Mechanical Behaviour of Adhesive Layers
Experimental Methods, Cohesive Laws, and Fracture Mechanics

ANDERS BIEL

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2008
Mechanical Behaviour of Adhesive Layers
Experimental Methods, Cohesive Laws, and Fracture Mechanics
ANDERS BIEL
ISBN 978-91-7385-135-0

© ANDERS BIEL, 2008.

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 2816
ISSN 0346-718X

Department of Applied Mechanics
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone + 46 (0)31-772 1000

Sweden 2008
Mechanical Behaviour of Adhesive Layers
Experimental Methods, Cohesive Laws, and Fracture Mechanics

ANDERS BIEL
Department of Applied Mechanics
Chalmers University of Technology

Abstract
Adhesive joining is today viewed as one of the key technologies to achieve decreased emissions in the automobile industry. To decrease weight, optimal material selection often results in different materials for different parts. This leads to the necessity to join mixed material. Here, the use of adhesives is the most promising joining technology. For a rational design process, good models for strength analysis of adhesively joined structures are essential. With cohesive modelling, fracture of the adhesive layer is modelled with a stress-deformation law. This law - often denoted a cohesive law - gives the traction exerted on the adherends due to the deformation of the adhesive layer.

This thesis is concerned with experimental methods to measure cohesive properties of engineering adhesives and standardized methods to measure the fracture energy of adhesives. A new method to measure cohesive laws is developed. With this method, the cohesive law of an epoxy adhesive is measured in shear. In peel loading, with elastically deforming adherends, the cohesive law is shown to be independent of the geometry of the specimen. If the adherends deform plastically the fracture energy increases. Experiments are performed in order to determine the temperature dependence of the cohesive layer for an epoxy adhesive. It is shown that the peak stress is strongly dependent on the temperature while the fracture energy shows only small temperature dependence. Experiments are also performed to study the influence of strain rate in peel and shear loading. The experiments show that the peak stress increases with an increasing strain rate and that the fracture energy increase in peel loading and decreases in shear with increasing strain rate. A new method to experimentally determine the relation between damage and plasticity in the adhesive during the fracture process is developed. For the present adhesive, it is shown that only minor plasticity occurs during the fracture process in peel loading.

For peel, several commonly used methods to evaluate the fracture energy using the double cantilever beam specimen are critically studied. For some methods the error in evaluated fracture energy is larger than 40 %. It is shown that the evaluated fracture energy is more dependent on the choice of method than on the cohesive properties of the adhesive layer.

Keywords: experimental method, adhesive layer, cohesive law, fracture, fracture energy, energy release rate, peel, shear
### Appended Papers

**Paper A**  
Biel, A. and Stigh, U.  
*An analysis of the evaluation of the fracture energy using the DCB-specimen*  

**Paper B**  
Biel, A. and Stigh, U.  
*Effects of constitutive parameters on the accuracy of measured fracture energy using the DCB-specimen*  

**Paper C**  
Andersson, T. and Biel, A.  
*On the effective constitutive properties of a thin adhesive layer loaded in peel*  

**Paper D**  
Alfredsson, K.S., Biel, A. and Leffler, K.  
*An experimental method to determine the complete stress-deformation relation for a structural adhesive layer loaded in shear*  

**Paper E**  
Carlberger, T. and Biel, A.  
*Influence of temperature and strain rate on cohesive properties of a structural epoxy adhesive*  
Submitted for publication.

**Paper F**  
Biel, A.  
*Cohesive laws for adhesives at repeated loading – an experimental method*  
Submitted for publication.
# Contribution to Co Authored Papers

<table>
<thead>
<tr>
<th>Paper</th>
<th>Contribution Details</th>
</tr>
</thead>
</table>
| Paper A | Responsible for the numerical simulations.  
Wrote the paper in collaboration with the co-author. |
| Paper B | Responsible for the numerical and analytical simulations.  
Wrote the paper in collaboration with the co-author. |
| Paper C | Predominantly responsible for the experiments.  
Evaluated the experiments in collaboration with the co-author.  
Took part in writing the paper. |
| Paper D | Performed the experiments in collaboration with the co-authors. |
| Paper E | Wrote the paper in collaboration with the co-author.  
Evaluated the experiments in collaboration with the co-author.  
Performed the DCB-experiments at slower strain rates.  
Performed the temperature experiments in collaboration with the co-author. |
| Paper F | – |
Contents

