Lund University

MECHANICAL PROPERTIES OF INTERLAYERS IN LAMINATED GLASS

Experimental and Numerical Evaluation

CAMILLA FORS

Structural Mechanics

Master's Dissertation

DEPARTMENT OF CONSTRUCTION SCIENCES

DIVISION OF STRUCTURAL MECHANICS

ISRN LUTVDG/TVSM--14/5198--SE (1-52) | ISSN 0281-6679

MASTER'S DISSERTATION

MECHANICAL PROPERTIES OF INTERLAYERS IN LAMINATED GLASS

Experimental and Numerical Evaluation

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Printed by Media-Tryck LU, Lund, Sweden, October 2014 *(Pl)*.

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Abstract

The architectural and engineering trend leads towards greater use of glass in buildings. Growing safety awareness often requires laminated glass. Laminated glass is formed as a sandwich of two or more sheets of glass and a plastic interlayer. Laminated glass can for example be used in stairs, floors, roofs, facades and balcony railings.

This thesis deals with the most common interlayer polyvinyl butyral (PVB). There are many varieties of PVB and this thesis investigates the mechanical properties of a variety of PVB. Experimental tensile tests have been conducted on six PVB with various properties. The tests have been conducted with different loading rates to take the time dependency into account. PVB shows time and temperature dependency and in numerical simulations it is often simplified as a linear elastic material. By using the generalized Maxwell model, which is a mechanical model that describes a linear viscoelastic material behaviour, a Prony series have been determined from the experimental tests. A tensile test has been modelled in the commercial finite element software Abaqus. The Prony series have been implemented in the Abaqus-model to create a viscoelastic material model. The model has been created for of one of the experimentally tested interlayers, a standard PVB with a thickness of 0.76 mm. Thereafter the viscoelastic model has been used in a laminated glass model to show how the time of loading affects the structural behaviour.

The results from the experimental tests show that there are differences in all the tested PVB. Some are stiffer, and some are softer. The numerical tensile test model was in good agreement with the laboratory results for standard PVB 0.76 mm. The numerical application where a laminated glass unit was subjected to long-term and short-term loads showed a loss in structural resistance due to the time dependent behaviour. One could see that with longer loading time, an increase in the stresses occur and the plate behaves more like a layered unit than a monolithic plate. This leads to the conclusion that it is important to take into account the time dependent behaviour when using laminated glass as a structural element.

Keywords: Laminated glass, Interlayers, PVB, Viscoelasticity, Prony series, Generalized Maxwell model, FEM, Abaqus, Tensile test

Sammanfattning

Trender inom arkitektur och ett större intresse hos ingenjörer för glas har lett till ett ökat användande av glas i byggnader. Ökat säkerhetsmedvetande kräver ofta att laminerat glas används. Laminerat glas består av två eller flera lager av glas med mellanskikt av plastfolie. Laminerat glas kan användas i exempelvis trappor, golv, tak, fasader och balkongräcken.

Detta examensarbete studerar den mest vanliga plastfolien polyvinyl butyral (PVB). Det finns många olika typer av PVB och syftet är att undersöka de mekaniska egenskaperna hos olika PVB. Experimentella dragprov har gjorts på sex PVB med olika egenskaper. Testerna har gjorts med olika töjningshastigheter för att ta hänsyn till tidsberoendet hos folien. PVB uppvisar ett tids- och temperaturberoende och förenklas ofta som ett linjärt elastiskt material i numeriska simulationer. Genom att använda sig av den generaliserade Maxwell modellen, som är en mekanisk modell som beskriver ett linjärt viskoelastiskt beteende, har en Prony-serie bestämts utifrån de experimentella resultaten. Ett dragprov har modellerats i finita element programmet Abaqus. Prony-serien har implementerats i Abaqus-modellen för att skapa en viskoelastisk materialmodell. Modellen har skapats för ett av de testade mellanskikten, standard PVB med tjockleken 0,76 mm. Därefter har en skiva av laminerat glas modellerats i Abaqus där den viskoelastiska materialmodellen har använts. Denna Abaqus-modell har gjorts för att visa hur lastvaraktigheten påverkar konstruktionens bärförmåga.

Resultaten från dragproven visade att de mekaniska egenskaperna skiljde sig bland de provade plastfolierna. Några av dem var styvare, medan andra var mjukare. Dragprovsmodellen i Abaqus med viskoelastisk materialmodell stämde bra överens med de laborativa värdena för standard PVB 0,76 mm. I den numeriska tillämpningen där en laminerad glasskiva var belastad med korttids- och långtidslaster uppvisades en förlust i lastförmåga på grund av det tidsberoende beteendet hos folien. Resultatet visade att spänningarna ökade med en längre lastvaraktighet. Det laminerade glaset betedde sig mer som om plastfolien inte fanns, som två glasskivor, än som en monolitisk skiva vid lång lastvaraktighet. Detta leder till slutsatsen att det är viktigt att ta hänsyn till det tidsberoende beteendet när laminerat glas används som bärande element.

Nyckelord: Laminaterat glas, mellanskikt, PVB, viskoelasticitet, Prony-serie, generaliserad Maxwell modell, FEM, Abaqus, dragprov

Preface

Five years have passed since I started my studies at LTH. When I started my studies someone told me that you could use glass to build columns. At that time I could not believe it was true but I found it very interesting. I have always had an interest in architecture and started to think about how glass columns can change the aesthetic look of a building, but I got even more curious about how such a brittle material could be used as a structural element.

My studies went on and in my fourth year I went to Germany to study one semester at Technische Universität München. In Munich I got the opportunity to learn more about glass in the course Structural Design of Glass Constructions taught by Professor Martin Mensinger. With interesting lectures and an inspiring excursion I got more interested in laminated glass. Then a thought started to grow, I wanted to write my master thesis about glass.

I am very thankful for having Kent Persson as my supervisor. He always had his door open and helped me with all my questions. So my acknowledgement goes directly towards Kent Persson at the Structural Mechanics Department for all his help during this thesis. I would like to thank Forserum Safety Glass for making it possible to do experimental tests by delivering interlayers to evaluate. I am also thankful to Zivorad Zivkovic at the Solid Mechanics Department for helping me out with the experimental tests.

Now, my five years have come to an end. Thanks Lund University for all the opportunities you have given me and thanks to all my friends for making these five years such an unforgettable time!

Camilla Fors

Lund, August 2014

Contents

Chapter 1

Introduction

1.1 Background

The architectural and engineering trend leads towards greater use of glass in buildings. Growing safety awareness often requires laminated glass. Laminated glass is formed as a sandwich of two or more sheets of glass and a plastic interlayer, see Figure 1.1. Laminated glass can for example be used in stairs, floors, roofs, facades and balcony railings. The interlayer is typically soft polymers like polyvinyl butyral (PVB), ethyl vinyl acetate (EVA) and SentryGlas® (SGP) from the company DuPont. When laminated glass shatters, the plastic interlayer keeps the pieces of glass in place. This reduces the risk of cuts caused by splinters.

Today there are many interlayers on the market with a large variation in their properties. For every project, in different areas of use, it is a challenging task to choose the most optimal interlayer.

PVB is the most common interlayer used in laminated glass and over the years many new varieties of PVB have been developed. Previous works on the mechanical properties of the interlayer have mainly focused on standard PVB. More recent research has been done on SGP and the results have been compared to PVB. At this time, none or little research have been done comparing a variety of PVB.

Glass is a complex material, and so is the behaviour of the viscoelastic material PVB. Therefore laminated glass is often analysed in a finite element program to capture the complex behaviour. PVB is often simplified as linear elastic material, this is however not the case due to the temperature and time dependent behaviour.

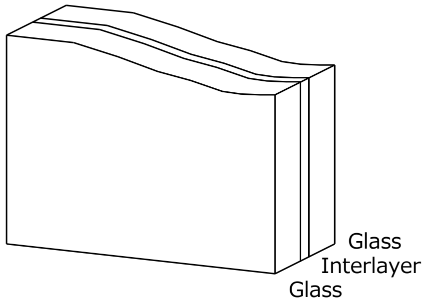


Figure 1.1: Laminated glass

1.2 Objective and Method

The main objective of this master thesis is to investigate a variety of interlayers of the type PVB and their mechanical properties. To evaluate the interlayers tensile tests with different strain rates will be conducted. A method on how to create a viscoelastic model from laboratory test suitable for implementations in a finite element program will be presented. For one of the tested interlayers, standard PVB 0.76 mm, a viscoelastic model suitable for simulations will be proposed as well as the procedure to derive it. A finite element model with a laminated glass unit subjected to short-term and long-term loads will be presented. This model will show how the time of loading affects the structural behaviour.

The finite element analyses will be done with the software Abaqus. The experimental tests and the numerical analyses will lead to guidelines on suitable interlayers for different field of applications.

1.3 Scope and Delimitation

The scope of the thesis is to evaluate the time dependent behaviour of the interlayer; however the temperature-dependency will be excluded.

1.4 Thesis Outline

The thesis is divided into several sections:

- Section 2 gives an introduction to the material glass and more detailed information about laminated glass.
- Section 3 explains the experimental tests. The results and discussion are also presented here.
- Section 4 describes mechanical models and the model used in the finite element analysis.
- Section 5 explains the finite element study. Here are also the results and discussion presented.
- Section 6 presents a finite element model with a laminated glass unit subjected to snow and wind load.
- Section 7 presents a summary of the results from the experimental tests and the finite element study.
- Section 8 discusses and draws conclusions from the results presented in section 7. Suggestions to possible further work are presented here.

Chapter 2

Laminated Glass

The mechanical properties of the interlayer are of high importance when using laminated glass as a structural element. To understand the structural behaviour of laminated glass it is also important with knowledge about glass.

In this chapter information of the material glass and laminated glass is provided. The first section treats the basics of glass, the manufacturing of float glass, the mechanical properties and post processing of float glass (heat-treated glass). In the second section laminated glass is described with information about the structural behaviour, the post-breakage behaviour, the properties of the interlayer and the current standards, guidelines and design methods for laminated glass.

2.1 Glass

Glass is a solid material that is hard and brittle. It is an amorphous solid, also called a non-crystalline solid, which means that the atomic structure is disordered [8]. Glass does not have an exact melting point like other materials; instead it transforms from a liquid to a solid state over a certain temperature range, usually around 500°C. One important property of glass is its high resistance to many chemicals which makes it a very durable material [8].

There are numerous types of glass with varying chemical and physical properties depending on the area of use. The most common glass is the soda-lime glass, also called soda-lime-silica glass. Soda-lime glass contains the raw materials sand (contains silica), soda ash and limestone, and also a smaller amount of various additives [8].

