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In-plane Compressive Response of Sandwich Panels

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Preface

The work presented in this thesis was carried out at the Department of Aeronautical and Vehicle Engineering, School of Engineering Sciences, Royal Institute of Technology (KTH). The work presented in the last two papers was carried out within the Centre for ECO^2 Vehicle Design.

The funding for the first three papers was provided by Rieter Automotive Management AG. The funding for the last two papers was provided by the Swedish Governmental Agency for Innovation Systems (VINNOVA) and the Royal Institute of Technology (KTH). The financial support of all parties is gratefully acknowledged.

First of all, I would like to express my gratitude to my supervisor, Dr. Stefan Hallström. This work would not have been possible without his encouraging guidance and our valuable discussions. Anders Beckman and Bo Magnusson are acknowledged for their invaluable assistance during my experimental work. I am maybe not known for my mechanical dexterity, but I hope that I have improved this skill during my many hours in the lab. I would also like to thank Brad Semeniuk, my former contact at Rieter, for his enthusiasm and support.

Further I would like to thank my friends and colleagues at the Department of Aeronautical and Vehicle Engineering for their support and companionship. The interesting discussions during lunch and tea (coffee) breaks have been invigorating for my work. My office mate Ivan Stenius deserves a special thanks, both for inspiring discussions and an enjoyable work atmosphere.

My friends outside of the department are acknowledged for their support but most of all for their friendship. To Mirela, thank you for your encouragement and love during the last hard working months of this thesis, it really made life much easier.

Finally, to my family, thank you for always believing in me and your tremendous support and encouragement.

Stockholm, September 2009

Anders Lindström

Abstract

The high specific bending stiffness of sandwich structures can with advantage be used in vehicles to reduce their weight and thereby potentially also their fuel consumption. However, the structure must not only meet the in-service requirements but also provide sufficient protection of the vehicle passengers in a crash situation. The in-plane compressive response of sandwich panels is investigated in this thesis, with the objective to develop a methodology capable of determining if the structural response is likely to be favourable in an energy absorption perspective.

Experiments were conducted to identify possible initial failure and collapse modes. The initial failure modes of sandwich panels compressed quasi-statically in the in-plane direction were identified as global buckling, local buckling (wrinkling) and face sheet fracture. Global buckling promotes continued folding of the structure when compressed beyond failure initiation. Face sheet fracture and wrinkling can promote collapse in the form of unstable debond crack growth, stable end-crushing or ductile in-plane shear collapse. Both the unstable debond crack propagation and the stable end-crushing are related to debond crack propagation, whereas the ductile in-plane shear mode is related to microbuckling of the face sheets.

The collapse behaviour of sandwich configurations initially failing due to wrinkling or face sheet fracture was investigated, using a finite element model. The model was used to determine if the panels were likely to collapse in unstable debond propagation or in a more stable end-crushing mode, promoting high energy absorption. The collapse behaviour is mainly governed by the relation between the fracture toughness of the core and the bending stiffness and strength of the face sheets. The model was successfully used to design sandwich panels for different collapse behaviour. The proposed method could therefore be used in the design process of sandwich panels subjected to in-plane compressive loads.

During a crash situation the accelerations on passengers must be kept below life threatening levels. The extreme peak loads in the structure must therefore be limited. This can be achieved by different kind of triggering features. Panels with either chamfered face sheets or with grooves on the loaded edges were investigated in this thesis. The peak load was reduced with panels incorporating either of the two triggering features. Another positive effect was that the plateau load following failure initiation was increased by the triggers. This clearly illustrates that triggers can be used to promote favourable response in sandwich panels.

Vehicles are harmful to the environment not only during in-service use, but during their entire life-cycle. By use of renewable materials the impact on the environment can be reduced. The in-plane compressive response of bio-based sandwich panels was therefore investigated. Panels with hemp fibre laminates showed potential for high energy absorption and panels with a balsa wood core behaved particular well. The ductile in-plane shear collapse mode of these panels resulted in the highest energy absorption of all investigated sandwich configurations.

Dissertation

This thesis consists of a brief introduction to the area of research, an overview of the performed work and the following appended papers:

Paper A

A. Lindström and S. Hallström: Energy Absorption of Sandwich Panels Subjected to In-plane Loads, 2006. Presented at the 8th Biennial ASME Conference on Engineering Systems Design and Analysis, Torino, Italy, 4-7 July, 2006.

Paper B

A. Lindström and S. Hallström: In-plane compression of sandwich panels with debonds, Composite Structures, doi:10.1016/j.compstruct.2009.08.039, 2009.

Paper C

A. Lindström and S. Hallström: Energy absorption of SMC/balsa sandwich panels with geometrical triggering features, submitted 2009.

Paper D

A. Lindström and S. Hallström: Design for various collapse behaviour of sandwich panels subject to in-plane compression; manuscript to be submitted 2009.

Paper E

A. Lindström and S. Hallström: Energy absorption of sandwich panels containing bio-based materials; manuscript to be submitted 2009.

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.

Paper C

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

Paper D

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

Paper E

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

Contents

1 Introduction

The effects of human activity on the environment is a subject of great concern in today's society. Especially the influence of greenhouse gases on the global warming and the climate is discussed intensively. International agreements such as the Kyoto Protocol [1] are vital for the work to reduce the emissions of greenhouse gases. Transportation in general and road transportation in particular are responsible for 23% and about 17% of the world carbon dioxide (CO_2) emissions from fuel combustion, respectively [2]. These numbers clearly show the importance of reducing emissions from vehicles. A legislation in the European Union limits the fleet average of CO_2 emissions of new cars by 2012 to 130 g/km [3]. The average CO_2 emissions of petrol cars in 2008 was 207 g/km [4]. More energy efficient vehicles are needed to meet the requirements of this legislation. This can for example be achieved by more efficient engines, bio-fuel and/or lighter vehicles. The power needed to operate the car is reduced with reduced vehicle weight, thereby creating a positive spiral where a weight reduction enables the use of smaller and more fuel-efficient engines. Even though the mass of the body in white is only about 25% of the total vehicle weight, a reduction of structural weight is needed to achieve the stated reduction of CO_2 emissions. The reduction of structural weight can be achieved by replacing the commonly used metal structures, with new structural designs and alternative materials such as composite structures.

