Strength of Sandwich Panels Loaded in In-plane Compression

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Preface

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First of all, I would like to express my gratitude to my supervisor, Dr. Stefan Hallström, for valuable discussions and encouraging guidance. Anders Beckman, Bo Magnusson and Peter Arfert are acknowledged for their invaluable assistance during my experimental work. I would also like to thank Brad Semeniuk, my former contact at Rieter, for his enthusiasm and support.

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Abstract

The use of composite materials in vehicle structures could reduce the weight and thereby the fuel consumption of vehicles. As the road safety of the vehicles must be ensured, it is vital that the energy absorbing capability of the composite materials are similar to or better than the commonly used steel structures. The high specific bending stiffness of sandwich structures can with advantage be used in vehicles, provided that the structural behaviour during a crash situation is well understood and possible to predict. The purpose of this thesis is to identify and if possible to describe the failure initiation and progression in in-plane compression loaded sandwich panels.

An experimental study on in-plane compression loaded sandwich panels with two different material concepts was conducted. Digital speckle photography (DSP) was used to record the displacement field of one outer face-sheet surface during compression. The sandwich panels with glass fibre preimpregnated face-sheets and a polymer foam core failed due to disintegration of the face-sheets from the core, whereas the sandwich panels with sheet molding compound face-sheets and a balsa core failed in progressive end-crushing. A simple semi-empirical model was developed to describe the structural response before and after initial failure.

The postfailure behaviour of in-plane compression loaded sandwich panels was studied by considering the structural behaviour of sandwich panels with edge debonds. A parametrical finite element model was used to determine the influence of different material and geometrical properties on the buckling and postbuckling failure loads. The postbuckling failure modes studied were debond crack propagation and face-sheet failure. It could be concluded that the postbuckling failure modes were mainly determined by the ratio between the fracture toughness of the face-core interface and the bending stiffness of the face-sheets.
Dissertation

This thesis consists of a brief introduction to the area of research and the following appended papers:

Paper A


Paper B

A. Lindström and S. Hallström: Strength of In-plane Compression Loaded Sandwich Panels with Debonds, manuscript to be submitted 2007
Division of work between authors

Paper A
Lindström performed the experiments, the analysis and wrote the paper. Hallström initiated and guided the work and contributed to the paper with comments and revisions.

Paper B
Lindström performed the finite element analysis and wrote the paper. Hallström initiated and guided the work and contributed to the paper with comments and revisions.
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Paper A Energy Absorption of Sandwich Panels Subjected to In-plane Loads A1-A16
Paper B Strength of In-plane Compression Loaded Sandwich Panels with Debonds B1-B16
1 Introduction

The increasing environmental concern and the increasing petrol cost in today’s society are incentives for the automotive industry to reduce the fuel consumption of vehicles. This reduction can be achieved by introducing composite materials into the vehicle structure, instead of the commonly used steel structures, and thereby reduce the vehicle weight.

Sandwich panels which have high bending stiffness and strength compared to their weight can be used with advantage in vehicle structures. Sandwich panels consist of two relatively thin and stiff face-sheets that are separated by and bonded to a lightweight core material as shown in figure 1. The face-sheets may consist of metal or composite material, whereas the core material may consist of either honeycomb structures, foam or wood. Sandwich structures mainly carry applied bending moments as tensile and compressive stresses in the two face-sheets, whereas applied transverse forces predominantly are carried by the core material as shear stresses [1]. By increasing the core thickness and thereby increasing the distance between the face-sheets the flexural rigidity of the structure is increased with low weight penalty, due to the low density of the core material.

![Figure 1: Schematic of structural sandwich panel](image)

A first step to reduce the weight of a vehicle is to replace secondary structure, that is structure with little or no load bearing function, with composite and sandwich components. To reduce the vehicle weight further and to fully utilise the structural properties of composite and sandwich materials primary load bearing structure needs to be replaced too. Such structures can only be replaced by composite and/or sandwich materials if the structural behaviour is competitive both during in-service use and in the case of a crash situation. The road safety of vehicles, which includes the safety of both the occupants of the vehicles and pedestrians, is an important issue for society. According to the International Road Traffic and Accident Database (IRTAD) [2] there were for example 43,334 fatalities in traffic accidents in the US alone during 2005. The vehicle structure should therefore not only be optimised for low weight but also for best possible energy absorption to improve the road safety. Energy absorption is here defined as transformation of the kinetic energy of the moving vehicle into other forms of energy through deformation of the vehicle structure. Even though it has been shown that the energy absorbing
CHAPTER 2. ENERGY ABSORPTION

