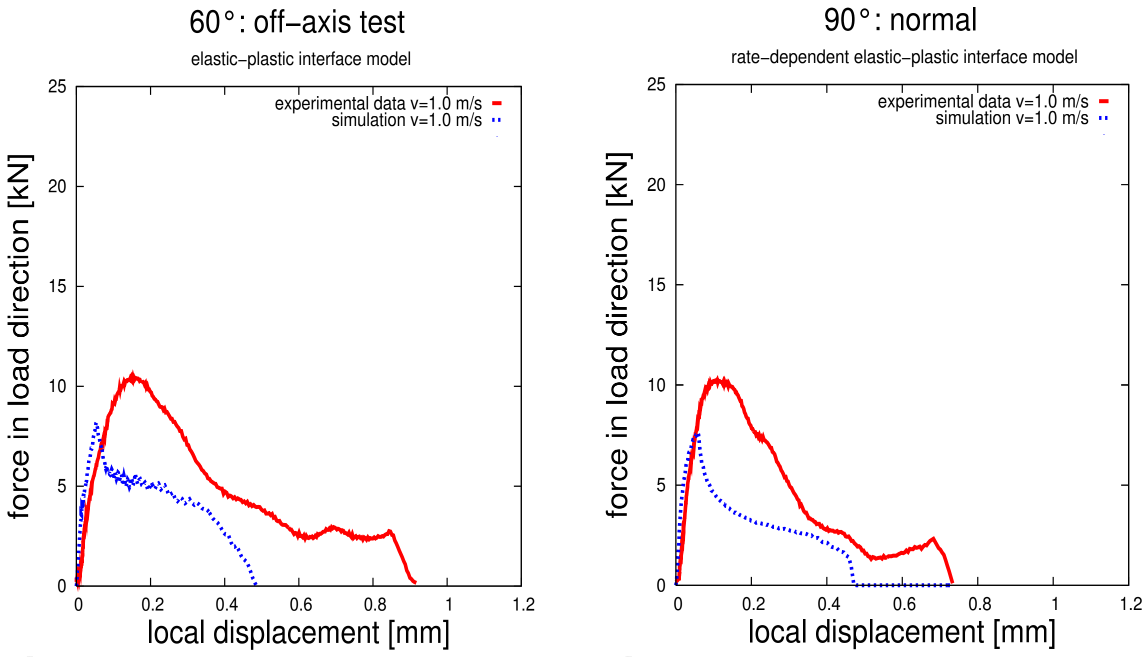

Fig. 8: *Simulation results of interface model and experimental data for combined loading (60°) and normal loading (90°)*

The experimental and numerical results for the load cases with forces of 60° and 90° with respect to the direction of the adhesive layer are presented in fig. 8. In both curves the peak forces are in the same order of magnitude.

A more reliable validation of the test data with the theoretical results is under way. One source of error is the force, measured far away from the adhesive layer as already mentioned and compared to the stress resultant of the adhesive layer. In contrast to the quasi static case, for which the corresponding results are published in [14], the entire test control unit must be modelled from the lower clamping up to the measurement device for the force in the case of dynamical loading. The internal force, calculated at the position of the measurement cell, must be compared to the experimentally found one.

Another uncertainty is the exact reproduction of the same mechanical properties for the adhesive layer. The liquid glue solidifies under heating of the entire specimen in the successive curing process. It is difficult to guarantee a specified quality of the adhesive bond with strength and fracture strain in a small interval of tolerance.

6 Summary and Outlook

The similarities of interface elements and continuum elements between relatively stiff parts have been discussed. Two different approaches for the modelling of thin adhesive layers under crash loading conditions are briefly outlined. An existing elastic-plastic continuum model is extended to account for a rate-dependent yield stress and for damage and failure of the adhesive bond. Alternatively, an elastic-plastic interface model with a traction-separation equation can be used to describe the effective bonding behaviour. Both constitutive models are tailored for an interface element and are successfully implemented into the finite element code LS-DYNA as the numerical examples show.

The interface elements with zero thickness may be massless and, thus, provide only stiffness to the structural matrices. A proposal for the estimation of the critical time step for interface elements is given. Its advantages with respect to estimates of the critical time increments are shown with respect to the usual criterion for the step length of solid elements. Especially, meshes for thin layers with solid elements provide inefficiently small critical step length for the time integration of the equations of motion with explicit schemes.

The results of the simulation show the capabilities and limits of the two modelling techniques proposed for the constitutive behaviour of adhesives at a widely accepted benchmark problem, where testing of adhesive layers has been done and experimental results have been achieved. Similar results can be gained by a finite element discretisation with a continuum model as well as a finite element discretisation based on an interface model. The comparison to the experimental data demonstrates the model's capability to capture the experimentally observed major effects of rate-dependent damage and failure. The numerical approximation of the experimental data must be still improved, e.g. by modelling the entire control unit and by better ensuring the experimental data. In order to draw conclusions from the simulation for the crashworthiness analysis of vehicle bodies, the finite-element idealization for the KS-II-test has to be simplified much more by lowering the number of elements considerably.

Further work is still needed to test the constitutive models presented, in order to check out their predictive capability. The objective of the current research project [13] is the development of an application oriented substitute model for the adhesive layer. Especially the use of the substitute element for the crashworthiness analysis of road vehicles is the primary goal of the project. This task is to a wide range now achieved. The next stage of development should be based on the experience, gained by the simulation of large car body components. The determination of adequate constitutive parameters for the substitute model is another important task. Finally, the models developed should be applied to the simulation of a B-pillar in a car body, which will be experimentally investigated by another research partner.

7 Acknowledgement

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