Composite materials are made by combining two or more constituent materials with different properties. The materials are combined in such a way that the composite properties are better than those of the individual constituents. The composite structures can be tailored for specific applications. Manufacturing of large structures with integrated functionality is also possible when using composite materials. Examples of composite materials are glass fibre and carbon fibre reinforced plastics. The bending stiffness and strength to weight ratio could be increased further by introducing sandwich 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 may consist of either honeycomb structures, lattice struc-

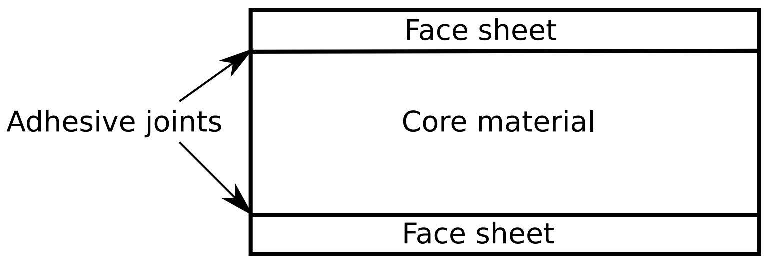


Figure 1: Schematic of structural sandwich panel.

tures, 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 [5]. 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.

Vehicles are a burden on the environment during their entire life cycle, including manufacturing, in-service use and end-life treatment. End-life vehicles yearly generate 8-9 million tonnes of waste in Europe [6]. This large amount of waste can be treated either through; re-use of the end-life components for the same purpose in another vehicle (re-use), reprocessing of the waste material into new components or biological transformation of organic material (recycling), generation of energy (recovery) or disposal of the waste in for example landfill (disposal). In the European Community the following targets should be attained by 2015; re-use, recycling and recovery for all end-life vehicles should be a minimum of 95% of the average weight per vehicle and year and re-use and recycling should be a minimum of 85% [6]. These goals for end-life treatment of vehicles could possibly complicate the use of composite materials in vehicle structures, due to their different material constituents. On the other hand, their relatively low weight is beneficial from a legislation point of view. There are several different strategies for end-life treatment of composite structures including; recycling of thermoplastic materials, energy recovery in form of heat, material recycling by chopping and milling down the structure to powder and fibres for use in new composite structures or in landfill [7]. The low demand for recycled composite material and the associated cost is the biggest obstacle for increased recycling of composite structures [8]. By using bio-composites, with natural fibres such as hemp or flex and bio-based resins, which can be biodegradable, the resulting structure would be based on renewable materials which also could be compostable.

A first step to reduce the weight of a vehicle is to replace the secondary structure, that is the structure with little or no load bearing function, with composite and sandwich components. To further reduce the weight and to fully utilise the beneficial specific strength and stiffness properties of composite and sandwich materials, primary load bearing parts need to be replaced as well. Such structures can only be replaced by composite and/or sandwich materials if their structural behaviour is competitive both during in-service use and in the case of a crash situation.

1.1 Road safety

The road safety of vehicles, which includes the safety of both the occupants of the vehicles and pedestrians, is an important issue for society. For example, there were 41 059 fatalities in traffic accidents in the US alone during 2007, according to the International Road Traffic and Accident Database (IRTAD) [9]. Road safety is also strongly regulated in many countries. To assess the safety performance of vehicles, organisations such as the National Highway Traffic Safety Administration (NHTSA) in the US and the European New Car Assessment Programme (Euro-NCAP) in Europe perform tests on vehicles. Frontal impacts, side impacts and pole impacts are used to evaluate the safety for the driver, and adult and child passengers. Further tests are conducted to assess the safety of pedestrians in crash situations. The abbreviated injury scale (AIS) [10] and the head injury criterion (HIC) [11] 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.

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). This energy transformation is often referred to as energy absorption. 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 δ as

$$W = U + W_a + W_d = \int_0^{\delta} P d\delta. \tag{1}$$

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. In order to compare energy absorbers of different shape and weight, normalised values are often used. The energy absorption can for example be normalised by crushed length, crushed volume or mass of the crushed volume [12]. The work per unit mass deformed material is often referred to as specific energy absorption and is defined as [12–16]

$$W_s = \frac{W}{A\rho\delta}, \tag{2}$$

where A is the gross cross section area and ρ is the density of the material. The specific energy absorption is a good measure when comparing the energy absorption capability of weight sensitive vehicle structures [12, 15, 16].

1.2 Energy absorbers

The most commonly used collapsible energy absorbers come in the form of tubes, frusta, struts, honeycomb cells and sandwich plates [17]. These collapse structures can consist of different materials, such as metal or composite materials. Metal and composite materials however, have different failure behaviour during compression. Metal structures tend to deform plastically, whereas composites deform in a more brittle manner and thereby mainly absorb energy through creation of fracture surface. 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 through 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 [12–14, 18–20] and even sandwich structures, either as tubes of sandwich materials [15, 21] or as sandwich panels with internal tubes [22]. The composite tubes can be designed to fail in Euler buckling, progressive folding or brittle fracture [12]. Euler buckling is an unstable failure mechanism which promotes low energy absorption and should therefore be avoided in favour of other failure modes.