2.1.1 Manufacturing of Float Glass

Flat glass is the most commonly used glass in laminated glass and is typically made of soda-lime glass. Flat glass can be produced in different ways; however the so called float glass procedure stands for 90% of the production of flat soda-lime glass [11]. In the float process, invented by Pilkington in year 1959, the glass is produced by letting molten glass float on a bath of liquid tin, see Figure 2.1. By this procedure the glass gets a flat surface on both sides [8]. The thickness of the float glass is controlled by the speed of which the glass is drawn off from the tin bath [15]. The glass is then

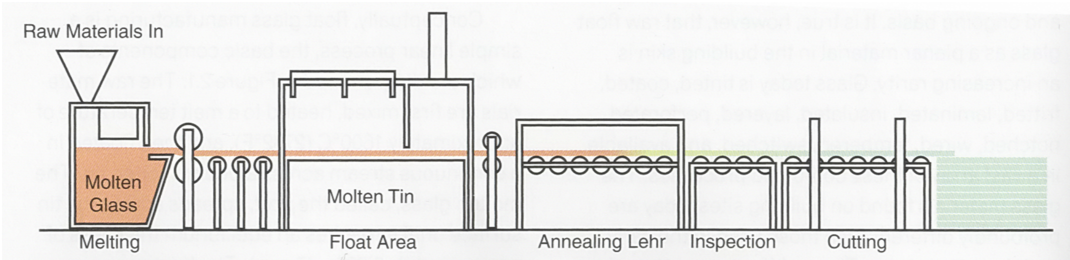


Figure 2.1: The float process [13]

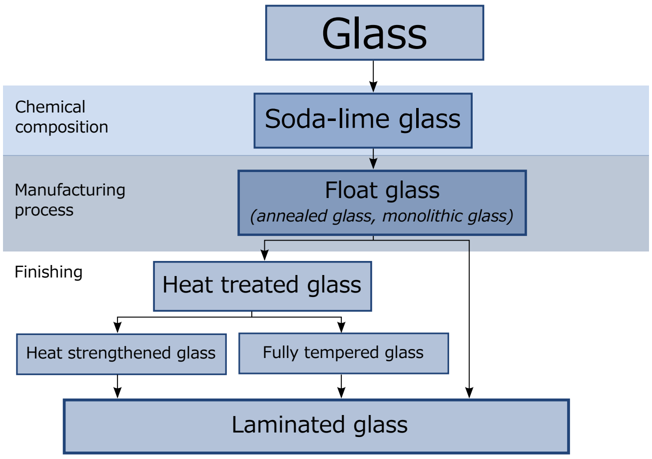


Figure 2.2: Overview of the most important glass products and the steps of processing

cooled down slowly after the tin bath in the annealing lehr, which is a long tunnel oven [13, 11]. The annealing process removes the internal stresses in the material by the controlled cooling process. It is of high importance with a controlled, slow cooling since uneven cooling can lead to a reduction of the mechanical strength. Another term for float glass is annealed glass. The last steps in the float process is inspection and cutting of the glass before delivering it to the customer [13]. However, the float glass can be processed further to produce glass products such as heat-treated glass and laminated glass, see Figure 2.2. The former is described in Section 2.1.3, while the latter is treated in Section 2.2.

2.1.2 Mechanical Properties

Glass is an isotropic and a brittle material at normal room temperature with no inherent ductility [9, 14]. It deforms elastically under stress and shows no plastic deformation before fracture [14]. Consequently is the behaviour of glass deemed as ideally elastic [9]. The compressive strength is significantly higher than the tensile strength [11]. Glass is sensitive to micro-cracks and flaws. The tensile strength is lower since stress concentrations develop in the micro-cracks and flaws for tension loading.

The momentary strength for glass is time dependent. The strength decreases with time when the glass is subjected to a load and was discovered in 1899 by Grenet [9]. Glass is sensitive to stress concentration and high stress concentration is for example caused by surface flaws. Since glass shows no plastic behaviour there is no stress redistribution to reduce the local stress concentration as in other material such as steel [9].

Flaws or defects play an important role regarding the mechanical strength. The practical value for the mechanical strength is always lower due to these defects [11]. The theoretical tensile strength, based on molecular forces, is very high, 32 GPa [9], while the practical value is much lower. Common values for the mechanical properties of glass is presented in Table 2.1.

Table 2.1: Mechanical properties of glass [8]

Compressive strength	880 – 930 MPa
Tensile strength	30 – 90 MPa
Flexural strength	30 – 100 MPa
Young's modulus	70 – 75 GPa

2.1.3 Heat-treated Glass

As shown in Figure 2.2, laminated glass may be produced from annealed or heat-treated glass, also called tempered glass. The structural performance of laminated glass is dependent on the glass and the interlayer. The main advantage with heat-treated glass is its improved mechanical strength. Due to the higher strength, tempered glass is a good option when enhanced load-bearing capacity is desired.

Annealed glass may be tempered in two ways; chemically or by a heat treatment. The chemically tempering is made by a process of ion exchange [9]. Chemical tempering is rare in structural applications, since this kind of tempering is only effective in very thin glass which are not common in buildings [13].

The mechanical strength of annealed glass may be further improved by a heat treatment, as done in the annealing step [13]. The heat treatment is often referred to tempering whereby the float glass is heated about 100°C above the glass transition temperature, approximately 600°C. In contradiction to annealing in the float process, the glass is then cooled down rapidly by jets of cold air, this is called quenching. The result of quenching is a glass with the surface in compression and the centre in tension [9].

There are two kinds of heat-treated glass, the fully tempered glass and the heat strengthened glass. The fully tempered glass is made by the process described above. The latter, the heat strengthened glass, is produced in the same way, but with a lower cooling rate [9]. Fully tempered glass breaks into small harmless pieces so it is considered as a safety glass. Heat strengthened glass is not regarded as a safety glass since it breaks into larger pieces [13]. The fracture pattern depends on the energy stored in the glass. Due to the high residual stress release in fully tempered glass at the fracture, i.e. high energy, the material breaks into small fragments in contradiction to annealed glass that breaks into large shards [9]. One could say that heat strengthened glass is a material with properties between those of annealed glass and fully tempered glass. With a lower cooling rate, the mechanical strength is also lower for the heat strengthened glass. Fully tempered glass is four to five times stronger than annealed

Table 2.2: Comparison of heat treated glass to annealed glass

Type of glass	**Fracture pattern**	**Mechanical strength**
Fully tempered	Small, harmless pieces	4-5 times stronger
Heat strengthened	Larger pieces than fully tempered, but smaller than annealed glass	2-3 times stronger

glass, whereas the heat strengthened glass is two to three times stronger [13]. See Table 2.2 for a comparison of the heat-treated glasses.

Any work, such as cutting, drilling or grinding, on heat-treated glass needs to be done prior to tempering. Another disadvantage with heat-treated glass is its risk for spontaneous breakage, i.e. the glass may shatter for no apparent reason. The cause for the spontaneous failure is nickel-sulphide inclusions in the glass, which is a small stone or a crystal [14, 13]. There is always a risk for nickel-sulphide inclusions during the production. The probability is very low, although not negligible due to the serious consequences of a spontaneous failure [9]. Annealed glass can also have nickel-sulphide inclusions but it is only a problem when it is present in heat-treated glass [13]. Due to the low cooling rate the nickel-sulphide particles are stable in annealed glass [11]. When annealed glass is subjected to a heat treatment, the nickel-sulphide particles increase in volume by the transformation into another state. This, in combination with the high tensile stresses in the glass core, is the cause for spontaneous breakage [9].

Spontaneous failure can occur days, or even years after production of heat-treated glass. To see which of the glasses that contain nickel-sulphide producers do a so called heat-soak test. By a heat-soak test the glass is slowly heated up and by maintaining a certain temperature where the transformation of the particles occur, the glasses that contain nickel-sulphide break [9]. The other glasses that do not break can be sold.

Heat-treated glass is more expensive due to the tempering process and the heat-soak test. Float glass exhibits very good optical properties and is largely free of distortion, but with a heat treatment visual distortion can occur. Therefore heat-treated glass may have inferior optical properties [13]. Tempering leads to a reduction of the time-dependence of the strength [9]. The big advantage with tempered glass is, and may be pointed out twice, the high mechanical strength. Values for the tensile strength in short-term tests for annealed, heat strengthened and fully tempered glass are presented in Table 2.3.

Table 2.3: Tensile strength in short-term tests

Annealed glass	$\approx 30 - 90$ MPa
Heat strengthened glass	$\approx 50 - 120$ MPa
Fully tempered glass	$\approx 100 - 160$ MPa

2.2 Laminated Glass

Laminated glass was invented in year 1909 by the French chemist Eduard Benedictus [17]. Laminated glass is used in many different fields of applications, such as in buildings, but also in airplane windows and windscreens in cars.

Laminated glass was in the beginning developed as a product with better load-bearing capacity than monolithic glass [13]. But laminated glass also has other desirable properties such as enhanced safety, security, fire resistance and sound attenuation properties [13, 9]. The resistance on impacts, such as bullets, and the resistance to blast loads is higher for laminated glass due to the plastic interlayer [13, 9]. By laminating the post-breakage behaviour is enhanced, therefore laminated glass is useful in structural applications [9].

Laminated glass consists, as mentioned before, of two or more sheets of glass bonded together by a plastic interlayer [8]. Laminated glass that consist of more than two sheets of glass are called a multiply and these are for example used in glass beams, columns, stair treads and landings [13]. The adhesive contact between the glass and the interlayer is made by high pressure and heat, around 140 °C. This process generally takes place in a vessel, the autoclave [8, 13].

The purpose of the interlayer is to retain the fragments after fracture in the laminated glass, which eliminate the risk of injury due to glass shards [9, 13]. Laminated glass may consist of different kinds of glass and interlayers, see Figure 2.3. The thickness of the panes may be equal or unequal and the panes can be annealed glass, heat-treated glass or a combination of the two [9, 13].

The interlayer used in laminated glass is for example polyvinyl butyral (PVB), ethyl vinyl acetate (EVA) and SentryGlas® Plus (SGP) from the company DuPont, see Figure 2.3. Laminated glass can also consist of a liquid resin instead of a sheet interlayer. This is not so common and will not be treated in this thesis [13].

2.2.1 Interlayers

There are a variety of interlayers on the market, which are suitable for different areas of use. Interlayers can be used as a decorative effect with tinted or patterned interlayers, which will give the building a different aesthetic look. Some interlayers are addressed

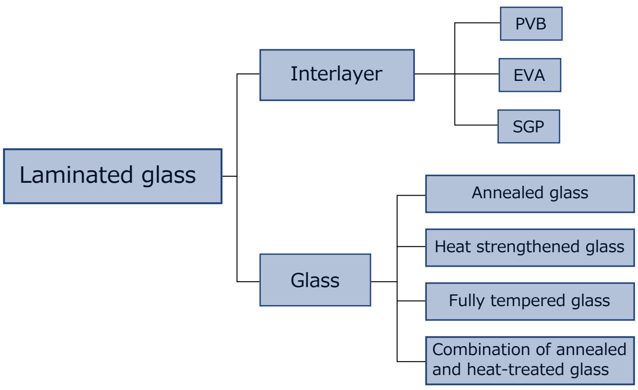


Figure 2.3: Components of laminated glass

to improve the thermal performance, the fire resistance and the safety and security properties.

The interlayers in laminated glass works in a wide range of temperatures, since it is usually subjected to different temperatures due to the seasonally changing weather (winter, summer). The interlayers are also subjected to loads with different time spans, such as impacts and permanent loads. Consequently it is important to evaluate the mechanical properties at different temperatures and times.

Interlayers used in laminated glass units are polymers with viscoelastic behaviour [5]. Materials with viscoelastic properties are dependent on time, temperature and load. These parameters influence the properties in different ways, for example; the higher the temperature, the weaker the interlayer. The interlayer creeps with high loads and with long loading time. Therefore it is common to assume that the interlayer creeps for sustained loads, i.e. ignore any shear transfer between the glass panels. By short load durations one may assume some shear interaction [9]. PVB, the most common interlayer, can usually transfer full shear stress between the two sheets of glass at a temperature below 0° C and for shorter times of loading. The ability to transfer shear stress is reduced by higher temperature and longer times of loading [9]. The temperature dependency will not be treated in this thesis due to the time limits of a master thesis, and also due to limitations of the testing equipment.

Interlayers in laminated glass are usually soft polymers like SGP, EVA or PVB. SGP is developed from the company DuPont and is said to have improved properties compared to PVB [13]. EVA does not require autoclaving and is for example used in photovoltaic glass where the laminated glass unit has integrated solar cells in the EVA-interlayer. Autoclaving would have damaged the solar cells so EVA is the appropriate interlayer for this application [9]. PVB is the most commonly used interlayer [9] and will be in focus for the thesis. PVB is the first interlayer used in laminated glass and over the years many new varieties of PVB have been developed. Previous works on the mechanical properties of the interlayer have mainly focused on standard PVB. More recent researches have been done on SGP and the results have been compared to PVB. At this time, none or few researches have been done comparing a variety of PVB. For some mechanical properties of PVB, see Table 2.4.

Table 2.4: Properties of PVB [9]

Tensile strength	$\geq$ 20 MPa
Shear modulus	0-4 GPa
Poisson's ratio	0.45 – 0.49

2.2.2 Structural Behaviour of Laminated Glass

The structural behaviour of laminated glass is complicated. There have been many research conducted within this field, mostly research deals with beams and plates of regular geometries subjected to standard point loads or uniformly distributed loads [7].