capability of composite structures can exceed that of metal structures [3–6], they are not commonly used in primary vehicle structure. One of the reasons for this is the lack of knowledge about the failure propagation in a composite structure during a crash situation, making it hard to predict the energy absorption. As no reliable methods describing the crash events exist, the development cost of the structure is high due to the large amount of experimental work needed to determine the structural response. The excellent energy absorbing capability of composite materials is fully utilised in Formula One racing cars [7]. If the structures used in the cost insensitive motor racing cars are to be used in massproduced vehicles the material, development and production costs need to be reduced. For example it may be more cost efficient to use glass fibre with short and randomly distributed fibres than to use uni-directional carbon fibres, both due to material and production costs. If composite and sandwich components are to be accepted for use in primary structures of vehicles, their failure behaviour during a crash event must be predictable.

2 Energy absorption

Road safety is strongly regulated in many countries. Test methods to ensure the safety of vehicles are developed by organisations such as the European Enhanced Vehicle-safety Committee (EEVC) and International Harmonized Research Activities (IHRA). These test methods are used by organisations such as the National Highway Traffic Safety Administration (NHTSA) and the European New Car Assessment Programme (Euro-NCAP) to assess the safety performance of cars. Frontal impacts, side impacts and pole impacts are used to evaluate the safety for the driver, adult and child passengers. Further tests are conducted to assess the safety of pedestrians in crash situations. The abbreviated injury scale (AIS) and the head injury criteria (HIC) are used to evaluate the injury afflicted to the vehicle occupants during the impact. During impact tests the occupants of the vehicle are represented by dummies equipped with measuring instruments. The AIS is an anatomical scoring system that ranks the severity of injury on a scale of 1-6, where 1 is a minor injury and 6 is lethal [8]. The HIC value is calculated as

$$HIC = \max_{t_1, t_2} \left\{ \frac{1}{(t_2 - t_1)^{1.5}} \left[ \int_{t_1}^{t_2} a(t) dt \right]^{2.5} \right\},$$

where $a$ is the acceleration in the centre of mass of the head measured in g’s and $t_1$ and $t_2$ are two time points maximising the function [9]. The timespan $(t_2 - t_1)$ maximising the function must not exceed 36 ms. The HIC value should not exceed 1000 in order to comply with the lower performance limit of the Euro-NCAP frontal impact test.

To achieve acceptable accelerations on the occupants of a vehicle and to ensure the integrity of the passenger compartment in a crash situation a complex system of both passive and active countermeasures are often employed. Safety belts, airbags
and crash zones are but a few examples. The crash zones, which are included in the primary vehicle structure, should convert the kinetic energy of the moving vehicle into other forms of energy. Those other forms could be elastic work $U$ (molecular stretching and bending), irreversible deformation work $W_a$ in the form of plastic work (molecular slip) or fracture work (creation of free surface) or dissipating energy $W_d$ in the form of heat (for instance from friction). The work $W$ of a force $P$ acting on the structure during a crash situation is given by the integration of the force over the compression length $\delta$ as

$$W = U + W_a + W_d = \int_0^\delta P d\delta.$$  \hspace{1cm} (2)

In order to maximise the energy absorption during the deformation of the structure, the reaction force $P$ should be as high as possible without resulting in unacceptable high accelerations on the vehicle occupants. The optimal energy absorption is therefore achieved if this critical load level $\hat{P}$ is maintained during the entire deformation. This behaviour is obviously strongly idealised, but a good energy absorber should imitate this behaviour as closely as possible.

2.1 Common energy absorbers

The most commonly used collapsible energy absorbers come in the form of tubes, frusta, struts, honeycomb cells and sandwich plates [10]. Foam materials and balsa wood are also good energy absorbers. The failure mechanisms and energy absorption of metal tubes are well documented and they are therefore extensively used in vehicle structures. Due to their symmetrical shape, tubes can be designed to deform in different stable failure modes. Metal tubes can for example be designed to plastically deform in tube inversion, which means that a dye is used to force the tube to turn inside out. A special case of tube inversion is tube splitting where the dye forces the tube to split. Another deformation mode is axial tube crushing where optimal energy absorption is reached if the tube progressively buckles plastically. Due to the favourable energy absorption of tubes their use has been extended to include composite materials [3–6, 11, 12] and even sandwich structures, either as tubes of sandwich materials [13, 14] or as sandwich panels with internal tubes [15]. The composite tubes can be designed to fail in Euler buckling, progressive folding or brittle fracture [5]. Euler buckling which is an unstable failure mechanism gives low energy absorption and should therefore be avoided in favour of other failure modes.