The failure mechanisms and energy absorption of metal tubes are well documented and they are therefore extensively used in vehicle structures. Composite structures on the other hand, with an energy absorption capability that can exceed that of metal structures [12, 14, 19, 20], are not as common. 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 difficult 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 however, fully utilised in more extreme and exclusive cars [23, 24]. If composite structures are to be used in massproduced vehicles the development and production costs need to be reduced. For example it may be more cost efficient to use glass reinforcement 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 crash events must be predictable.

Most of the studied energy absorbing structures are tubes [15], even though beams, plates or more complex shapes are common in vehicle structures. Furthermore combined axial and bending loads are likely during a crash event [20]. The loading conditions during impact of sandwich panels incorporated in vehicle structures can be either in-plane, transverse or oblique to the face sheets. However, the majority of the studies of energy absorption of sandwich structures consider transversely loaded plates or beams and mainly focus on the localised impact problem [25]. Both impact damage of the face sheets and sub-interface core damage have been studied. In this thesis the structural behaviour of in-plane compression loaded sandwich panels is investigated.

1.3 Objective

The objective of the work presented, is development of a methodology able to predict and controll the in-plane compressive response of sandwich panels. The method should be able to identify and predict active failure modes. It should furthermore allow for controll of the collapse behaviour by choice of material and geometrical properties, or through mechanical manipulation towards desired behaviour.

2 In-plane compression loaded sandwich panels

The high specific bending stiffness and strength of sandwich panels can be fully utilised when incorporated into vehicle structures. During normal use of a vehicle the structure mainly carries bending loads, whereas in a crash situation the loading conditions could 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 composite structures. The structural response of sandwich panels compressed in the in-plane direction depends on both material and geometrical properties of the different constituents. To achieve high energy absorption during a controlled deformation, the failure mechanisms and their propagation need to be predictable.

The mechanical response of composite materials in general are strain rate dependent. The impact velocity will thereby generally affect the collapse behaviour of composite and sandwich structures. Several studies show an increase of Young's modulus, strength and ultimate strain for compression loaded uni-directional glass and carbon fibre reinforced epoxy composites [26–28]. This may indicate that the energy absorption of composite structures will improve with increasing impact velocity. However, the energy absorption is dependent on both the structural and material response in a crash situation. The energy absorption of composite tubes can either increase or decrease with increasing impact velocity [29]. The structural behaviour is controlled by the strain rate dependency of the governing collapse mechanisms. In the following only quasi-static in-plane compression loaded sandwich panels are investigated, with the focus to identify different possible failure modes of such panels.

The structural response of in-plane quasi-statically loaded sandwich panels can be separated into two main phases; failure initiation and propagation. A typical load-deformation response is presented in Figure 2. Common for most panels investigated in this thesis is that the response can be considered as linear until first

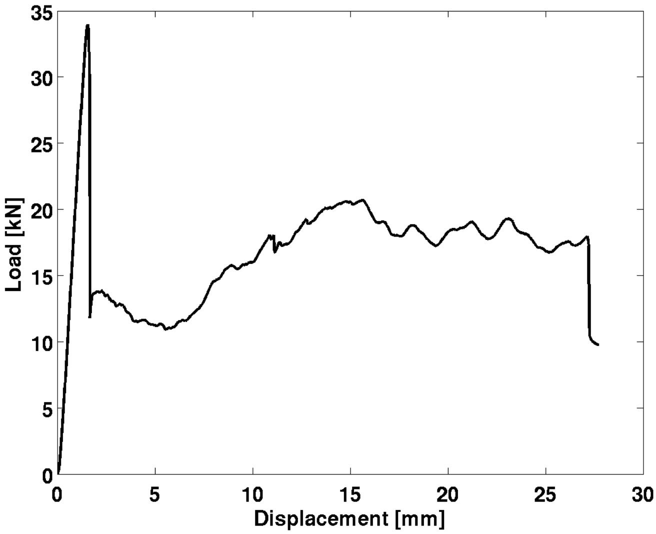


Figure 2: A load-displacement curve of a compression loaded sandwich panel.

failure occurs. 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

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

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.

2.1 Initial failure

The initial failure of sandwich columns loaded quasi-statically in in-plane compression is either related to global buckling, local buckling or face sheet fracture [30]. In theory the core could of course also fracture, but in most cases of practical interest the ultimate strain of the core exceeds that of the faces. If the material properties of the different constituents are known, the failure load for the different failure modes can be analytically calculated using laminate and sandwich theory [5]. In the following section a uni-axially loaded sandwich panel, with dimensions as illustrated in Figure 3, is considered.

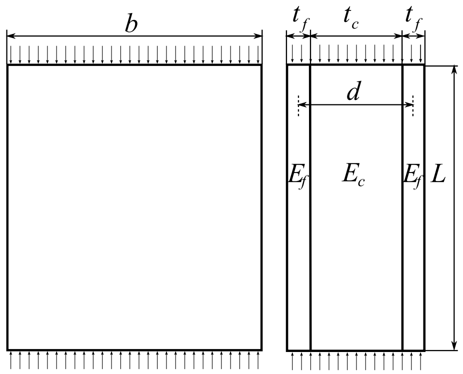


Figure 3: Dimensions of a uni-axially loaded sandwich panel.