One of the first to study the structural behaviour was J.A. Hooper who conducted a study on laminated beams subjected to four-point bending [10]. This study was an

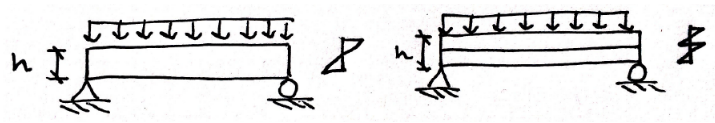


Figure 2.4: Stress distribution along cross section; monolithic and layered unit

outcome from when J.A. Hooper did the structural design of the glass walls for Sydney Opera House [10]. The conclusion from the work was that the bending strength is dependent on thickness and modulus of the interlayer. The study also implies that when laminated glass is subjected to sustained loads, such as snow or self-weight load, the laminated glass unit should be considered as two independent glass layers [10].

Two models to describe the structural behaviour are often mentioned in previous works, the layered glass unit model mentioned by Hooper and a monolithic glass plate model. A monolithic glass plate model is a simple model that consists of a monolithic glass, while the layered glass unit model consists of two sheets of glass and no interlayer, see Figure 2.4. The behaviour of laminated glass units are somewhere between these two models. The real behaviour may be calculated by the finite element method. One article dealing with this matter was conducted by Behr, Minor, Linden and Vallabhan in year 1985 [1]. The main objective of the study was to determine whether the structural behaviour of laminated glass units is best characterised by the monolithic or the layered behaviour. The study was conducted on plates, instead of beams as in the work conducted by Hooper. The conclusion from the study was that the laminated glass behaved like a monolithic glass plate with equal glass thickness in room temperature. However, at elevated temperatures it deflects like a layered glass unit having the same thickness [1].

2.2.3 Post-breakage Behaviour

Laminated glass has enhanced post-breakage behaviour compared to monolithic glass panes. The behaviour can be described in three stages, see Figure 2.5, where both glass sheets are intact in the first stage. In the next stage, stage two, the bottom glass panel is fractured and the top panel is carrying all the loads. In stage three the top sheet is also fractured; the interlayer is in tension and the glass pieces are locked together in compression [9].

There is a risk for so called dropouts in stage three, for example when laminated glass is used in ceilings or roofs. Dropouts may happen when both glass plies have

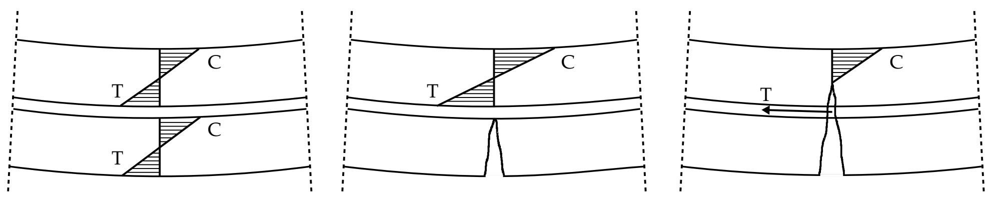


Figure 2.5: Post-breakage stress distribution, T=tension, C=compression [9]

broken and the interlayer is carrying the load. The glass panel may then separate from the support and fall down [13]. The risk of dropouts is higher for laminated glass units made of fully tempered glass. It is good to avoid fully tempered glass in laminated glass due to the post-breakage behaviour. However it may be used in combination with annealed or heat strengthened glass. If the laminate consists of one fully tempered glass, it is important that the fully tempered glass pane is located on the tensioned side of the laminated unit [9].

The remaining load-bearing capacity after failure is dependent on the fragmentation of the glass, e.g. which tempering that is used, and type of interlayer. Larger fragments lead to better post-break behaviour of the laminated glass. Due to the fracture pattern with very small pieces, the post-failure performance by fully tempered glass is less favourable than that of annealed glass. The fully tempered glass will sag like a wet towel and the post-breakage capacity relies solely on the tensile strength of the interlayer in this case. Therefore are the stiffness and the tensile strength important properties for the post-breakage structural capacity. Accordingly it is important to choose the right type of glass and interlayer for the application when designing laminated glass as a structural element, since the remaining load bearing capacity is dependent on these [9].

2.3 Current Standards, Guidelines and Design Methods

The current standards and guidelines for glass is not sufficient since they do not apply to all types of glass configurations, loading and support conditions [9]. Most of the guidelines only cover glass elements of rectangular shape with continuous support and to uniformly distributed out-of-plane loads [9]. In other words, there are no simple guidelines for designing a structural element made of glass. One design method is experimental tests, it is however expensive and not a long-term solution to have as a design method.

In the draft for the European standard (prEN 16612: Glass in building - Determination of the load resistance of glass panes by calculation and testing) the engineer is advised to do finite element simulations or to use a simplified calculation method to determine the load resistance of laminated glass. It also says that the viscoelastic properties of the interlayer material shall be considered when calculating the resistance to bending of laminated glass. One shall also take into account the variation with temperature and load duration for the interlayer. The viscoelastic properties of the interlayer shall be determined according to prEN 16613. In this standard one shall undertake tensile test to determine the shear modulus. It also prescribes that one shall do other tests regarding the time dependent behaviour.

Chapter 3

Experimental Tests

Experimental tests were performed at the Laboratory for Mechanics of Materials at the Solid Mechanics Department at LTH. The purpose of the experimental tests was to determine the mechanical properties of various interlayers. This was done with uniaxial tensile tests with different loading rates.

3.1 Performed Tests

Tensile test was conducted for six PVB-interlayer with various properties:

- Standard PVB with a thickness of 0.38 mm (PVB_0.38)
- Standard PVB with a thickness of 0.76 mm (PVB_0.76)
- PVB with enhanced acoustic properties with a thickness of 0.76 mm (PVB_0.76Ac)
- Saflex H, storm interlayer, with a thickness of 1.27 mm (DMJ1)
- Vanceva Storm (PVB /pet film / PVB composite) with a measured thickness of 0.68 mm (VS02)
- Saflex DG Interlayer (plasticized polyvinyl butyral) with a thickness of 1.27 mm (DG41)

The term storm is used from the producers of interlayers to indicate that these interlayers are appropriate in laminated glass in areas with risk for hurricanes, typhoons and violent storms.

The experiments were done at five different loading rates in order to pay attention to the time dependence of the mechanical properties and to different loading situations. The performed loading rates were 200 mm/min, 50 mm/min, 10 mm/min, 2 mm/min and 0.5 mm/min.

3.2 Test Design

The specimens were cut out of the interlayer sheets to the dimension 120 mm x 20 mm. The specimens were marked 30 mm from both ends to easier obtain the distance 60 mm

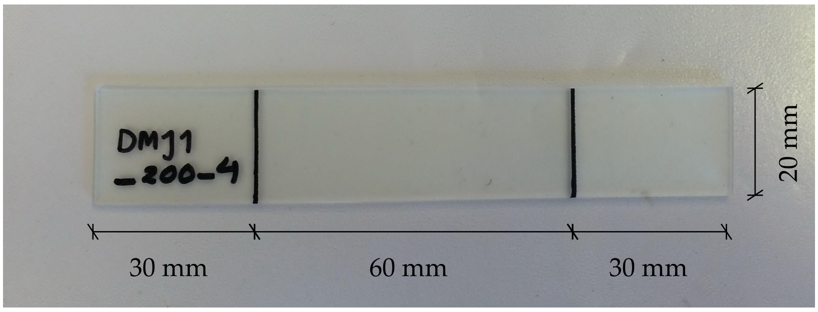


Figure 3.1: Dimension of specimens

in the testing machine. Every specimen was also marked with type of interlayer and load rate, see Figure 3.1. The thickness was measured to be later used in calculations, see Table 3.1.

Table 3.1: Thickness of the interlayers

Interlayer	**According to the producer [mm]**	**Measured [mm]**
PVB_0.38	0.38	0.43
PVB_0.76	0.76	0.80
PVB_0.76Ac	0.76	0.81
DMJ1	1.27	1.29
VS02	Not known	0.68
DG41	0.76	0.81

The uniaxial tensile tests were performed in an Instron testing machine with a 5000 N load cell. The distance between the lower clamp and the upper clamp was approximately 60 mm for all tests. A thermometer was located close to the lower clamp to measure the temperature. The test setup is depicted in Figure 3.2.

As mentioned above, the tensile tests were conducted with different loading rates. Five specimens of every kind of interlayer were tested for the loading rates 200 mm/min and 50 mm/min. For the loading rate 10 mm/min were three specimens tested and for 2 mm/min and 0.5 mm/min were one specimen tested, see Table 3.2.

Table 3.2: Number of performed tests for each type of interlayer

Load rate	**Number of tests**
200 mm/min	5
50 mm/min	5
10 mm/min	3
2 mm/min	1
0.5 mm/min	1

The specimens were loaded in tension until rupture. To protect the specimens from the uneven hard metal surface in the clamps and to prevent gliding, sandpaper was placed between the clamps and the specimens. The rupture was almost always

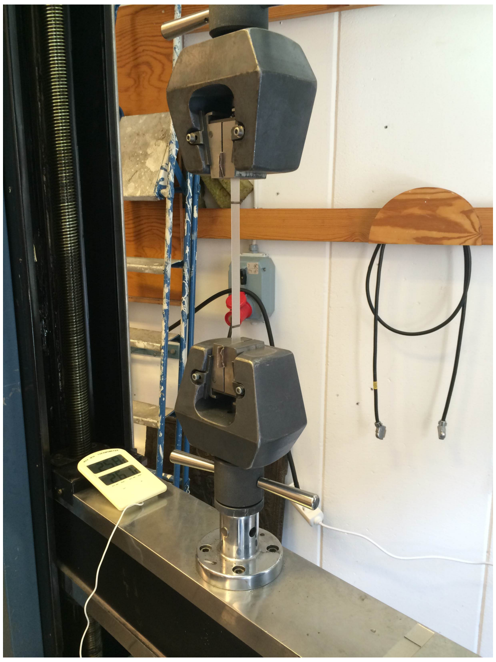


Figure 3.2: Testing machine

located close to one of the clamps due to the high stress concentrations there. The data measured was force and time and was retrieved with the program LabVIEW. The sample rate was one per second and the force was sampled with an accuracy of 0.1 N. However, for some of the first tests the retrieved data for the force were with an accuracy of 1 N, for example DG41-200-1 (Interlayer DG41, loading rate 200 mm/min, specimen 1).

3.3 Stress-strain Diagram

Stress-strain diagrams can be produced by various approaches. The stress and strains can be calculated either as true stress/strain or engineering stress/strain. True stress and true strain are based upon instantaneous values of cross sectional area and gage length. Engineering strain and stress are the more simple approach to obtain a stress-strain diagram and is adopted here. The engineering stress is calculated from

$$\sigma = \frac{F}{A} \tag{3.1}$$

where F is the applied load and A is the cross sectional area. The cross sectional area was calculated with the measured thickness, see Table 3.1. The engineering strain is calculated from

$$\epsilon = \frac{\triangle L}{L} = \frac{\ell - L}{L} \tag{3.2}$$

where ϵ is the engineering strain, L is the original length and ℓ is the final length of the specimen. It was not possible to use an extensometer in the tests; the length was instead measured with the loading rate and the time data. By using Equation 3.1 and Equation 3.2 a stress-strain diagram can be produced.

3.4 Results

For every test setup five, three or one specimens were tested. For the tests where five or three specimens were tested a mean value curve was created, which is presented here. The results from the experimental tests are shown in Figure 3.3. In Appendix A the stress-strain diagrams from all tests are presented.

It is evident that the mechanical behaviour for all interlayers is time dependent, since the mechanical properties were dependent on the velocity.

For all six interlayers it can be seen that with a decreasing loading rate, smaller stresses develop. Since the stress-strain diagrams are dependent on the loading rate, the conclusion can be made that the interlayers are time dependent. The thickness seems to have no influence on the mechanical properties for the standard PVB with the thickness 0.38 mm respectively 0.76 mm, since the stress-strain diagram are very similar. However, if the properties are influenced by the thickness when the interlayer is used in laminated glass cannot be determined from these tests.