Abstract ............................................................................................................................................. i
Appended Papers ........................................................................................................................ iii
Contribution to Co-Authored Papers ......................................................................................... iv
Contents ........................................................................................................................................ v
Preface ........................................................................................................................................... vii

Review and Summary of Thesis .................................................................................................. 1

1 Background .................................................................................................................................. 1
2 Strength of adhesive joints ......................................................................................................... 2
3 Theory .......................................................................................................................................... 5
4 Experiments ................................................................................................................................. 8
   DCB-experiments ...................................................................................................................... 9
   ENF-experiments ..................................................................................................................... 10
   Analyse of measurement data ............................................................................................... 11
5 Properties of adhesive layers ................................................................................................... 11
6 Future work ................................................................................................................................. 13
References ...................................................................................................................................... 14

Appended Papers
Paper A
Paper B
Paper C
Paper D
Paper E
Paper F
Preface

The work is a result of a co-operation between the group of Mechanics of Material at the University of Skövde and the Department of Applied Mechanics at Chalmers.

First of all I would like to thank my supervisor Prof. Ulf Stigh for his support and extensive guidance during the past years. Furthermore, I would like to thank my co-authors Svante Alfredsson, Tobias Andersson, Thomas Carlberger and Karin Leffler for their constructive collaboration which has been very successful.

I would also like to thank Stefan Zomborcsevics and Eiler Karlsson for help with manufacturing the specimens, Kent Salomonsson for help with handling ABAQUS, Bertil Enquist at Växjö University for help with performing ENF experiments and all the colleagues at the department which have been affected by the work.

Last but not least, I would like to thank my parents Henrik and Maj-Britt for their infinite help and support.

Skövde, 1 May 2008

Anders Biel
Review and Summary of Thesis

1 Background

Apart from the evolutionary development of natural adhesives used by e.g. acorn barnacles, the major development of adhesives originates in the petrochemical industry during the 19th and the 20th centuries. Today, light and strong structures are demanded since the design goals often are to reduce the fuel consumption, to increase the load carrying capacity or to increase the crashworthiness. Because of this, adhesive joining has become an interesting alternative to more conventional joining methods. The design processes of today always include numerical simulations to validate and optimize the structure. To be able to trust the simulations to a degree where the simulations can replace full scale experiments, the models and material parameters used in the simulations must have high quality and known limits of use. A model showing good capability to predict the behaviour of adhesive layers is the cohesive zone model. In this model, the tractions acting on the adherends are given by a cohesive law. In its simplest form, this law determines the tractions by the separation of the adherend/adhesive interfaces.

To make quantitative numerical simulations of structures including adhesives, the properties of the adhesive has to be known. Because of this, experimental methods to determine the cohesive properties of adhesive layers are of great importance. In an adhesive joint the adhesive is in a state of prescribed deformation and typically two types of deformation dominate the behaviour, cf. e.g. Klarbring (1991) and Schmidt (2007). These are denoted peel (corresponding to modus I in fracture mechanics) and shear (modus II/III), cf. Fig 1. In a general case these two types occur in combination denoted mixed mode.

During crack propagation a zone of damaged adhesive precedes the crack tip. This zone is denoted the damage zone. The length of this zone is typically much longer than the thickness of the adhesive layer. Figure 2 shows a typical damage process for an epoxy adhesive layer exposed to peel loading. The adhesive is an engineering epoxy used in the automobile industry, DOW-Betamate XW1044-3. The thickness of the adhesive layer is
0.2 mm. A crack propagates from left to right in the figure. At A the adhesive is undamaged and in a state of elastic deformation. At B micro cracks can be found throughout the entire thickness of the adhesive layer. Some amount of stress whitening is visible and the adhesive has begun to soften. At C the stress whitening is formed to streaked areas which precede the macroscopic crack. At D large cracks are visible and at E the tip of the macro crack is identified. It should be noted that the maximum peel stress in the layer is achieved somewhere between A and B. It is also apparent that all experimental methods to evaluate the fracture energy of engineering adhesives that include the measurement of the crack length are destined to give uncertain values since it is very difficult to identify the crack tip experimentally.