Global buckling

Global buckling of uni-axially loaded sandwich panels involves 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

$$P_b = \frac{n^2\pi^2 Db}{L^2}, \tag{4}$$

where n is the buckling mode, D is the flexural rigidity per unit width, 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 be described as

$$P_s = Sb = \frac{G_c d^2 b}{t_c}, \tag{5}$$

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 3. This approximation is valid for a sandwich with thin faces $t_f << t_c$, compliant core $E_c << E_f$ and high shear modulus of the face sheets. The total critical buckling load can be calculated from

$$\frac{1}{\widehat{P}} = \frac{1}{P_b} + \frac{1}{P_s}, \tag{6}$$

or

$$\widehat{P} = \frac{n^2\pi^2 bD/L^2}{1 + \dfrac{n^2\pi^2 D}{L^2 S}}. \tag{7}$$

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 [31] 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 [32]. 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 $\widehat{P}_w$ can be described as [31]

$$\widehat{P}_w = 2b\sqrt{D_f k} = 2b\sqrt{D_f \frac{E_c}{t_c}}, \tag{8}$$

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 [33]

$$\sigma_w = 0.91\sqrt[3]{E_f E_c G_c}. \tag{9}$$

However they suggested that for practical design the more conservative formula

$$\sigma_w = 0.5\sqrt[3]{E_f E_c G_c}, \tag{10}$$

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

$$\widehat{P}_w = 1.14b\sqrt[3]{D_f E_c G_c}. \tag{11}$$

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 once the yield strength of the material is exceeded. If the face sheets consist 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 [34], shown in Figure 4. The critical failure mode is determined by the material and geometrical properties of the composite, meaning that the composite should be considered as a structure rather than a material [35]. 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

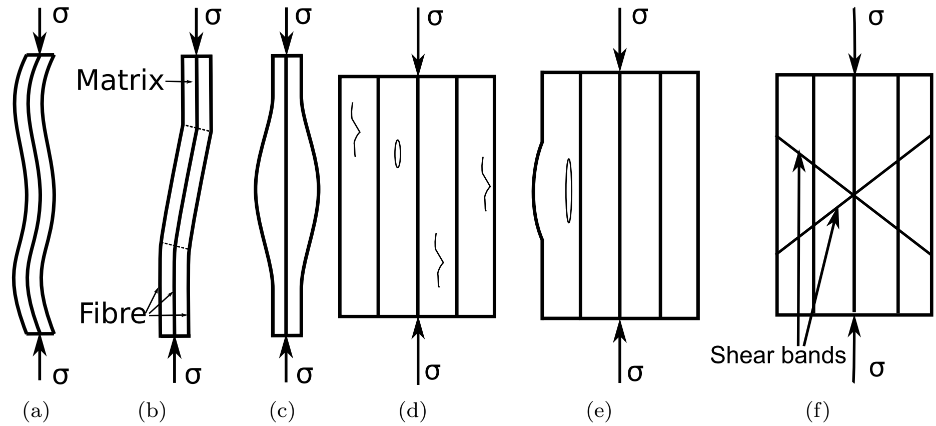


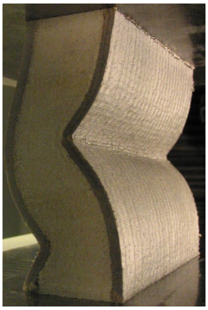
Figure 4: The most common compressive failure modes of unidirectional fibre composites are; (a) elastic microbuckling, (b) plastic microbuckling, (c) fibre crushing, (d) splitting, (e) buckle delamination, (f) shear band formation (redrawn from [34]).

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. The matrix can yield and fracture in the form of shear bands if the fibre volume fraction is low. The most common fracture mode of unidirectional laminates is plastic microbuckling also called kinking [34, 36]. For composites with short and randomly distributed fibres failure is generally more complex and it is often difficult to distinguish one single failure mode.

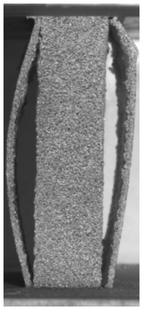
Failure criteria for composite structures is a widely studied subject [35, 37]. There exist criteria for individual failure modes, as well as general criteria for a complete composite [35]. Failure criteria can be based either on strength or fracture mechanics theories. In the World-Wide Failure Exercise (WWFE), 19 different theoretical approaches to predict deformation and failure response of composites were assessed [37]. Another approach is to determine the critical failure stress $\hat{\sigma}_f$ of the composite experimentally, rather than theoretically.

2.2 Damage propagation

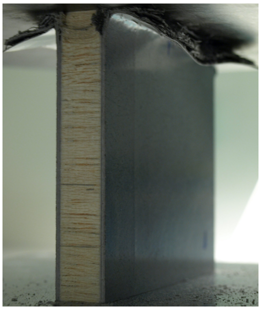
If the compression of a sandwich panel is continued after failure initiation, damage will start to propagate in the structure. Mamalis et al. [38] experimentally studied the crushing response of quasi-statically in-plane compression loaded sandwich panels. By testing sandwich panels with different material concepts they identified the following three types of collapse modes: global buckling, unstable sandwich disintegration and stable end-crushing. A fourth failure mode called ductile in-plane shear, was identified in paper E of this thesis. The different collapse modes are illustrated in Figure 5.



(a) Buckling



(b) Unstable sandwich disintegration



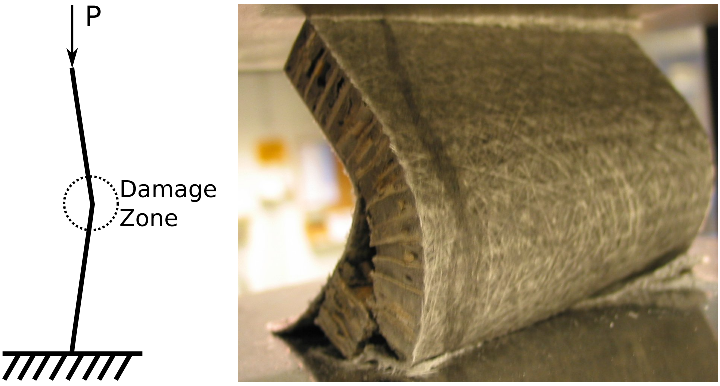
(c) Stable end-crushing

(d) Ductile in-plane shear

Figure 5: Collapse modes of sandwich panels loaded quasi-statically in in-plane compression.