The PVB with enhanced acoustic properties is less stiff than the standard PVB. The storm interlayer DMJ1 have similar stress-strain diagram as the standard PVB and PVB Acoustic, however being slightly stiffer. The interlayer DG41 and the other storm interlayer, VS02, shows a more stiff behaviour, where stresses of the order 0-15 MPa are developed, in comparison to 0-2 MPa for PVB 0.38 mm, PVB 0.76 mm, PVB Acoustic 0.76 mm and DMJ1.

In almost every tensile test, the fracture occurred close, or inside one of the clamps. The elongation before fracture was approximately $200\% - 450\%$ and after the tensile test the specimen almost directly returned to the original length and shape.

3.5 Discussion

By the calculations to obtain the stress-strain diagrams, the stress has been divided by the initial cross sectional area. The cross sectional area does not remain the same when a load is applied, more correct would have been to use the instantaneous cross sectional area. This was, however not possible, because the area could not be measured during the tests.

It would have been desirable to collect data more rapid than one sample per second. It is hard to capture the behaviour for the faster load rates, such as 200 mm/min, with only one data per second. It was not possible to retrieve data more than one time per second with the available test instrument.

The correct strain could not be determined from the tests. The reason for this is that a part of the interlayer in the clamps was pulled out during the measurement. To reduce this and to better determine the elongation, the specimen could have been shaped as a dog bone and an extensometer could have been used.

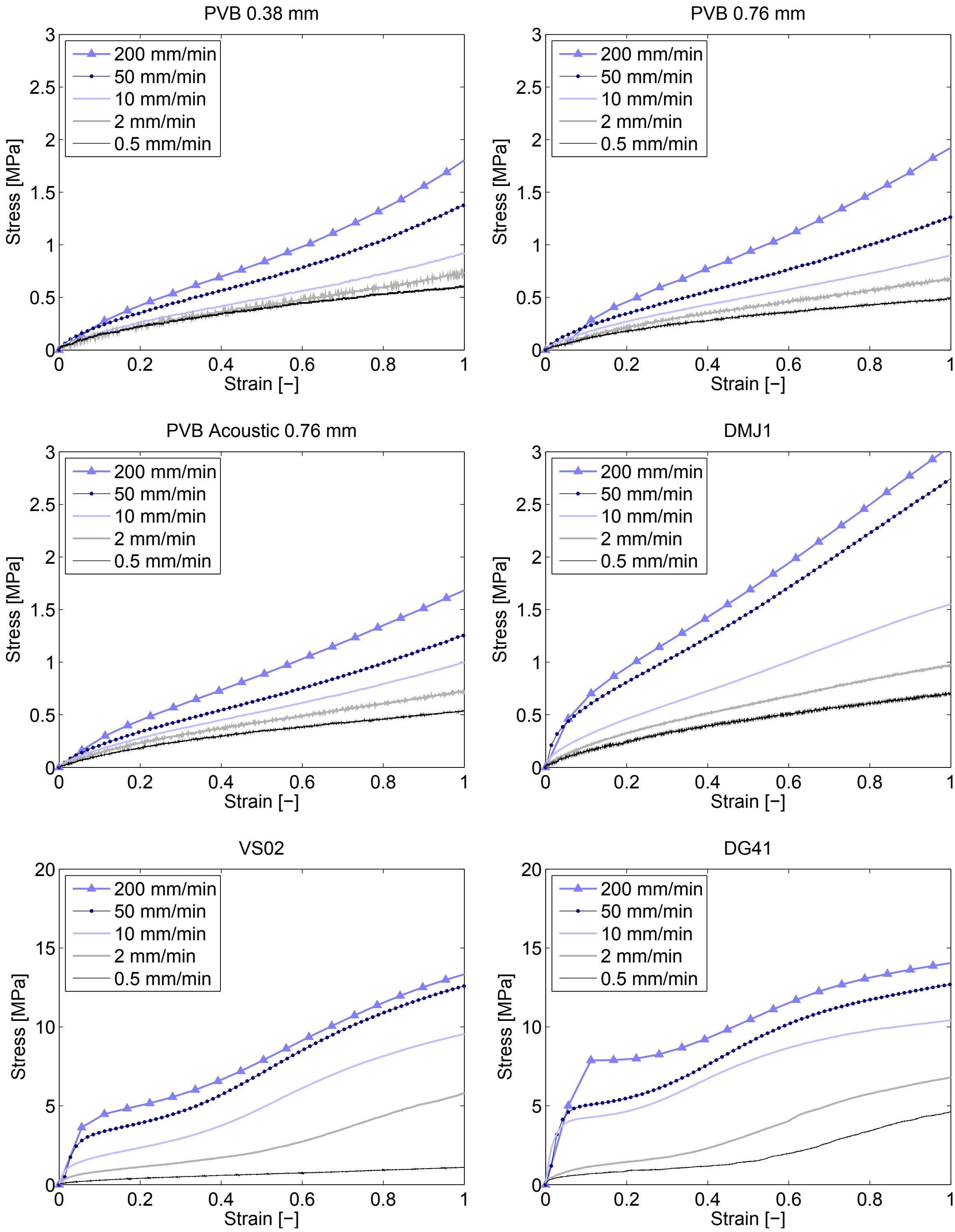


Figure 3.3: Tensile test

Chapter 4

Material Model

A viscoelastic material model aimed at numerical simulations is treated here. PVB is often simplified as a linear elastic material, due to the complicated calculations for viscoelastic materials [9]. However, since PVB has time dependent properties with influence on the structural behaviour, a viscoelastic model is here proposed.

4.1 Mechanical Model

Mechanical model, also called rheological model, describes the behaviour of a material. They are built from basic elements such as a spring and a linear dashpot [6]. The spring represents a linear elastic material with the stiffness E. The constitutive equation (Hooke's Law) is stated as

$$\epsilon(t) = \frac{\sigma(t)}{E} \tag{4.1}$$

where the stress-strain relation is linear [4]. For a linear viscous material, which responds as a linear dashpot (also called Newtonian dashpot), the constitutive equation is stated as

$$\dot{\epsilon} = \frac{d\epsilon}{dt} = \frac{\sigma}{\eta} \tag{4.2}$$

where η is the viscosity constant. As evident from the equation the mechanical response of the dashpot is time dependent, since the stress is linearly proportional to the time derivative of strain. By combining the spring and the linear dashpot mechanical models can be created that are time dependent [6].

4.1.1 Mechanical Models for Viscoelasticity

Two models to describe the viscoelastic behaviour are the Maxwell model and the Kelvin model. The spring and dashpot are in series in the Maxwell model, in contrast to the Kelvin model where the spring and dashpot are in parallel [6]. In Figure 4.1 are the two models schematically exemplified.

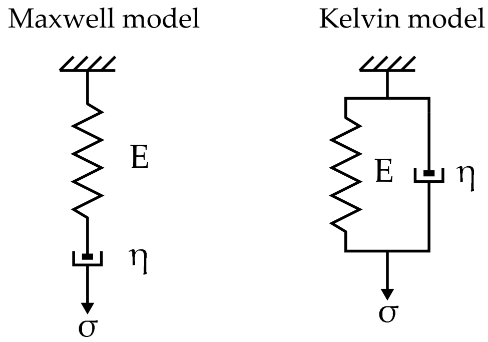


Figure 4.1: Rheological models; Maxwell model to the left and Kelvin model to the right

Generalized Maxwell Model

A polymer does not relax with a single relaxation time as predicted by the previous models. The long molecular segments relax after much longer time than the shorter and simpler segments. This leads to a distribution of relaxation times, which in turn produces a relaxation spread over a much longer time than what can be model with a single relaxation time. A model that considers this is the generalized Maxwell model, also known as the Wiechert model or the Maxwell-Wiechert model.

In this rheological model the relaxation occur at different time scales, each one associated with a Maxwell spring-dashpot unit. The model combines in parallel a series of Maxwell units and a Hookean spring, see Figure 4.2 [2]. The isolated spring produces the recovery of deformation after unloading [3]. The generalized Maxwell model is generally used in numerically researches with PVB.

From the rheological model the shear modulus of the linear viscoelastic material can be expressed as

$$G(t) = G_0 \left(1 - \sum_{i=1}^{n} g_i \left(1 - \mathrm{e}^{-\frac{t}{\tau_i}}\right)\right) \tag{4.3}$$

where $G(t)$ is the time dependent shear modulus, G_0 is the instantaneous shear modulus, g_i is the i'th Prony constant and τ_i represents the relaxation times. Series like this is mathematically known as a Prony series [2]. The bulk modulus may be described in the same way

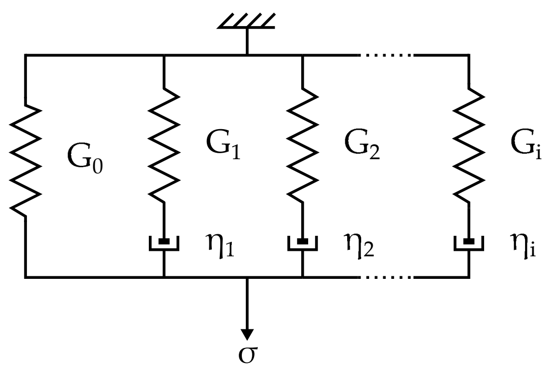


Figure 4.2: Rheological model, the generalized Maxwell model [16]

$$\kappa(t) = \kappa_0 \left(1 - \sum_{i=1}^{n} \kappa_i \left(1 - \mathrm{e}^{-\frac{t}{\tau_i}}\right)\right) \tag{4.4}$$

where κ_0 is the instantaneous bulk modulus, κ_i is the i'th Prony constant and τ_i represent the relaxation times.

Determining a Prony Series from test data

The coefficients in a Prony series can be determined from test data with known strain-rate history. By expressing the generalized Maxwell model in stresses instead of the shear modulus the fitting can be made. In the present case, the testing was made with constant strain rate. It is then easy to fit the test data to the generalized Maxwell model if it is rewritten in terms of $\sigma(t)$. The stresses may be found by integrating the expression in Equation 4.3 in time, see equations below.

$$\sigma(t) = \int_0^t G(t-\tau)\dot{\epsilon}(\tau)\,d\tau \tag{4.5}$$

$$\sigma(t) = G_0\dot{\epsilon} \int_0^t 1 - \sum_{i=1}^{n} g_i \left(1 - \mathrm{e}^{-\frac{t-\tau}{\tau_i}}\right) d\tau \tag{4.6}$$

$$\sigma(t) = G_0\dot{\epsilon} \left[\tau - \sum g_i \tau + \sum g_i \tau_i \mathrm{e}^{-\frac{t-\tau}{\tau_i}}\right]_0^t \tag{4.7}$$

$$\sigma(t) = G_0\dot{\epsilon} \left(t - \sum g_i t + \sum g_i \tau_i - \sum g_i \tau_i \mathrm{e}^{-\frac{t}{\tau_i}}\right) \tag{4.8}$$

By using two Prony terms ($n = 2$) in Equation 4.8, the result will be

$$\sigma(t) = G_0\dot{\epsilon} \left[(1 - g_1 - g_2)\,t + g_1\tau_1 \left(1 - \mathrm{e}^{-\frac{t}{\tau_1}}\right) + g_2\tau_2 \left(1 - \mathrm{e}^{-\frac{t}{\tau_2}}\right)\right] \tag{4.9}$$

Divide both expression above, Equation 4.9, and test data by $\dot{\epsilon}$ and fit model to experimental data. The Prony series for the shear modulus and the bulk modulus are assumed equal. The Prony series is also equal for the Young's modulus, since a constant Poisson's ratio (ν) is assumed, i.e. the Prony series is fitted to the Young's modulus from the experimental tests.