Fig. 2 Damage process in an adhesive; to the left, visible crack and to the right, undamaged adhesive.

2 Strength of adhesive joints

Early test setups of adhesive layers are based on simple test geometries aiming to achieve a constant stress distribution over the glued area. Examples are the butt joint for peel and the single lap joint for shear, cf. Fig 3. In the late 1930s it was pointed out that the stress distribution in the single lap joint is non-homogenous. Volkersen (1938) performed analytical and experimental analyses on riveted single lap joints. In the analytical study the joint is represented with an ideally elastic layer loaded in shear. Both results show that the shear stress varies along the joint. Although this geometry mainly results in shear stresses, peel stresses are introduced as well due to the bending of the adherends or simply due to the loads being applied in different planes, cf. Fig. 3. Goland and Reissner (1944) presented solutions that show the influence of peel stresses in the single lap joint. Although these early results, the single lap joint is frequently used and the strength measured is used as a value of the shear strength. The main argument for using this specimen is its ease to use.

Fig. 3 Two types of test geometries which give a non-homogenous stress distribution.
Even for the butt joint, a homogenous stress distribution is never achieved. Adams and Coppendale (1979) performed analytical and experimental analyses that show that the stress distribution is non-homogenous. At the edges of the specimen the peel stress is increased and small amount of shear stress exists. Due to elastically stored energy in the testing machine and specimen, these kinds of experiments are often terminated prematurely due to unstable crack propagation. However, since they are easy to perform and seemingly easy to analyze these methods are still in common use. Several standards have been developed based on these methods, e.g. ASTM D 897 (2001) for peel and ASTM D 1002 (2005) for shear. It is however hard to use the results from experiments with single lap joints and butt joints as a basis for the development of accurate simulation models.

The more fundamental theory of fracture mechanics, starting with Griffith (1920) has also been applied to strength predictions for adhesives. The double cantilever beam (DCB) specimen is a convenient specimen to evaluate cleavage properties, cf. Fig. 4. The specimen is suitable for evaluation of the strength of adhesives loaded in peel. By using linear elastic fracture mechanics, Irwin and Kies (1954) introduce a method to measure the fracture energy using the compliance of the specimen. A large number of different expressions for the relation between the load, load point deflection, crack length and fracture energy can be derived using Euler-Bernoulli beam theory. For all of these expressions, the adherends are assumed to be clamped at the start of the adhesive layer. These expressions are used in different methods to measure the fracture energy of adhesives. In some methods, influences of the softening of the adhesive at the crack tip are included by an artificial increase of the crack length. Other attempts to improve the accuracy are to include effects of shear deformation of the adherends by use of Timoshenko’s beam theory (Mostovoy et al. 1967) and the use of a power-law adaptation of the compliance of the specimen (Berry, 1963).

![Fig. 4 Deformed DCB-specimen for peel with used notation.](image-url)
In Paper A it is shown that most of these methods give large errors. For short crack lengths the error is often larger than 40%. However, several standard, e.g. ASTM D3433 (1999) and BS7991 (2001), are based on these methods. For most of these methods the accuracy is strongly dependent on the crack length. In Paper B it is shown that the cohesive law only has a minor influence in the accuracy of the evaluated fracture energy. It is also shown that the closed-form solution presented by Stigh (1988) can be used to simulate a DCB-specimen with good accuracy. In this solution, the cohesive law is approximated with saw-tooth shaped cohesive law. The relation between the evaluated fractures energies from the different methods are in accordance with the experimental results presented by e.g. Blackman et al. (2003). An alternative method based on linear elastic fracture mechanics that excludes the crack length have shown to give surprisingly good accuracy cf. e.g. Tamuzs et al. (2003).