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 Figures 5(a) and 6(a), the resulting energy absorption is low. The buckling collapse of sandwich panels can 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 6(b), but also to delamination and fracture of the face



(a) Schematic (b) Post-failure

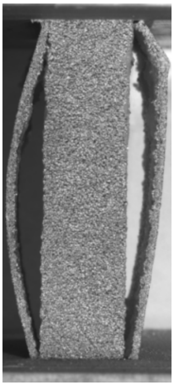
Figure 6: Buckling of in-plane compressed sandwich panel.

sheets. Figure 6(b) also illustrates the complexity of the collapse mode, resulting in difficulties to determine the sequence of failure events.

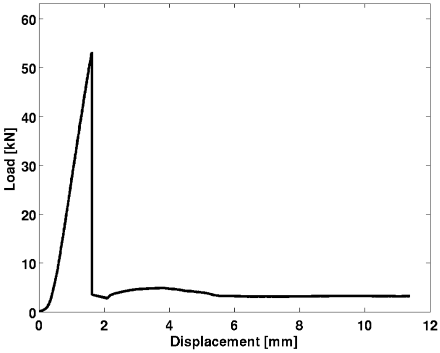
Unstable sandwich disintegration and stable end-crushing

Local buckling and face sheet fracture can initiate delaminations in the face sheets and cause 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 fall apart. Little damage occurs in the core and face sheets during propagation of the debond crack, as shown in Figure 7. A plausible load displacement response of this unstable collapse mode is illustrated in Figure 7(b), which typically results in a low energy absorption. This unstable sandwich disintegration will also be referred to as unstable debonding throughout this thesis.

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. A necessary condition for stable crack growth is that the crack driving force is sufficiently reduced with increasing crack length. This means that the crack eventually arrests and other failure modes in the structure start to dominate, e.g. delamination propagation and face sheet fracture. This complex mix of different failure modes, clearly shown in Figures 5(c) and 8(a), enables high energy absorption of the progressive end-crushing collapse mode. Failure in the form of progressive end-crushing typically shows a response illustrated in Figures 2 and 8(b). After initial failure the load bearing capacity of the structure is reduced. However, the load level for further compression of the panel is relatively high and



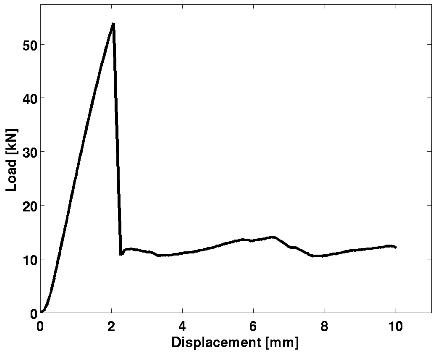
(a) Post-failure



(b) Load-displacement curve

Figure 7: Unstable debond collapse.

(a) Post-failure



(b) Load-displacement curve

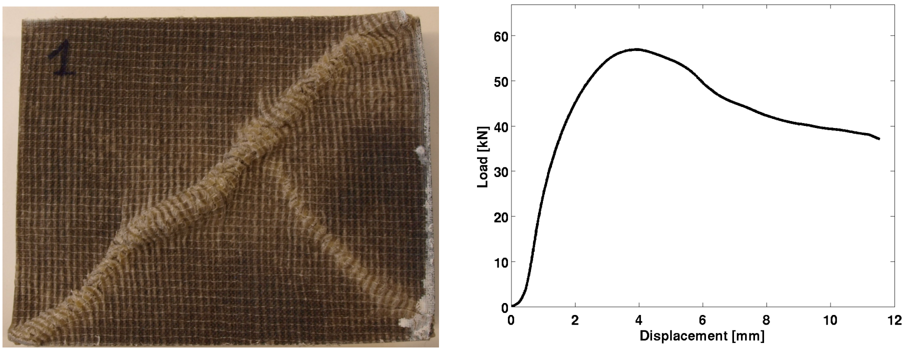
Figure 8: Stable end-crushing collapse.

constant as shown in Figure 8(b). For the sandwich configuration presented in Figure 8 the plateau load is about 25% of the peak load. The progressive failure mode has a load-displacement response that promotes relatively high energy absorption.

Ductile in-plane shear

Sandwich panels consisting of face sheets with unidirectional fibres and a core material with high stiffness in the transverse direction, can initially fail due to in-plane kinking of the fibres. A 45 degree shear band may occur, as illustrated in

Figures 5(d) and 9(a). If the face sheet material is ductile the damage may also progress in a stable manner. This collapse mode was identified in paper E for panels with hemp fibre laminates and a balsa wood core. The hemp fibres behaved non-linearly during compression. The resulting load-displacement response is shown in Figure 9(b). The load reduction after failure initiation is moderate, which promotes exceptionally high energy absorption.



(a) Post-failure (b) Load-displacement curve

Figure 9: Ductile in-plane shear.

3 Predicting postfailure behaviour

To achieve the best possible energy absorption of in-plane loaded sandwich panels, the collapse mode must be of a stable kind. As already concluded both the unstable debonding and the stable end-crushing collapse modes include delamination and/or debond propagation. The collapse mode can thereby be determined by considering a sandwich structure with debonds. The behaviour of panels failing in ductile in-plane shear collapse was encountered late in the work. The underlying mechanisms are essentially different than for the cases analysed previously. Ductile in-plane failure was therefore not modelled in the presented work.