4.1.2 Application to Standard PVB 0.76 mm

Curve fitting in MATLAB

In MATLAB the experimental test data for PVB 0.76 mm was fitted to the expression shown in Equation 4.9 divided by $\dot{\epsilon}$, see Equation 4.10.

$$\sigma(t) = E_0 \left[(1 - g_1 - g_2)\,t + g_1\tau_1 \left(1 - \mathrm{e}^{-\frac{t}{\tau_1}}\right) + g_2\tau_2 \left(1 - \mathrm{e}^{-\frac{t}{\tau_2}}\right)\right] \tag{4.10}$$

The stresses with different loading rate were plotted against the time and each one of the five curves was divided with the strain rate. By dividing with the strain rate, the

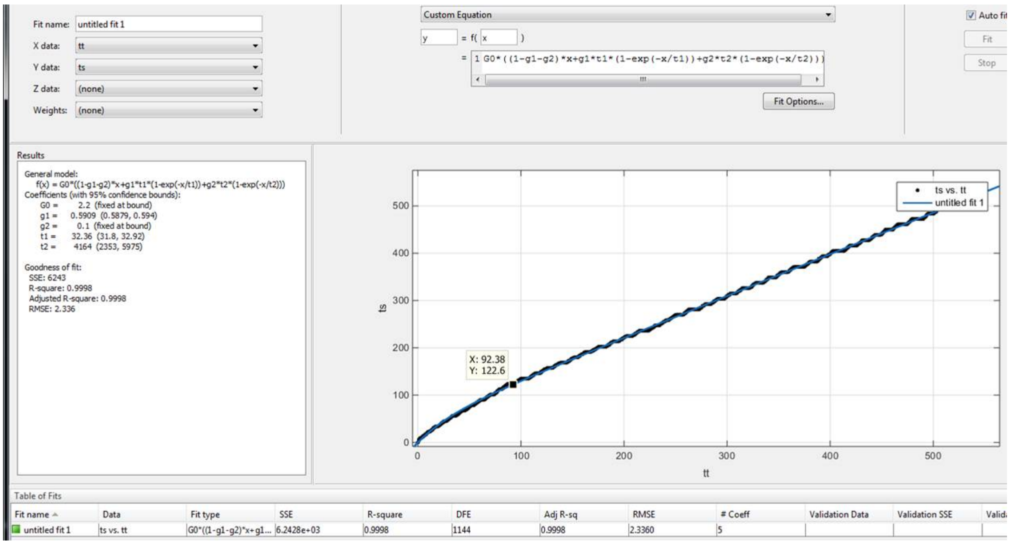


Figure 4.3: Curve fitting Tool in MATLAB

curves coincided in one curve as it should for a linear viscoelastic material. This curve was fitted to Equation 4.10 and E_0, g_1, g_2, τ_1 and τ_2 was determined, see Table 4.1 and Figure 4.3.

Table 4.1: Determined coefficients in Prony Series

E_0	g_1	g_2	τ_1	τ_2
2.2	0.5909	0.1	32.36	4164

Numerical Implementation in Abaqus

To implement the Prony series in Abaqus, some adjustments have to be made to the Prony series in Table 4.1. The adjustments have to be made since large strains are not accounted for in the model and since material from the interlayer in the clamps was pulled out during the tensile tests. The values for g_1, g_2 and G_0 had to be adjusted in the model since Abaqus states that

$$g_1 + g_2 < 1 \tag{4.11}$$

Abaqus assumes that the viscoelastic behaviour is defined by a Prony series expansion of dimensionless relaxation modulus [18]

$$g(t) = 1 - \sum_{i=1}^{n} g_i \left(1 - \mathrm{e}^{-\frac{t}{\tau_i}}\right) \tag{4.12}$$

The parameters g_1 and g_2 were made dimensionless, see Equation 4.13 and 4.14. By inserting the coefficients in the finite element model in Chapter 5, g_2 had to change value from 0.1 to 0.48 to correspond to the model.

$$g_1 = \frac{g_1}{g_1 + g_2} = \frac{0.5909}{0.5909 + 0.48} = 0.5518 \tag{4.13}$$

$$g_2 = \frac{g_2}{g_1 + g_2} = \frac{0.48}{0.5909 + 0.48} = 0.4482 \tag{4.14}$$

$$E_0 = E_0\,(g_1 + g_2) \cdot 10^6 = 2.3560 \text{ MPa} \tag{4.15}$$

The parameters are summarized in Table 5.2 in Section 5.2.1.

Chapter 5

Finite Element Study

In this chapter the basis of the finite element method is outlined and a finite element study on viscoelastic behaviour is reported.

5.1 The Finite Element Method

The finite element method is a numerical technique to solve differential equations approximately. A finite element (FE) analysis is required when the differential equations are too complicated to be solved by analytical methods. Many physical problems are described by partial differential equations. For this reason the finite element method is a very useful tool. With the FE method an object, called body, is divided into a large number of small parts, called finite elements, and within these elements an approximation is made. The approximation may for example be that the variable in the differential equation varies in a linear way over each element. The finite element mesh is the name for a body's total elements and by determine the behaviour for every element, the whole body's behaviour can be determined [12]. For a fundamental description of the finite element method, the reader is referred to existing literature, such as for example Ottosen and Petersson (1992).

There are several software available that are based on the finite element method. In this thesis the finite element study was carried out with the FE software Abaqus.

5.1.1 Elements in Abaqus

Depending on the element used, different variables will be calculated during an analysis. The degrees of freedom (dof) are the calculated variables during the analysis. In a stress/displacement simulation the degrees of freedom are the translations at each node, meaning that Abaqus are calculating the translation in direction x (1), y (2) and z (3) in every node [18].

There are linear and quadratic elements and these decide the number of nodes for each element. The linear element have nodes at their corners, see the 8-node brick in Figure 5.1, while the quadratic elements also have nodes along the edges of the brick, see the 20-node brick in the same figure [18].

It is important to know if the elements are linear or quadratic, since the degrees of

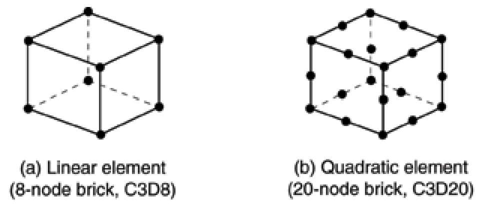


Figure 5.1: Linear and quadratic elements [18]

freedoms will only be calculated in the nodes. The displacements at any other point are calculated by interpolating from the nodal displacements. The linear elements use linear interpolation, while the quadratic elements use quadratic interpolation [18].

5.2 Finite Element Model

The tensile test set-up that was used in the experimental testing was modelled with Abaqus. In the model a viscoelastic material model was employed for the interlayer PVB 0.76 mm. The dimension of the PVB-specimen was 60 mm x 20 mm with a thickness of 0.76 mm, as in the experimental tests, see Figure 5.2. However, the thickness was set to 0.76 mm instead of the thickness of the samples measured of 0.80 mm. The input for the model was given in SI units.

The part of the specimen inside of the clamps was not modelled. Instead boundary conditions were applied on the top and the bottom of the specimen, see Figure 5.2.

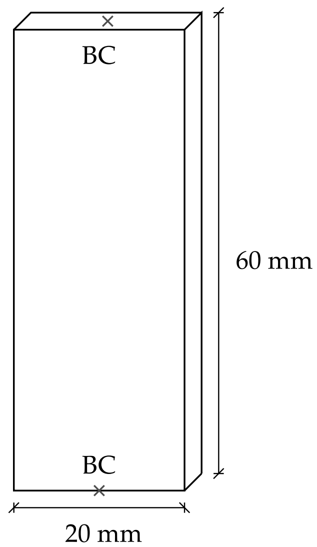


Figure 5.2: FE model

5.2.1 Material Model

To obtain the viscoelastic behaviour of the PVB, the material was defined by combining linear elasticity with viscoelasticity. The time dependent variables $G(t)$ and $E(t)$ are calculated from

$$G(t) = G_0 \left(1 - g_i \left(1 - \mathrm{e}^{-\frac{t}{\tau_i}}\right)\right) \tag{5.1}$$

$$E(t) = E_0 \left(1 - k_i \left(1 - \mathrm{e}^{-\frac{t}{\tau_i}}\right)\right) \tag{5.2}$$

where G_0 and E_0 are the instantaneous shear and elastic moduli. In the elastic model the PVB has been defined as an isotropic material with a Young's modulus of 2.36 MPa, a Poisson's ratio of 0.45 and is specified for the instantaneous response, see Table 5.1. G_0 is determined from E_0 and ν defined in Table 5.1 using $G_0 = E_0/2(1 + \nu)$.

Table 5.1: Elastic parameters in Abaqus

Young's Modulus (E_0)	2.36 MPa
Poisson's Ratio (ν)	0.45
Moduli	Instantaneous

Viscoelasticity

The viscoelastic material parameters can be defined by inclusion of for example creep test data, inclusion of relaxation test data or by direct specification of the Prony series parameters [18]. The viscoelastic properties of the PVB have been specified in the time domain viscoelasticity by using Prony series, see Table 5.2. The Prony series parameters have been determined from the experimental tensile tests data, see Section 4.1.2. The values for k_i (κ_i) are specified as the same as g_i, see Equation 4.3 and 4.4.

Table 5.2: Prony series

	g_i Prony	**k_i Prony**	**tau_i Prony**
1	0.551	0.551	32.36
2	0.448	0.448	4164

5.2.2 Boundary Conditions

The specimen is in the experiment clamped in two clamps. This is realized in the model by applying boundary conditions at the top and bottom surfaces. The boundary conditions for the lower surface were set to zero in the x-, y- and z-direction for the translation (U1, U2, U3=0). For the upper surface where the specimen is drawn in tension, the boundary conditions are set to zero as above, except for U2, which is set to 100% elongation (U2=0.06).

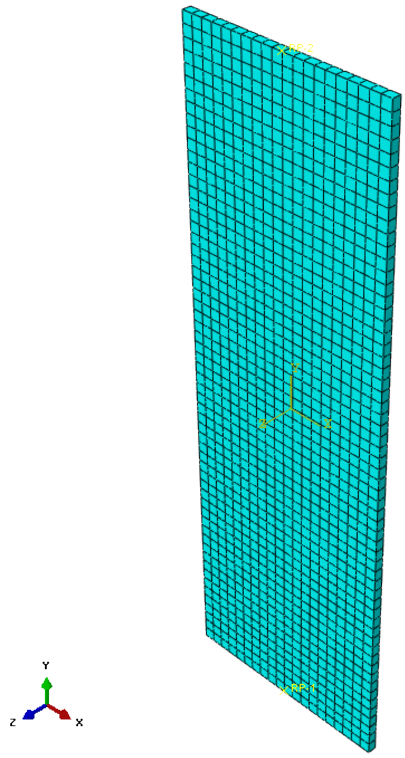


Figure 5.3: Mesh

5.2.3 Element Type and Mesh

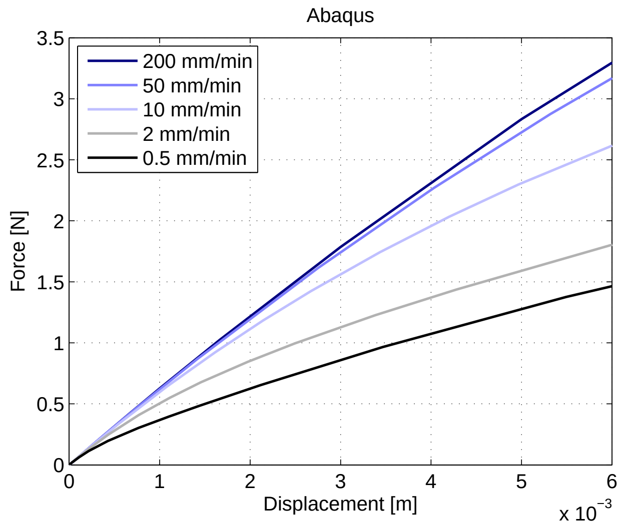
The element type used in this analysis is in Abaqus denoted C3D20R. C3D20R, indicates it is a 3D continuum element with quadratic approximation with 20 nodes and reduced integration [18]. For the element type C3D20R the active degrees of freedom are 1, 2 and 3, meaning that Abaqus are calculating the translation in the x-, y- and z-direction in each node [18]. The element size was set to 0.001 x 0.001 m and the mesh is depicted in Figure 5.3.