Nowadays when the paper, pencil and slide rule have been exchange to computers with finite element (FE) programs supported by people creating meshes, the use of cohesive laws have shown to be a well working method to represent adhesive layers. The origin of cohesive laws is the influential analyses by Barenblatt (1962) and Dugdale (1960). Starting in the mid 1970s, cohesive zones begun to be used with the finite element method cf. Hillerborg et al. (1976), Needleman (1987) and Stigh (1987). During the past twenty years, the finite element method has improved rapidly and the uses of cohesive laws and elements have been implemented as an engineering tool in many commercial FE-programs. Today the crucial point for a well performed numerical simulation is high-quality material data, i.e. for adhesives the cohesive law. Olsson and Stigh (1989) evaluate the DCB-specimen using Euler-Bernoulli beam theory and show that the cohesive law can be measured using an exact inverse method. Stigh and Andersson (2000) show that the inverse formula is derivable using the concept of energetic forces (Eshelby, 1951) and Andersson and Stigh (2004) use Rice’s $J$-integral to derive the inverse formula (Rice, 1968). Similar analytical analyses have been done by, Paris and Paris (1988) which derived a solution using the $J$-integral, Suo et al. (1992) analyse a DCB-specimen loaded with pure bending moments, and Nilsson (2005) extend the theory to large deformations. For shear, Barett and Foschi (1977) develop the end notch flexure (ENF) specimen, cf. Fig. 5. The method has been improved by Russel and Street (1982) that derive a simple formula for the energy release rate.

Using Euler-Bernoulli beam theory, Paper D and Alfredsson (2004) show how the cohesive law can be measured using the ENF-specimen. Leffler et al. (2007) derive the same inverse formula by use of the $J$-integral. By using this method the entire cohesive law can be measured experimentally.

Some methods to measure cohesive laws for mixed mode behaviour have recently been developed; cf. e.g. Högberg et al. (2007) and Sørensen and Jacobsen (2003). One problem with these experiments is to achieve a constant mode-mix during the entire experiment.
3 Theory

With the DCB-specimen, the peel stress is given by,

$$\sigma = \frac{d}{dw} \left( \frac{2F\theta}{b} \right)$$

and with the ENF-specimen, the shear stress is given by,

$$\tau = \frac{d}{dv} \left( \frac{9}{16} \frac{F^2 a^2}{E b h^3} + \frac{3}{8} \frac{F v}{b h} \right)$$

where $b$ is the width of the specimen and $E$ is Young’s modulus of the adherends. Notation is given in Figs. 4 and 5. A short background is given in the sequel based on the $J$-integral (Rice, 1968). The $J$-integral is given by,

$$J = \int_S \left( W dy - T \cdot \frac{\partial u}{\partial x} \right) ds$$

where, $W$ is the strain energy density, $T$ is the traction vector, $u$ is the displacement vector, and $n$ the unit outward normal to the integration path $S$. The coordinates system is shown in Fig. 6. The integration path $S$ can be chosen arbitrarily as long as it does not circumscribe any object that would alter the energy if it is moved in the $x$-direction and if the material is homogeneous in the $x$-direction within the material circumscribed by the integration path. If $S$ is such a path, and if $S$ is a closed path starting and ending at the same point, $J = 0$. 

Fig. 5 Deformed ENF-Specimen for shear with used notation.
A useful expression for the $J$-integral is derived by choosing the open integration path $A$-$B$-$C$-$D$, cf. Fig. 6. Here the points $A$ and $D$ are taken in the adherends just below and above the start of the adhesive layer, respectively. Moreover, the points $B$ and $C$ are taken far away from the loaded end of the specimen. Now, $J = J_{AB} + J_{BC} + J_{CD}$. Since the contribution from the strain energy density term, $Wdy$, is zero along the path $A$-$B$ we arrive at,

$$J_{AB} = -\int \left( \tau_{xy} u_{x}^{l} + \sigma_{yy} u_{y}^{l} \right) \, dx$$