Modelling of in-plane compression loaded composite and sandwich structures with delaminations and/or debonds have received considerable attention in recent research e.g. [39–55]. Composite structures with delaminations and/or debonds tend to buckle when loaded in compression, due to the reduced stiffness in the debonded area. Buckling can lead to secondary failure in the form of debond and/or delamination crack propagation due to opening of the crack, or face sheet failure due to bending. A debond is an interfacial crack between two elastically dissimilar materials. This difference of elastic properties can result in a mixed fracture mode [46–48, 56, 57]. This means that the crack tip will be subjected to both shear and normal forces, even if a pure opening load is applied to the structure. More precisely, a pure mode I load case cannot be applied since there is no symmetry present a the crack. The classical opening $\mathscr{G}_I$ and shearing $\mathscr{G}_{II}$ strain energy release rates are thereby not easily defined. The total energy release rate $\mathscr{G}$ can be calculated, by for example the path independent J-integral [45, 50], the virtual crack closure technique (VCCT) [48, 51] or from the potential energy of the system using the variational principle [42, 49]. Crack propagation will only occur if the energy release rate $\mathscr{G}$ is larger than the fracture toughness $\mathscr{G}_c$. The mode mixity at the crack tip can lead to kinking of the crack into either the core material [47, 57] or even into the face sheet [57]. Crack growth into the face sheet can lead to fibres bridging from one crack surface to the other (fibre bridging), which increases the fracture toughness of the crack. The fracture toughness is generally specified for a certain material, or material combination, under a certain type of loading condition and even then the scatter is often substantial. Debond cracks can propagate in the core material, face sheet or in the face-core interface. The strength of the core material of many sandwich structures, is lower than for both that of the faces and of the interface between the two. This means that crack propagation is predominantly governed by properties of the core material, even when 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 geometric and elastic properties of the faces and the core. For cases were the local stress field around the crack tip is reasonably similar for all studied crack lengths, it is believed that the use of a single value for the fracture toughness can be justified.

Several analytical and numerical models to calculate the buckling load of the delaminated/debonded structure exist [39–45]. A first approximation is to consider the problem as a clamped beam with a length equal to the delamination/debond crack length. The elastic foundation of the matrix for the laminate case, respectively the core for the sandwich case, will however provide less rigid boundary conditions. The buckling load is therefore overestimated when using this approximation. A better solution is to consider the structure as a beam supported on an elastic foundation [39–41]. Vizzini and Lagace [39] considered a delaminated laminate as a beam partly supported by a Winkler foundation, as shown in Figure 10. By

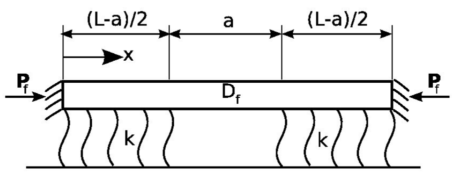


Figure 10: Winkler model of delaminated laminate.

assuming that the deformed shape can be described by the complete symmetric

Fourier series for clamped-clamped boundary conditions, the buckling load, and corresponding 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

$$f = \frac{ka^4}{D_f} = 12\frac{E_c}{E_f}\left(\frac{a}{t_f}\right)^4\frac{t_f}{t_c}, \tag{12}$$

where a is the delamination length. The foundation length ratio η is defined as

$$\eta = 1 - \frac{a}{L}. \tag{13}$$

The buckling load can then be described as

$$\hat{P}_f = \frac{\acute{c}E_f t_f^3 b\pi^2}{12a^2}, \tag{14}$$

where the effective coefficient of fixity $\acute{c}$ is a correction term that describes the boundary condition at the delamination crack tip. The coefficient of fixity $\acute{c}$ increases with increasing foundation stiffness and decreasing foundation length ratio. Niu and Talreja [40] studied sandwich panels with one or two arbitrary located debonds and 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. A Winkler foundation model only takes the transverse stiffness of the core into account, which may be insufficient for sandwich structures as the core can be subjected to large shear strains. Cheng et al. [41] developed a model that accounts for both transverse and shear properties of the core. Another method to solve the buckling and postbuckling problem is to separate the sandwich or composite structure into different beam parts with different thicknesses and material properties [42, 43, 45]. 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.

Finite Element (FE) analysis have also been extensively used to solve the buckling and postbuckling problem of debonded composite and sandwich structures [50–52, 54, 55]. In Figure 11 a FE model of a sandwich panel with a debond crack is illustrated. Sankar and Narayanan [50] used a FE model to determine the buckling load and the postbuckling behaviour of in-plane compression loaded sandwich panels with one-sided midspan 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. The stresses in the face sheet and core were recorded together with J-integral values. These results were then used to determine if the crack would propagate or if the face sheet or core would fracture during the postbuckling analysis. A similar approach was used in paper B and D in this thesis. Reeder et al. [51]

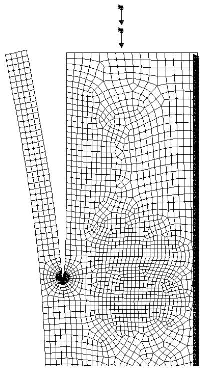


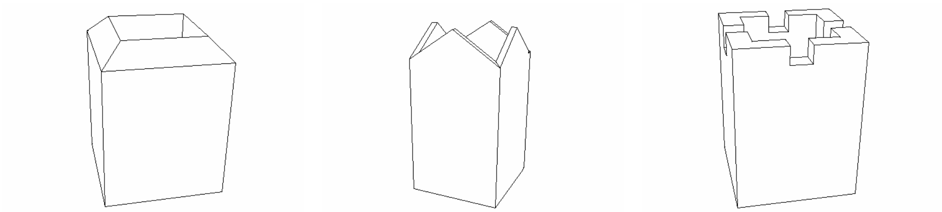
Figure 11: FE model of a sandwich with a debond.

investigated the postbuckling behaviour and delamination growth in curved composite plates subjected to compressive loads. A nonlinear postbuckling FE analysis was conducted to identify the load at delamination growth. The strain energy release rate was calculated using VCCT and compared to a mixed mode fracture toughness failure criterion. Østergard [52] studied the influence of global and local imperfections on the compressive strength of sandwich panels with an initial one-sided midspan debond using a FE model. The debond was propagated using a cohesive zone model. During compression a damage zone was created with weakened properties, resulting in lower buckling loads. The effect is dependent on both the local imperfection and the properties of the interface. Cohesive zone modelling can be used to model large fracture process zones, such as fibre bridging [52]. Both the VCCT and cohesive zone models can propagate cracks [58] during the analysis. A crack must be predefined if VCCT is used, which is not the case for cohesive zone models. Instead the delamination/debond crack can be initiated during the analysis.