5.2.4 Analysis and Step

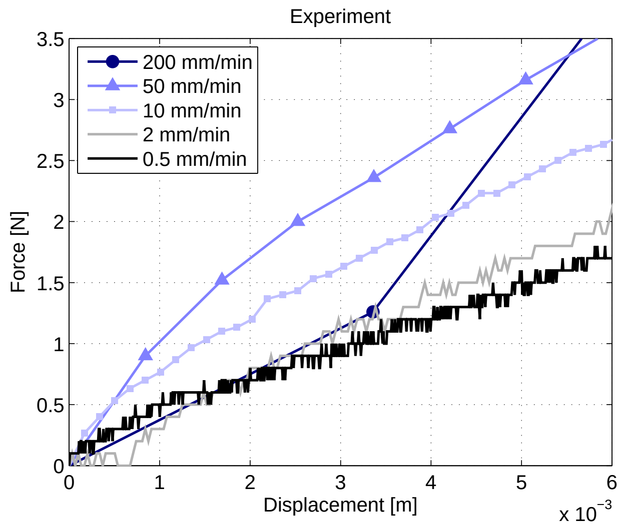
A quasi-static stress analysis was made by using the visco step. The analysis was set to take into account the non-linear effects from large displacements and deformations (geometric non-linearity) [18].

5.3 Results

From the FE model the reaction forces and displacements was plotted in MATLAB and compared with the experimental results, see Figure 5.4. The data is collected from where the prescribed displacement of 0.06 m is applied.



(a) Abaqus, PVB 0.76 mm



(b) Experiment, PVB 0.76 mm

Figure 5.4: Comparison of result

5.4 Discussion

The result from the Abaqus-model is in good agreement with the force-displacement diagram from the experiment, except for the load rate 200 mm/min. Even though the result is not in good agreement with the load rate 200 mm/min, the author believes the viscoelastic model to be valid within the limits of the strain rates performed in the testing. The deviation is due to the test method, since the data was collected one time per second. It is shown in Figure 5.5, that the curve for 200 mm/min follows the curves better after 100% elongation. Please note that Figure 5.4 is expressed in force-time, while Figure 5.5 in stress-strain.

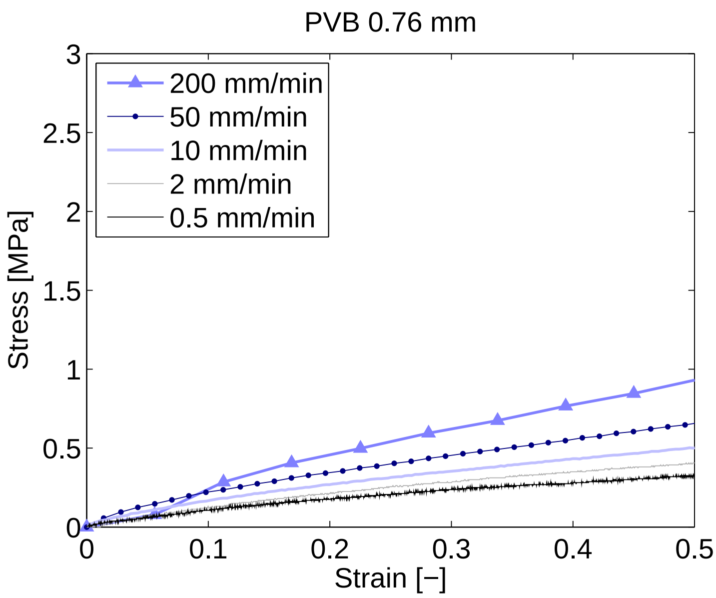


Figure 5.5: PVB 0.76 mm

Chapter 6

Numerical Application of the Viscoelastic Model

The time dependency of the interlayer implemented in the viscoelastic model was described in Chapter 5. To investigate how the creep in the interlayer affects a laminated glass unit subjected to short-term or long-term loads, a FE model was created subjected to various loads. An example of when laminated glass is subjected to a long-term load, such as snow load, is found for laminated glass roofs. Laminated glass facades are on the other hand more likely designed to resist short-term wind loads instead of snow load. The results from the analysis of these two loading conditions show how the time of loading affects the mechanical strength of the glass structure.

6.1 FE Model

The study was performed on a quadratic, simply supported laminated glass unit subjected to uniform loading. The laminated glass unit consisted of two sheets of glass and an interlayer with the thickness 0.76 mm. The dimension of the plate was 1.5 m x 1.5 m with a thickness of 10.76 mm. Everything in the model was given in SI-units. The supports were two-sided.

The glass was modelled as a linear elastic material with isotropic properties. The density was given as 2500 kg/m^3 (soda-lime-silica glass) [9], the Young's Modulus as 75 GPa and the Poisson's Ratio as 0.21, see Table 6.1.

Table 6.1: Properties of glass used in Abaqus

Density (ρ)	2500 kg/m^3 [9]
Young's Modulus (E_0)	75 GPa
Poisson's Ratio (ν)	0.21
Moduli	Long term

The interlayer was modelled as a standard PVB 0.76 mm with the material model proposed in Section 5.2.1. The density was specified to 1070 kg/m^3 to be able to apply the self-weight of the unit [9].

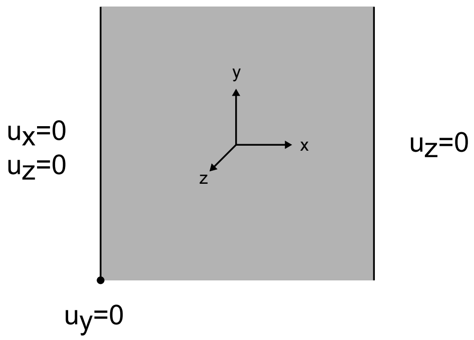


Figure 6.1: Boundary conditions

The boundary conditions were modelled where one side of the unit was constrained in the z-direction ($u_z = 0$). On the other side the translations in the x-direction and the z-direction were both set to zero ($u_x = u_y = 0$). To avoid rigid body motion a point on the corner on the same side was set to $u_y = 0$. See Figure 6.1 for boundary conditions.

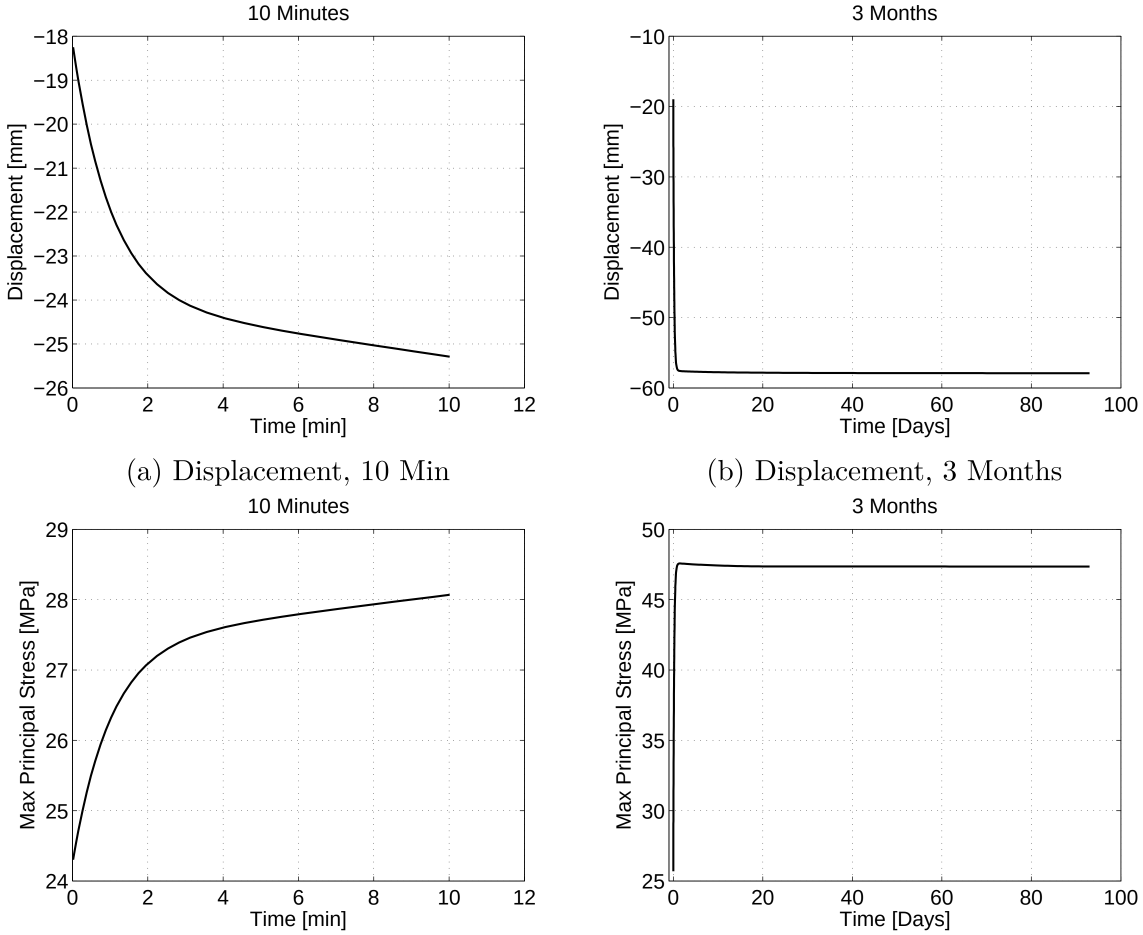
The unit was subjected to dead load in combination with snow load or wind load for the two load cases respectively. The value of the load was assumed to be of the same magnitude for the snow load and the wind load, but with different loading duration (3 months and 10 minutes respectively). The dead load was modelled in Abaqus by creating a gravity load with the acceleration of gravity of 9.81 m/s^2 and also by specifying the density of the glass and the interlayer. The wind load and the snow load was modelled as a surface traction with the magnitude 1200 Pa (see Appendix B). The load was assumed to not follow the rotation of the structure and the traction was defined per unit undeformed area.

Two steps were created, a general static step and a visco step. In the general static step the displacements and stresses caused by the loads are calculated, with no account taken of the creep of the interlayer. In the visco step the additional displacements and stresses due to viscoelasticity of the interlayer are calculated. The results from the analysis were only taken from the visco step, since the model was created to see how the creep of the interlayer affects the structural behaviour of the laminated glass. The model was taking into account geometric non-linearity. The time and increment size were specified differently in the visco step depending on whether the subjected load was the snow load or the wind load. The time for the snow load was specified as 8035200 s and the wind load as 600 s.

The mesh consisted of quadratic elements, element type C3D20R, the same as in the other FE model.

6.2 Result

The displacements and stresses from the results were saved and imported into MATLAB to plot diagrams, see Figure 6.2. The displayed results are taken from the midpoint of the tensioned side of the unit where the maximum stresses occurred. The stresses shown in the graphs are the maximum principal stresses. In Figure 6.2d the peak is reached after one day.



(a) Displacement, 10 Min

(b) Displacement, 3 Months

(c) Stress, 10 Min

(d) Stress, 3 Months

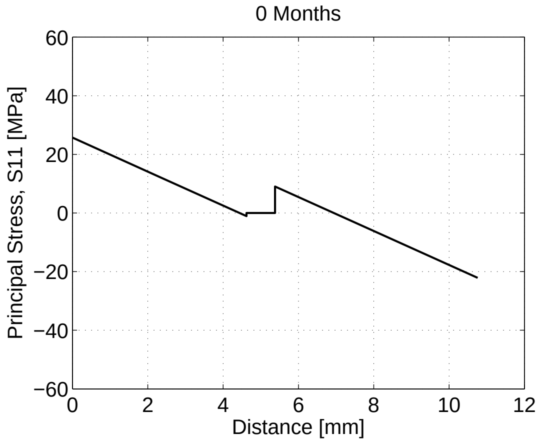
Figure 6.2: Stresses and displacements

The distribution of the stresses along the cross section are depicted in Figure 6.3 for the snow load. The stress in this figure is the principal stress in the x-direction (S11). Please note the differences in stresses on the compression side and the tension side, see Table 6.2.