Even though tubes show good energy absorbing capability, beams and plates may be better suited for in-service use as they exploit the bending properties of sandwich structures fully. The majority of the studies of energy absorption of sandwich structures considers transversely loaded plates or beams and mainly focuses on the localised impact problem [16]. Both impact damage of the face-sheets and sub-interface core damage have been dealt with. As sandwich panels can be used
at different locations in a vehicle structure, the loading condition during an impact does not necessarily have to be transverse to the face-sheets. The panels can also be loaded in-plane or oblique to the face-sheets. It is therefore important to study these impact situations. This thesis focuses on in-plane compression loaded sandwich panels.

### 2.2 Energy absorption of in-plane compression loaded sandwich panels

Sandwich panels should be incorporated in the vehicle structure so that their advantage of high specific bending stiffness and strength is fully utilised. During normal use of the vehicle the structure mainly carries bending loads, whereas in a crash situation the loading condition could as already mentioned be completely different. When compressed in the in-plane direction the load is mainly carried by the face-sheets of the sandwich, whereas the core stabilises the structure and prohibits premature buckling of the face-sheets. The high flexural rigidity increases the buckling load of sandwich structures compared to single skin (monocoque) composite structures. The structural response of in-plane quasi-statically loaded sandwich panels is mainly determined by the failure initiation and propagation and can for example take the form presented in figure 2. To achieve high energy absorption dur-

![Figure 2: A force-displacement curve of a compression loaded sandwich panel](image)
2.2. ENERGY ABSorption OF IN-Plane Compression LOADed SANDwich PANELs

ing a controlled deformation, the failure mechanisms and their propagation need to be predictable.

As illustrated in figure 2 the structural response, of the sandwich panels investigated in this thesis, can be considered linear until first failure occurs during in-plane compression loading. This linear response can be described by an effective Young’s modulus $E_e$ of the structure, which in turn can be calculated from the material and geometrical properties of the different constituents as

$$E_e = \frac{1}{2t_f + t_c}(2t_f E_f + t_c E_c),$$  \hspace{1cm} (3)

where $t_f$ and $t_c$ are the thicknesses of the face-sheets and core, respectively and $E_f$ and $E_c$ are moduli in the load direction of the face-sheets and core, respectively. The initial failure is either related to global buckling, local buckling or face-sheet fracture [17]. In theory the core could of course also fracture, but in most cases of practical interest the ultimate strain for the core exceeds that of the faces.

If the compression of the structure is continued after initial failure the damage will start to propagate. Mamalis et al. [18] experimentally studied the crushing response of quasi-statically in-plane compression loaded sandwich panels. By testing sandwich panels with different material concepts they identified the following three types of collapse modes: global buckling, unstable sandwich disintegration and stable end-crushing.

Buckling

If the initial failure is buckling the structure will continue to fold in an unstable manner when loaded further. As the damage is confined within a small area during this folding process, as illustrated in figure 3(a), the resulting energy absorption is low. Buckling of the sandwich panel can for example lead to secondary failure in the form of debonding of the face-sheets from the core and shear failure of the core as shown in figure 3(b), but also to delamination and fracture of the face-sheets.

Unstable sandwich disintegration

Face-sheet fracture can initiate delaminations in the face-sheets and debonds in the face-core interface. The delaminated and/or debonded face-sheets are prone to buckle away from the core. This buckling displacement may promote crack propagation. In cases where the bending strength of the face-sheets is high in comparison to the fracture toughness of the interface the sandwich will rapidly disintegrate. Little damage occurs in the core and face-sheets during propagation of the debond crack, as shown in figure 4, which results in low energy absorption and an unstable collapse mode.


Stable end-crushing

If the strength of the interface and the core is sufficiently high in comparison to the bending strength of the face-sheets the debond crack propagation will be more stable. This means that the crack propagation arrests and promotes other failure modes in the structure as for example delamination propagation and face-sheet fracture. This complex mix of different failure modes, clearly shown in figure 5,
enables high energy absorption of the progressive end-crushing collapse mode. The structural response of sandwich panels failing in progressive end-crushing can take the form illustrated in figure 2. After initial failure the load bearing capacity of the structure is significantly reduced. The load needed to propagate the damage is however relatively high and stable, which promotes high energy absorption.