4 Triggering of failure mechanisms

During a vehicle crash situation the integrity of the passenger compartment must be ensured and the resulting accelerations on the passengers must be kept below life threatening levels. This creates restrictions on both the maximum deflection and the resultant loads in the structure, resulting in limitations of possible energy absorption. The maximum displacement of the crash zones should be as long as possible, however the physical length of the energy absorbing structure is often restricted by the design of the vehicle body. The harmful peak loads achieved during impact can be reduced by the use of different kind of triggering means, in the following referred to as triggers. The triggers can be geometrical features or mechanical devices that introduce stress concentrations into the structure. These stress concentrations ensure failure initiation at a certain location in the structure, leading to a more predictable and repeatable damage initiation. Correct employment of triggers can also lead to favourable collapse behaviour with enhanced energy absorption.

Triggers are used extensively to induce favourable collapse modes in metal structures. Geometrical imperfections can be used to trigger progressive plastic folding and different kind of dyes are often used to force the parts into certain responses [17]. Progressive crushing can also be induced in brittle composite structures by use of different geometrical features such as chamfered, tuliped and notched edges [18–20], as shown in Figure 12, or by metallic dyes. The structural behaviour during impact and thereby the energy absorption can be highly dependent on the triggering geometry [18, 20]. Chamfering of tube edges has been reported to reduce both the peak load and the stiffness [18]. The stiffness reduction is structural, coming from early crushing of the chamfered edges. Furthermore the level of load reduction after damage initiation depends on the chamfer angle.



(a) Chamfered (b) Tulip (c) Notched

Figure 12: Different triggering geometries on tubes.

Pitarresi et al. [15] conducted an experimental study on the energy absorption of sandwich tubes of different design. The effects of a tulip edge and external metallic triggers on the structural behaviour were investigated. The initial and propagating failure was unpredictable for tubes without triggers, whereas all specimens with tulip shaped edges initiated damage leading to progressive collaps. It was further concluded that the metallic triggers were effective to initiate stable progressive failure resulting in high energy absorption. Stapleton and Adams [59] investigated the influence of external triggers on the energy absorption of sandwich panels, loaded dynamically in edgewise compression. Both internal and external fixture based triggers was used to initiate local fracture in four different sandwich configurations. Some promising results were obtained but it was also concluded that the effect of the initiators was depending on the stiffness and strength properties of the sandwich constituents and the fracture toughness of the face/core interface, in agreement with the results presented in paper B of this thesis. Velecela et al. [16] investigated the influence of face sheet thickness, length/width aspect ratio and different triggering features on the specific energy absorption of both monolithic laminates and sandwich panels. The panels were supported laterally by a fixture to prevent unstable global collapse. Three types of geometrical triggering features on the plate edges were investigated. A triangular triggering shape gave the best results, promoting stable progressive end-crushing. It was concluded that the face sheet thickness influenced the energy absorption more than the triggers.

5 Summary of appended papers

The objective of this thesis was to develop a methodology for predicting the in-plane compressive response of sandwich panels and if possible design sandwich panels for high energy absorption. To determine the energy absorbing capability of in-plane compression loaded sandwich panels, the possible failure modes must be known. The approach was therefore to identify and describe the structural behaviour of possible failure modes. With this knowledge it should be possible to design sandwich panels for favourable energy absorption.

In paper A an experimental study to determine possible failure modes was conducted. Sandwich panels were quasi-statically compressed in the in-plane direction between two flat steel panels without additional support as shown in Figure 13. The examined sandwich panels consisted of either sheet molding compound (SMC)

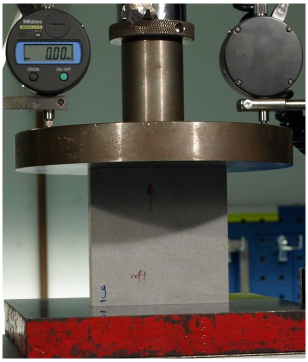


Figure 13: Test setup.

glass fibre face sheets with a balsa core or preimpregnated (prepreg) glass fibre face sheets with a polymethacrylimide (PMI) foam core. The displacement fields of one outer face sheet surface were measured using a digital speckle photography (DSP) equipment, also often referred to as digital image correlation technique. Furthermore, the structural response before and after initial failure was described by a simple semi-empirical model. Stable end-crushing and unstable debonding, previously presented by Mamalis et al. [38], were the identified collapse modes for the SMC/balsa and the prepreg/PMI panels, respectively. The unstable debond collapse mode resulted in relatively high energy absorption, even though the face sheets rapidly debonded from the core. For one configuration the resulting energy absorption was comparable with that of panels failing in stable end-crushing. This can be explained by the high peak loads of these panels. The panels that failed in unstable debonding are still unsuitable for use in vehicle structure due to their unstable collapse behaviour and high peak loads.