(4)

where superscript $l$ indicates the lower adherend and a comma partial differentiation. If the path $B$-$D$ is taken sufficiently far away from the start of the adhesive layer, i.e. at a region there the contribution from the stresses and the strains are insignificant, the contribution to $J$ from this path becomes,

$$J_{BC} = 0$$

(5)

For the path $C$-$D$, is the contribution from the term, $Wdy = 0$ and,

$$J_{CD} = \int \left( \tau_{xy} u_{x}^{u} + \sigma_{yy} u_{y}^{u} \right) \, dx$$

(6)

where superscript $u$ indicates the upper adherend. Summing up the contributions from the different paths yields,

$$J_{ABCD} = \int \sigma_{yy} \left( u_{y,x}^{u} - u_{y,x}^{l} \right) \, dx + \int \tau_{xy} \left( u_{x,y}^{u} - u_{x,y}^{l} \right) \, dx$$

(7)

Using the peel and shear deformation of the adhesive according to Fig. 1 gives,

$$w = u_{y}^{u} - u_{y}^{l} \quad \quad \quad v = u_{x}^{u} - u_{x}^{l}$$

(8a,b)

By changing variables in Eq. (7) according to,
\[
\begin{align*}
dw &= \frac{dw}{dx} \\
dv &= \frac{dv}{dx}
\end{align*}
\]
(9a,b)

we get,

\[
J_{ABCD} = \int \tau dv + \int \sigma dv
\]
(10)

Similar analyses using an exterior integration path, gives the energy release in terms of applied load, cf. Fig. 7, Andersson and Stigh (2004), and Leffler et al. (2007). As an example, study the DCB-specimen.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig7.png}
\caption{A $J$-integral approach which circumscribe one of the applied loads.}
\end{figure}

Andersson (2002) use the path A-B-C-D in Fig. 7 to determine the energy release rate for the DCB-specimen. The only non-zero contribution originates from the path B-C. Along this path, the traction and displacement vectors from Euler Bernoulli beam theory can be used with good accuracy provided the crack length, $a$, is large compared to the height, $h$, of the adherend. Since the shear strains are zero in this theory, the strain energy density is given by,

\[
W = \frac{1}{2} \sigma_{xx} \varepsilon_{xx} = \left\{ \varepsilon_{xx} = \frac{\sigma_{xx}}{E} \right\} = \frac{1}{2} \frac{\sigma_{xx}^2}{E}
\]
(11)

where $E$ is Young’s modulus of the adherends. For the DCB-specimen the normal stress in section BC is given by,

\[
\sigma_{xx} = \frac{Fx}{I}
\]
(12)

where $I = bh^3/12$ is the area moment of inertia of the adherend and $t$ is the thickness of the adhesive layer. The shear stress for the section BC is given by,
\[ \tau_{xy} = -6 \frac{F}{bh^3} \left( \frac{h^2}{4} - y^2 \right) \]  

(13)

Inserted into Eq. (3) and using, \( \partial u_y/\partial x = -\theta_{bc} \) gives,

\[ J_{bc} = \int_{-h/2}^{h/2} \left( -\frac{F^2 x^2}{2EI} y^2 + 6 \frac{F}{bh^3} \left( \frac{h^2}{4} - y^2 \right) \theta_{bc} \right) dy \]  

(14)

and by using \( \theta = Fx^2/2EI + \theta_{bc} \) where \( \theta \) is the rotation of the loading point we get,

\[ J_{bc} = \frac{F \theta}{b} \]  

(15)

Since the DCB-specimen has two loaded legs, \( J = 2F \theta \). Due to symmetry, \( \nu = 0 \) for the DCB-specimen, and by setting this equation for \( J \) equal to Eq. (10) we arrive at Eq. (1) after differentiation with respect to \( w \).

An alternative for peel, based on linear elastic fracture mechanics has shown to give good accuracy,

\[ \sigma = \frac{d}{dw} \left( \frac{F^2}{Elb} \left( \frac{3EI\Delta}{2F} \right)^{1/2} \right) \]  

(16)

where, \( \Delta \) is deflection of the crossheads. The method has shown to give good accuracy both in numerically simulations (Paper E) and in comparison to experimental results (Paper F).