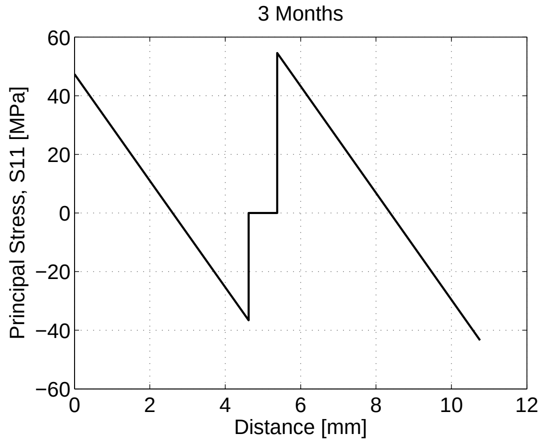
6.3 Discussion

It is shown in the graphs that the stresses and displacements increase in time. The laminated glass subjected to snow load is more likely to be broken after three months, see Figure 6.2d. The stress is 48 MPa and according to Eurocode (prEN 16612) the characteristic value of the bending strength is 45 N/mm^2 for annealed glass.

It is also evident that the presence of the interlayer affects the distribution of the stresses over the cross section. The duration of loading affects the distribution of stresses. At the start of the loading, the laminated glass unit behaves more close to



(a) Cross section, 0 Months



(b) Cross section, 3 Months

Figure 6.3: Cross section

Duration of load	Compression side [MPa]	Tension side [MPa]
0 Months	-22.14	25.69
3 Months	-43.41	47.35

Table 6.2: Stresses on surfaces, in (σ_{xx})

a monolithic glass structure. With time, when the interlayer creeps, the behaviour changes and is more close to the layered unit model.

Chapter 7

Results

The result from the experimental tests shows that there are differences in all the tested PVB. Some are stiffer, and some are softer. This shows that a PVB have various properties and by for example choosing a PVB with enhanced acoustic properties, the mechanical strength is lowered. By the knowledge of the differences of the interlayers one can choose the most optimal interlayer for the application.

From the experimental tensile tests a viscoelastic material model can be created to be used in simulation. The result from the FE study is in good agreement with the laboratory results for standard PVB 0.76 mm.

The numerical application where a laminated glass unit was subjected to sustained loads and short-term loads showed the loss in structural resistance due to the time dependent behaviour. One could note that with longer loading time, an increase in the stresses occurs and the plate behaves more like a layered unit than a monolithic plate. This leads to the conclusion that it is important to take into account the time dependent behaviour when using laminated glass as a structural element.

However, it would be desirable to compare the FE model with the laminated glass unit with experimental results.

Chapter 8

Conclusions and Future Work

8.1 Conclusions

The conclusion from the experimental tests is that PVB with various properties also show different mechanical behaviour. One conclusion which also could be made during the study was that a viscoelastic model can be determined from tensile tests with standard PVB 0.76 mm in good agreement with experimental results. Out of the results gained in this report the author concludes the importance to consider the time dependent behaviour when using laminated glass as a structural element, since the increase of stress in the laminated glass is high due to creeping in the interlayer.

8.2 Future Work

Future work that may be done is to evaluate the other interlayers and create a Prony serie which can be used in numerical simulations. For a more comprehensive determination of the viscoelastic properties further studies may be done on the temperature dependency of the material. It would also be of interest to compare the laminated glass model in Abaqus with experimental research to see how good the model is. It would also be interesting to do shear tests with the interlayers bonded together with the glass. The adhesion of the interlayer to the glass is also of interest when using laminated glass as a structural element.

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Appendix A

Experimental Test Results

The test results from all interlayers are presented here with the different load rates. Please note the scale on the x-axis. The elongation before fracture varied between the interlayers and the x-axis is scaled just before fracture. The y-axis has the same scale on every figure.