The specimens tested in paper A displayed several different types of damage, such as face sheet failure, delaminations, matrix failure, debonds and core failure. It was also noted that the location of initial damage could differ not only between specimens, but also between the two face sheets. It can therefore be concluded that the precise course of damage events and thereby the energy absorption is difficult to predict. Instead of modelling the complete collapse behaviour another modelling scheme was chosen, where the most critical failure mode was identified. Results from paper A together with results from previous studies (e.g. [38]) 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 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 mode of failure propagation. A linear buckling analysis was used to calculate the buckling load and mode of the initially debonded face sheet, for several crack lengths for each sandwich configuration. A nonlinear postbuckling analysis was also performed to determine if the critical failure mode for a range of debond lengths would be debond propagation or face sheet failure. The J-integral was used to calculate the strain energy release rate. In Figure 14 critical loads for one of the investigated sandwich configurations are displayed for several debond lengths. It can be seen that for short debond lengths the face sheets fracture before they buckle. For larger debond lengths the face sheets buckle before they fail. No debond propagation would be expected for this panel. The unstable debond collapse mode was judged likely to occur if debonding was identified as the critical failure mode for all studied debond lengths. Cases with predicted face sheet failure were considered more promising for favourable response. As no failure of the face sheet was included in the models, it was not possible to quantify the actual energy absorption. It could however be concluded that the postfailure mode is mainly determined by the relation between the fracture toughness of the core and the bending stiffness and strength of the face sheets.

During an impact situation it is important that the accelerations on the structure and the passengers are kept below critical levels. It can therefore be necessary to reduce the peak loads of the energy absorbing structure. This can as already mentioned be achieved by different kind of triggering means. In paper C the influence of two different types of geometrical triggers was investigated experimentally, using the same experimental setup as in paper A. The investigated triggers were chamfering of the face sheet edges and sawed grooves on the upper loaded sandwich

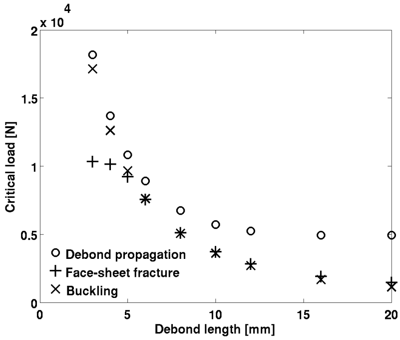


Figure 14: Failure modes for different debond lengths for a panel with t_f=1 mm, t_c=10 mm, E_f=25 GPa, E_c=240 MPa.

edge, as illustrated in Figure 15. The latter was investigated using a FE model, showing that the failure initiation was governed by the stress intensity at the corners of the grooves for panels with few grooves and by the average stress for panels with more grooves. Both methods successfully reduced the peak load. Moreover the energy absorption of the panels with triggers was increased, due to an increased plateau load.

In paper D the FE model developed in paper B was used to design sandwich panels for different collapse behaviour. These panels were then manufactured and experimentally tested using a similar setup as in papers A and C. Sandwich pan-

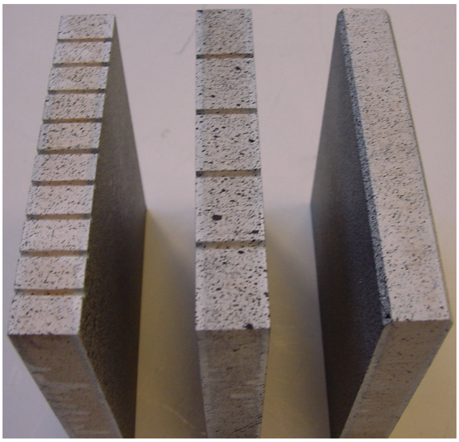


Figure 15: Panels with chamfered edges, 4 and 9 grooves.

els with chopped strand mat (CSM) glass fibre face sheets of two different thicknesses and PMI or polyethyleneterephtalate (PET) foam core were examined. The FE model predicted the failure behaviour accurately, showing that the developed method can be used to identify sandwich panels with potential for high energy absorption.

As already mentioned, it is important to reduce the impact on the environment during the entire life cycle of vehicles. This can for example be achieved by introducing bio-based materials. The structure may then be made from renewable materials which can even be bio-degradable. In paper E a study on sandwich panels with hemp fibre laminates was conducted. For comparative reasons vinylester resin was used, reducing the environmental benefits slightly but nevertheless illustrating the potential of bio-based materials. The panels were compared with the more traditional sandwich panels presented in paper D. Sandwich panels with either PMI, PET or balsa wood core were studied. The nonlinear response of the hemp fibre face sheets could however, not be modelled using the analytical formulae and FE model developed in paper B, since they assume linear elastic material properties. The resulting specific energy absorption of the tested panels was overall high, with exceptionally high values for the panels with balsa core. This indicates that bio-based sandwich panels can be used to achieve high energy absorption during in-plane compression loading. However, the behaviour during high strain rate loading needs to be investigated before the panels can be introduced in vehicle structures.

6 Discussion and conclusions

The structural behaviour of sandwich panels compressed in the in-plane direction has been investigated. Possible initial failure modes have been identified as face sheet failure, global and local buckling. Four different collapse modes have been identified, of which two were unstable and two were stable. The unstable collapse modes, buckling and unstable debonding, can in some cases promote higher energy absorption than panels failing in the stable end-crushing collapse mode. However, the unstable collapse modes will eventually lead to catastrophic failure of the structure. Sandwich panels loaded in in-plane compression should therefore be designed for stable collapse. If that is not possible, triggering features can be employed to enforce a favourable behaviour. Triggers can for example be used to ensure face sheet failure instead of buckling behaviour. Analytical formulae and a numerical approach have been used to estimate the collapse mode of sandwich panels initially failing in wrinkling or face sheet fracture. The probability of unstable debond propagation and stable end crushing can be determined. Paper D shows that the developed approach can be used in the design process to estimate the collapse mode of different panel configurations. The energy absorption of the panels could however not be determined. To do so a more detailed model is needed. The model must include damage initiation and propagation in the face sheets and in the core, plastic behaviour of the core material, debond and delamination growth.

Bio-based sandwich panels showed good potential for high energy absorption, especially panels failing in the stable ductile in-plane shear mode. The nonlinear behaviour of the hemp fibre vinylester face sheets aggravate the modelling of these panels. A more thorough investigation on the bio-based sandwich panels are needed, but the initial experimental results are promising.

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