3 Failure modes

3.1 Initial failure

As already mentioned Fleck and Sridhar [17] identified the initial failure modes of in-plane quasi-statically loaded sandwich columns as global buckling, local buckling and face-sheet failure. If the material properties of the different constituents are known the failure load for the different failure modes can be analytically calculated by using laminate and sandwich theory [1]. These solutions are also valid for uni-axially loaded sandwich panels. In the following section a uni-axially loaded sandwich panel, with dimensions as illustrated in figure 6, is considered.

Global buckling

Global buckling of uni-axially loaded sandwich panels can be treated as an Euler buckling part and a shear buckling part. The Euler buckling load $P_b$ for a simply supported uni-axially loaded sandwich plate is defined as

$$P_b = \frac{n^2 \pi^2 D_b}{L^2},$$

(4)
where $n$ is the buckling mode, $D$ is the flexural rigidity, $b$ is the width of the panel and $L$ is the panel length in the direction of the applied load. The shear buckling load $P_s$ can approximately be defined as

$$P_s = Sb = \frac{G_c d^2 b}{t_c},$$

where $S$ is the shear stiffness, $G_c$ is the shear modulus of the core and $d$ is the distance between the middle axis of the two face-sheets as illustrated in figure 6. This approximation is valid for a sandwich with thin faces $t_f << t_c$, compliant core $E_c << E_f$ and large shear modulus of the face-sheets. The total critical buckling load can be calculated from

$$\hat{P} = \frac{1}{P_b} + \frac{1}{P_s},$$

which gives

$$\hat{P} = \frac{n^2 \pi^2 bD/L^2}{1 + \frac{n^2 \pi^2 D}{L^2 S}}.$$

Local buckling

Local buckling can take the form of localised buckling, dimpling and wrinkling. Localised buckling occurs in the vicinity of the load introductions, whereas dimpling is buckling of the face-sheets into the cavities of a honeycomb core. Wrinkling can occur simultaneously all over the surface of the face-sheets [19] and is dependent on the material properties and geometry of the core and face-sheets. One way to calculate the critical wrinkling load is to consider the panel as a beam on an elastic foundation [20]. The simplest form of an elastic foundation, which implies a series
of closely spaced springs, is often referred to as a Winkler foundation. The critical wrinkling load $\hat{P}_w$ can be described as [19]

$$\hat{P}_w = 2b\sqrt{D_f k} = 2b\sqrt{D_f \frac{E_c}{t_c}},$$

(8)

where $D_f$ is the flexural rigidity of the face-sheet and $k$ is the foundation stiffness. The drawback with the Winkler foundation model is that the shear stiffness of the core is neglected. Several analytical solutions with included shear behaviour exist. Hoff and Mautner derived the following formula [21]

$$\sigma_w = 0.91\sqrt[3]{E_f E_c G_c}.$$  

(9)

However they suggested that for practical design the more conservative formula

$$\sigma_w = 0.5\sqrt[3]{E_f E_c G_c},$$  

(10)

should be used. This formula is conservative with respect to idealised conditions but does not take any material inhomogeneity or perturbed geometry into account. The critical load can then be calculated as

$$\hat{P}_w = 1.14b\sqrt[3]{D_f E_c G_c}.$$  

(11)

**Face-sheet failure**

Depending on the material in the face-sheets the compressive failure behaviour could vary. The compressive failure of metal face-sheets is characterised by plastic deformation when the yield strength of the material is exceeded. If the face-sheets consists of a composite material with long aligned fibres the main compressive failure modes are elastic microbuckling, plastic microbuckling, fibre crushing, splitting, buckle delamination and shear band formation [22]. The critical failure mode is determined by the material and geometrical properties of the composite. In the following a short description of the different failure modes are presented.

Both elastic and plastic microbuckling are shear buckling instabilities. But the critical stress for elastic microbuckling is only dependent on the shear modulus of the composite, whereas the critical stress for plastic microbuckling depends on fibre misalignment and plastic shear deformation in the matrix. Another possible failure mode is fibre crushing, which occurs if the strain of the loaded composite exceeds the crushing strain of the fibres. Fibre crushing can both take the form of fibre splitting and microbuckling within fibres. If there are inhomogeneities within the composite, cracks can start to propagate and lead to splitting. Manufacturing flaws, impact damage and out-of-plane loading induced by fibre waviness can trigger delamination. Buckling of the delaminated laminate promotes delamination crack propagation. If the composite has low fibre volume fraction and a polymer matrix, the matrix can yield and fracture in the form of shear bands during compression of the composite.
The most common fracture mode of unidirectional laminates is plastic microbuckling, also called kinking [22, 23]. For composites with short and randomly distributed fibres failure is generally more complex and it is often impossible to distinguish a single failure mode. Instead of assuming a specific failure mode, the critical failure stress $\hat{\sigma}_f$ of the composite can be experimentally determined and used to calculate the critical load as

$$\hat{P} = 2tfb\hat{\sigma}_f.$$  \hspace{1cm} (12)