### 4 Experiments

In the present thesis, an automotive engineering epoxy, DOW-Betamate XW 1044-3 is used in all experiments with a nominal layer thickness, \( t = 0.2 \) mm. The curing condition for this adhesive is 30 minutes at 180ºC. After curing the specimens are left in the oven to slowly cool in order to minimize residual stresses. The non-bounded area, i.e. the crack in a macroscopic sense, is created by inserting a film of PTFE. This film also works as a distance in order to give the desired adhesive layer thickness. Additional methods are used to secure the desired layer thickness along the specimens. For ENF-specimens, steel wires are used. However, the adhesive area at the loaded end of the specimen is left undisturbed. Two types of manufacturing principles are used:

- For some DCB-specimens, two plates are first joined. After curing the plates are cut to specimens with a band saw.
- For some DCB-specimens and for all ENF-specimens, the adherends are joined and cured piece by piece.
No influence of the manufacturing method has been noted for the experimental results with the DCB-specimens.

**DCB-experiments**

Figure 8 shows the experimental setup used for the DCB-experiments with low rate of deformation. During an experiment the specimen is oriented vertically. The tensile test machine is based on two ball screws separating the two crossheads/loading points symmetrically. The separation of the crossheads is measure with a linear potentiometer or manually by use of a dial indicator. The force is measure with a load cell with a maximum capacity of 500 N placed at the right crosshead. The angle, $\theta$, is measured with an incremental shaft encoder placed on the left crosshead. The present shaft encoder has a resolution of $2 \times 10^5$ pulses per revolution. The elongation of the adhesive layer, $w$, at the loaded end of the adhesive layer is measured with two *linear variable differential transformers* (LVDT). One LVDT on each side of the specimen, cf. Fig. 8B. Since the adhesive is many times more compliant than the adherends, the measurement of $w$ is accurate by this method.

![Fig. 8 Experimental setup with the DCB-specimen](image)

All experiments are performed with a nominally constant crosshead velocity. When designing the specimens, two things have to be taken into account, the rotation of the loading point has to be large enough to give a good resolution for the incremental shaft encoder and it is preferably if the specimen remains elastic during the experiment. However, the evaluation method is not dependent on elastically deforming adherends. Plastic deformation of the specimens do not directly influence the analyses but the deformation of the adhesive layer will be much more difficult to measure since the specimen will slowly move downwards in the test machine due to large deformations.
Figure 9 shows an alternative test setup for peel used in Paper E. By using Eq. (16) the cohesive law can be evaluated by measuring the force $F = P/2$, the displacement, $\Delta = 2\delta$ and the deformation of the adhesive layer, $w$. More details are given in Paper E.

**ENF-experiments**

Figure 10 shows two experimental setups for the ENF-specimen using a three point bending fixture. The main differences between the equipments are the load capacity and the method to measure the shear deformation of the adhesive layer. In Fig. 10A the shear deformation is measure with an optical measurement system using a speckle pattern painted on the specimen. In Fig. 10B the shear deformation is measured using a LVDT. Another method that has been used for measuring the shear deformation is to use a clip gauge fixed on two measurement arms (Paper D). This is not showed in the figures. All the experiments are performed with constant velocity of the loading point or with a constant rate of shear deformation. The length of the initially unbounded part of the specimen is critical for this type of experiments. The crack length has to be long enough to avoid instability but at the same time, the distance between the applied force at the centre of the specimen and the start of the adhesive layer has to be long enough to contain the entire damage zone. More details are given by Leffler et al. (2007).
Fig. 10 Experimental setups with the ENF-specimen; A: University of Växjö, B: University of Skövde.

Analyse of measurement data
As suggested by Fernberg and Berglund (2001) measured values of $J$ are first adapted to a Prony series before the cohesive law is derived by differentiation. The Prony series is given by,

$$J(w) = \sum_{i=1}^{k} A_i \exp\left(\frac{-kw}{iw_{\max}}\right)$$

where the parameters $A_i$ are determined by a least square fitting procedure using $k$ terms. The choice of the number of terms is done based on a visual comparison of the adapted and experimental $J$-curves. The value of the fracture energy $J_c$ can often be identified as the maximum value of $J$. However, in some cases a more intricate method has to be used to identify $J_c$, cf. Paper E.