3.2 Postfailure

To achieve the best possible energy absorption of in-plane loaded sandwich panels, the collapse mode must be of the stable end-crushing type. To achieve this the sandwich should be designed so that the face-sheets fail before local and global buckling of the structure occurs. One of the failure modes of face-sheet failure is delamination. Delamination can lead to buckling of the face-sheets, which in turn can promote debonding of the face-sheets from the core. Depending on the core, face and interface properties the debond crack propagation will be stable or unstable. A necessary condition for stable crack growth is that the crack driving force is sufficiently reduced with increasing crack length. In-plane compression loaded composite and sandwich structures with delaminations and/or debonds have received considerable attention in recent research (e.g. [24–34]). There are several failure modes of in-plane compression loaded structures with delaminations and/or debonds.

Composite structures with delaminations and/or debonds tend to buckle when loaded in compression. Buckling can lead to secondary failure in the form of debond/delamination crack propagation and laminate failure due to bending. As a first approximation the buckling load can be calculated by assuming clamped boundary conditions at the crack tip. The elastic foundation of the matrix and the core for the laminate case and the sandwich case, respectively, will however provide a less rigid boundary condition. The buckling load is therefore overestimated when using this approximation. A better solution may be to again consider the structure as a beam supported on an elastic foundation [24–26]. Vizzini and Lagace [24] considered a delaminated laminate as a beam partly supported by a Winkler foundation, as shown in figure 7. By assuming that the deflection shape can be described by the complete symmetric Fourier series for clamped-clamped boundary conditions the buckling load, and mode, can be calculated using a Rayleigh-Ritz energy method. It was found that the buckling load is only dependent on two non-dimensional parameters describing the foundation stiffness and length. The foundation stiffness parameter $f$ is defined as

$$f = \frac{ka^4}{D_f} = 12\frac{E_c}{E_f}\left(\frac{a}{tf}\right)^2\frac{tf}{t_c},$$  \hspace{1cm} (13)
where $a$ is the delamination length. The foundation length ratio $\eta$ is defined as

$$\eta = 1 - \frac{a}{L}. \quad (14)$$

The buckling load can then be described as

$$\hat{P}_f = \frac{\dot{c} E_t a^3 b \pi^2}{12a^2}, \quad (15)$$

where the effective coefficient of fixity $\dot{c}$ is a correction term that describes the boundary condition at the delamination crack tip. The coefficient of fixity $\dot{c}$ can be described as

$$\dot{c} = \frac{\hat{P}_f L}{E_t a^2 \pi^2 \eta^2 b}. \quad (16)$$

The coefficient of fixity $\dot{c}$ increases with increasing foundation stiffness $f$ and decreasing foundation ratio $\eta$. Niu and Talreja [25] studied sandwich panels with one or two arbitrary located debonds with different boundary conditions. They found that the buckling load is significantly reduced when the debond is located at the edge of sandwich panels with free-free boundary conditions. The face-sheet is then acting as a cantilever beam partially supported by an elastic foundation. Cheng et al. [26] treated a discontinuous sandwich structure with a debond as a continuous system without debonds, but with an added fictitious force system. Their model considers a beam on an elastic foundation with a force system that cancels out the interfacial traction forces of the separated regions. Their model accounts for both transverse, normal and shear properties of the core, whereas a Winkler foundation only takes the transverse stiffness into account. A Winkler foundation model may therefore not be sufficient for sandwich structures as the core can be subjected to large shear strains. Another method to solve the buckling and post-buckling problem is to separate the sandwich or composite structure into different beam parts with different thicknesses and, in the case of a sandwich, different material properties [27–29]. The governing beam equations for the different parts give a set of equations that can be solved by considering the boundary conditions and equilibrium equations at the crack tip.

When the structure is compressed beyond buckling the mode shape of the buckled debonded face-sheets can lead to both debond crack propagation due to opening
of the crack and face-sheet fracture due to bending. As a debond is an interfacial crack between two elastically dissimilar materials the fracture mode is mixed [30–32], which results in that the decomposition of the energy release rate \( G \) into the classical opening \( G_I \) and shearing \( G_{II} \) components is not possible. The total energy release rate \( G \) is however well defined and can be calculated, either by the path independent J-integral [29] or from the potential energy of the system using the variational principle [27, 33]. The damage propagation during the postbuckling phase is determined by the fracture toughness \( G_c \) of the core-face interface and the strength of the face-sheets. Crack propagation will only occur if the energy release rate \( G \) is larger than the fracture toughness \( G_c \). The fracture toughness is typically specified for a certain material, or material combination, under a certain type of loading condition. For many sandwich materials the strength of the core material is lower than for the faces and for the interface between the two. This means that crack propagation is predominantly governed by properties of the core material, even if the crack propagates along the face-core interface. The local stress field at the crack tip is also likely to vary with crack length and different geometry and elastic properties of the faces and the core. Using a single value for the fracture toughness is however believed to be justified, assuming that the local stress field around the crack tip is reasonably similar for all cases handled in the analysis.

Sankar and Narayanan [34] used a finite element (FE) model to determine the buckling load and the postbuckling behaviour of in-plane compression loaded sandwich panels with one-sided centrally positioned debonds. They compared the failure loads from experiments with the maximum load obtained from the FE model. It could be concluded that the linear buckling analysis alone was not sufficient to predict the load bearing capacity of the structure. Therefore a nonlinear postbuckling analysis was conducted. For the material and geometrical configurations investigated the structure did not fail due to the expected debond crack propagation, instead the failure was probably triggered by core failure. In paper B in this thesis a parametrical FE model was used to investigate the influence of different material and geometrical properties on the buckling load and postbuckling failure mode of sandwich panels with edge debonds symmetrically located on both interfaces. The investigated postfailure modes were debond crack propagation and face-sheet failure.

4 Summary of thesis

To determine the energy absorbing capability of in-plane compression loaded sandwich panels, the possible failure modes have to be known. One purpose of this thesis is therefore to identify and describe the structural behaviour of possible failure modes. With this knowledge it should be possible to design sandwich panels with favourable energy absorption.

In paper A an experimental study to determine possible failure modes was conducted. Sandwich panels with glass fibre sheet molding compound (SMC) face-
sheets and a balsa core and sandwich panels with preimpregnated (prepreg) glass fibre face-sheets and a foam core were quasi-statically compressed in the in-plane direction. The displacement fields of one outer face-sheet surface was measured using a digital speckle photography (DSP) equipment. One sandwich configuration failed by stable end-crushing, whereas the others failed due to unstable sandwich disintegration. The structural response before and after initial failure was described by a simple semiempirical model.

Results from previous studies (e.g. [18]) and results from paper A in this thesis suggest that debond propagation is an important postfailure mechanism during in-plane compression loading of sandwich panels. The structural behaviour of sandwich panels compressed beyond the initial failure is comparable to that of sandwich panels with debonds symmetrically located at the edges of both face-sheet/core interfaces. In paper B a parametrical FE model of sandwich panels with edge debonds was used to study the influence of different material and geometrical properties on the buckling load and postbuckling failure mode. A linear buckling analysis was used to calculate the buckling load and mode for several crack lengths for each sandwich configuration. Further a nonlinear postbuckling analysis was used to determine the load at debond crack propagation and face-sheet failure. It can be concluded that the postfailure mode is mainly determined by the fracture toughness of the core and the bending stiffness of the face-sheets.

5 Future Work

The core materials investigated in this thesis show plastic behaviour when loaded in compression. The FE model however, so far only included linear elastic material models. This resulted in unrealistically high load transfer through the core, as the yield stress in the core was exceeded. The calculated load at debond propagation and/or face-sheet failure was therefore unrealistically high for some crack lengths and sandwich configurations. To get more reliable values for the postbuckling failure loads plasticity has to be included in the model.

The current FE model could be used to design sandwich panels to fail due to either debond propagation or face-sheet failure. The postfailure behaviour should be verified through experiments.

It would be interesting to include damage to the face-sheets, as the current model overpredicts the bending stiffness of the face-sheets. If the initial damage size could be predicted it would be possible to decide if a material and geometrical configuration would give favourable postbuckling behaviour or not. Finally, it would be interesting to propagate the damage in both the core and face-sheets. In doing so the complete structural behaviour during in-plane compression loading of sandwich panels could be predicted.
Bibliography