Presently, the methods to measure cohesive laws have been used successfully to evaluate several different adhesives: epoxies, cyanoacrylates, and polyurethans. Moreover, the methods have been used to measure cohesive laws for delamination of composites. It may also be noted that Gunderson et al. (2007) use Eq. (15) to measure the modus I interlaminar fracture energy (peel) for a composite.

5 Properties of adhesive layers
The fracture energy is typically larger for shear than for peel loading, cf. e.g. Paper C for peel and Leffler et al. (2007) for shear. Figure 11 shows a typically curve of $J$ vs. the deformation of the adhesive layer for peel and shear. Figure 12 shows the constitutive relation obtained by differentiating $J$ with respect to the deformation of the layer.
In Paper C it is shown that the cohesive law for an adhesive layer loaded in peel can be evaluated by use Eq. (1). The previously presented results using this method but a slightly different experimental setup did not catch the entire cohesive law (Andersson and Stigh, 2004). Furthermore, it is shown that the same cohesive law can be used with different geometries of the specimens. However, when the adherends deform substantially through plastic deformation, the fracture energy tends to increase. Salomonsson and Stigh (2008) present numerical simulations that show that elastically stored energy in the adhesive layer due to in-plane straining of the adhesive layer may explain the increased fracture energy. However, so far no experimental study has verified their conclusions.

In Paper D it is shown that the cohesive law for an adhesive layer loaded in shear can be evaluated by use of Eq. (2). The method has been used in further analyses by Leffler et al. (2007) and Paper E.
In Paper E effects of temperature and strain rates are studied. For peel loading, the influence of the temperature is studied in a temperature range from -40°C to +80°C. It is shown that the fracture energy is rather unaffected of the temperature but the shape of the cohesive law is strongly dependent of the temperature. The strain rate dependence is determined in both peel and shear. For peel it is shown that the fracture energy increases slightly with increasing strain rate and in shear, the fracture energy decreases with increasing strain rate. The peak stresses in peel and shear both increase with increasing strain rate.

In constitutive theories, the inelastic response of materials is postulated to be due to two different mechanisms: plasticity and damage. Plasticity is manifested by a permanent deformation after unloading the material; damage is manifested through a decreased elastic stiffness of the material, cf. e.g. Alfredsson and Stigh (2004). Under monotonically increasing deformation, as is the case in the DCB- and ENF-experiments, there is no way to determine if the inelastic deformation is due to plasticity or damage. This is however an important distinction to be made when developing constitutive models for adhesive layers. In order to distinguish between effects of plasticity and damage, a novel method is developed in Paper F. Experiments are performed that show that the fracture process, for the present adhesive layer, only includes minor plasticity. In the experiments, a DCB-specimen is exposed to a repeated loading in order to achieve inelastic behaviour at the start of the layer. With a well defined pre-load, the size of the region of in-elastic behaviour is predicted with good accuracy. When the specimen is re-loaded, the properties of the in-elastically loaded adhesive influence the result. By comparing with numerical simulations, the relation between damage and plasticity can be estimated.

6 Future work
During this work several possibilities for further work has been identified. Some of them are:

- The DCB-specimen is theoretically stable but in spite of this some experiments show unstable crack propagation. The reason might be the strain rate dependence of the cohesive law. Numerical and experimental studies might reveal if this assumption is correct.
- An extension of the new method to deduce the balance between damage and plasticity developed in Paper F to shear experiments using the ENF-specimen seems straight-forward. Numerically analyses by Salomonsson and Andersson (2008) indicate that the fracture process in shear involve substantial plasticity.
- A new experimental setup with mixed mode loading where the relation between peel and shear is constant is under development.
- New experiments with plastically deforming adherends in order to determine the cohesive law with substantial in-plane straining of the adhesive. Numerical analyses presented by Salamonsson and Stigh (2008) can be used for comparisons.
References