A.1 Load Rate 200 mm/min

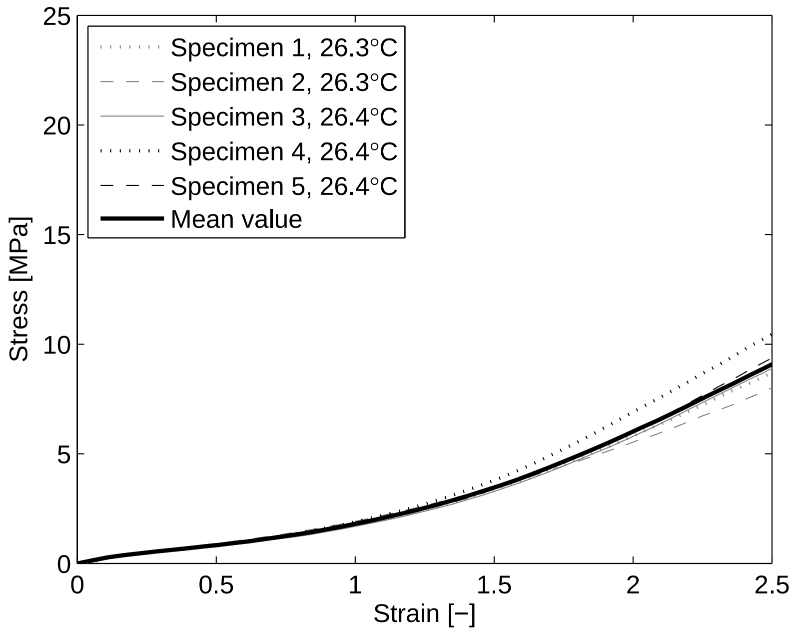

Figure A.1: PVB 0.38 mm, 200 mm/min

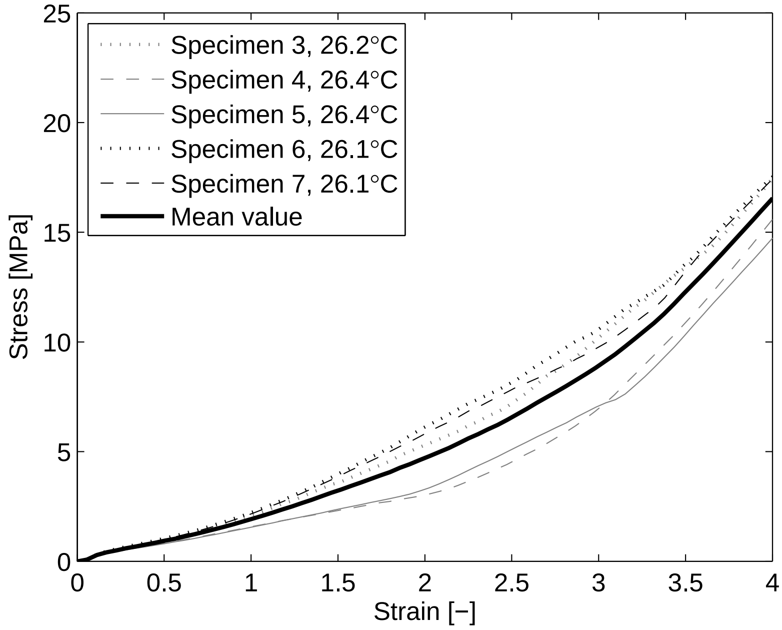

Figure A.2: PVB 0.76 mm, 200 mm/min

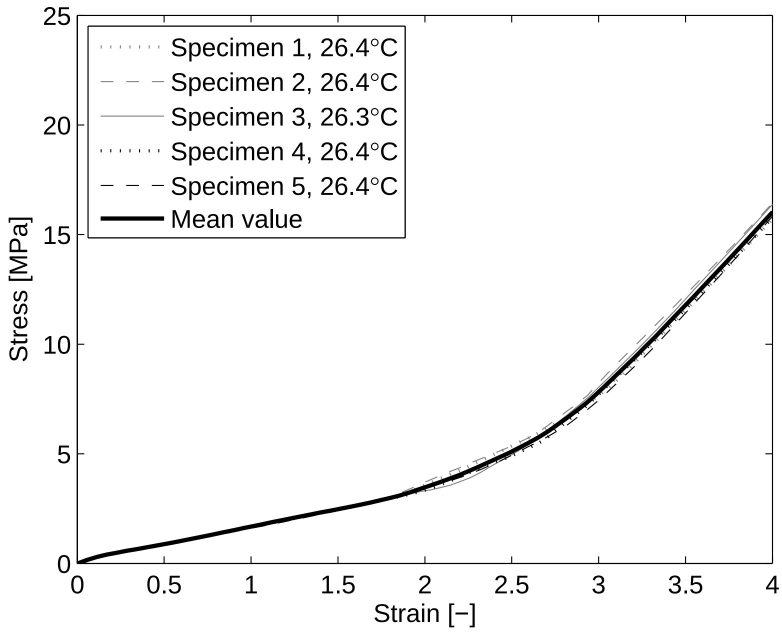

Figure A.3: PVB Acoustic 0.76 mm, 200 mm/min

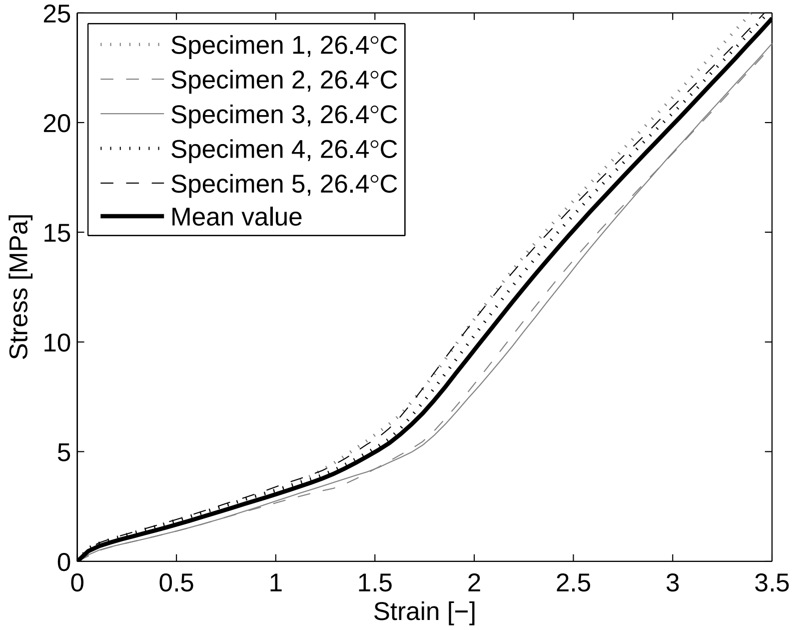

Figure A.4: DMJ1, 200 mm/min

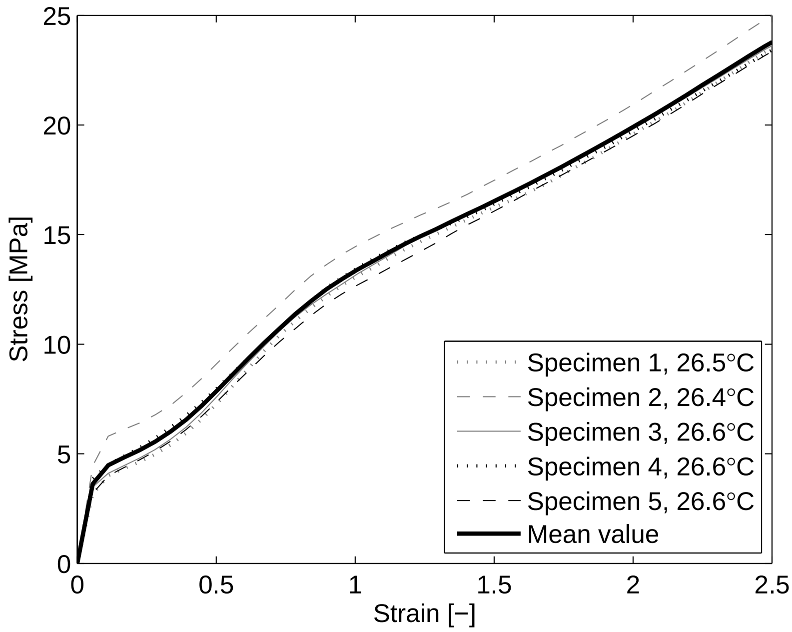

Figure A.5: VS02, 200 mm/min

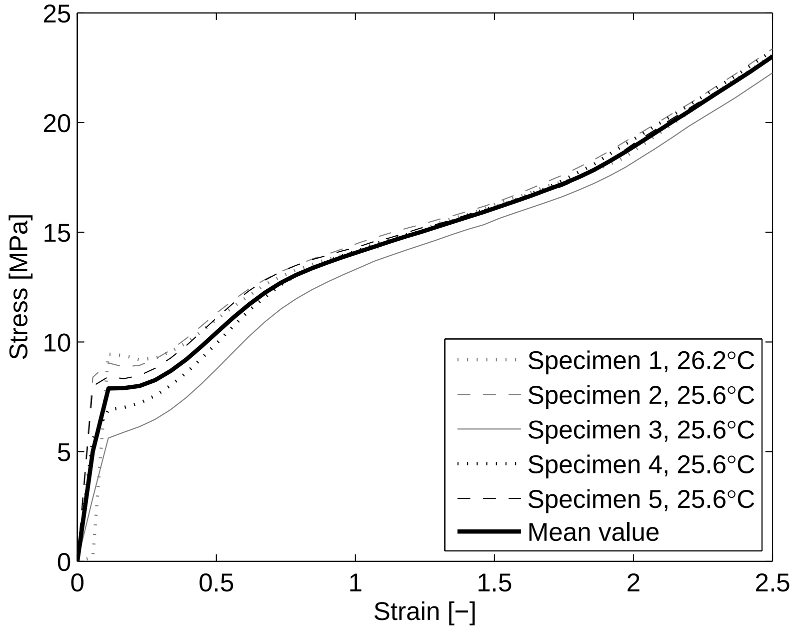

Figure A.6: DG41, 200 mm/min

A.2 Load Rate 50 mm/min

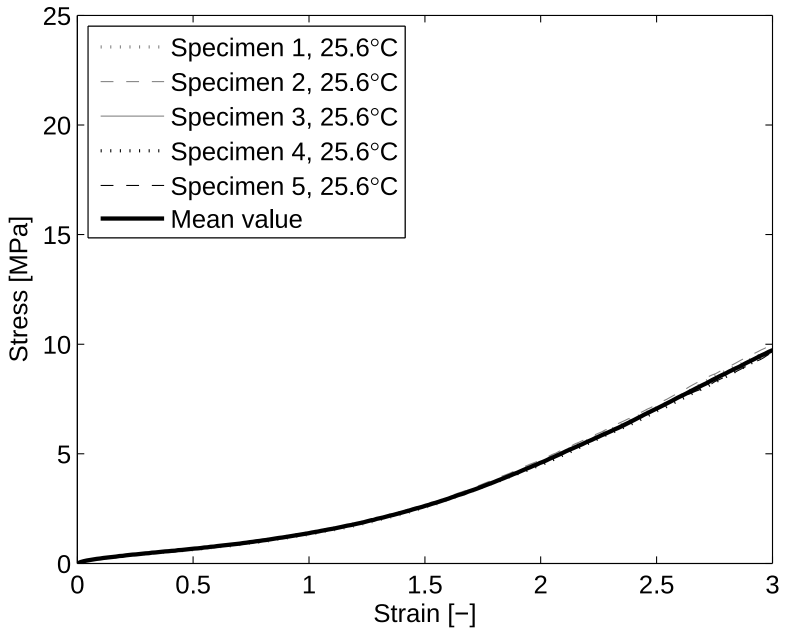

Figure A.7: PVB 0.38 mm, 50 mm/min

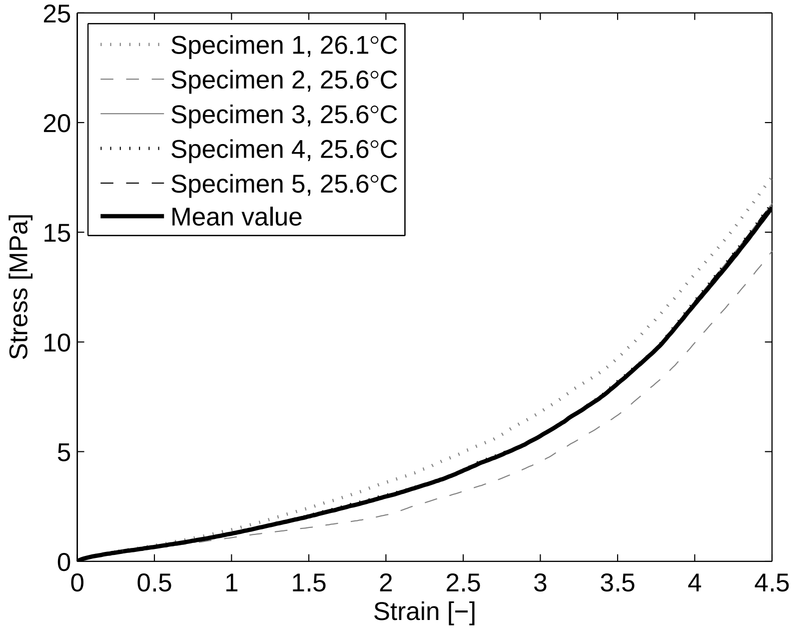

Figure A.8: PVB 0.76 mm, 50 mm/min

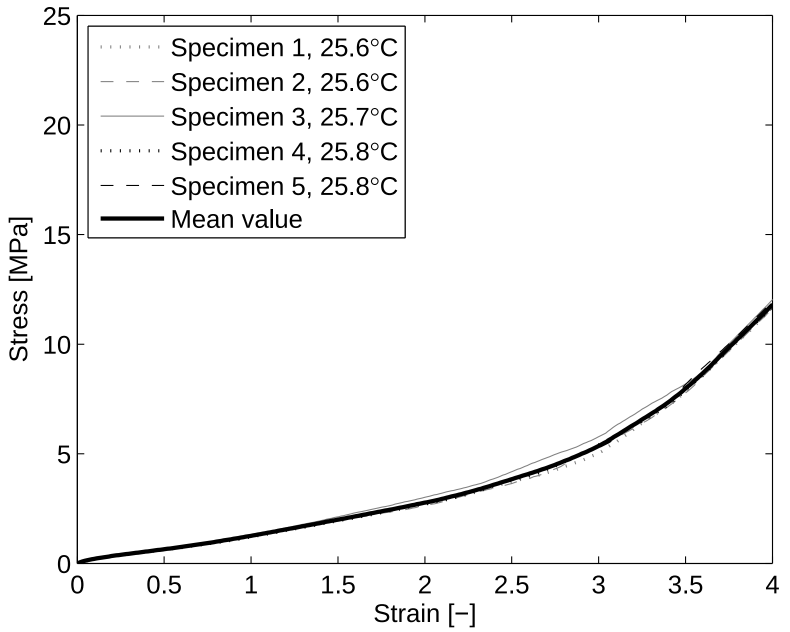

Figure A.9: PVB Acoustic 0.76 mm, 50 mm/min

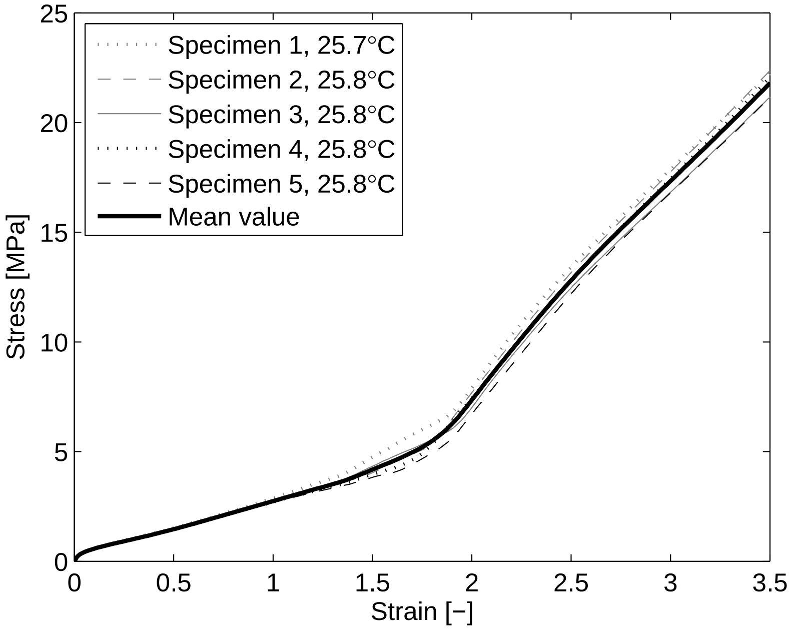

Figure A.10: DMJ1, 50 mm/min

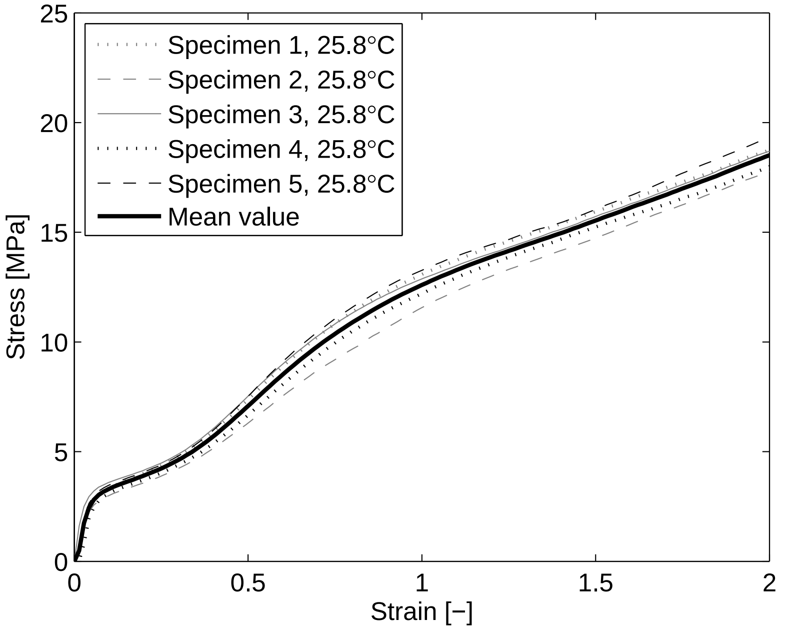

Figure A.11: VS02, 50 mm/min

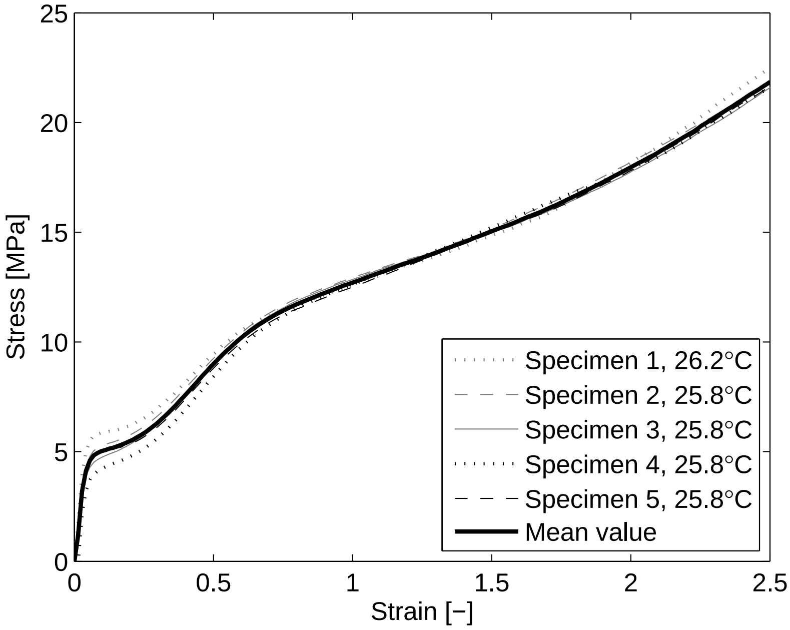

Figure A.12: DG41, 50 mm/min

A.3 Load Rate 10 mm/min

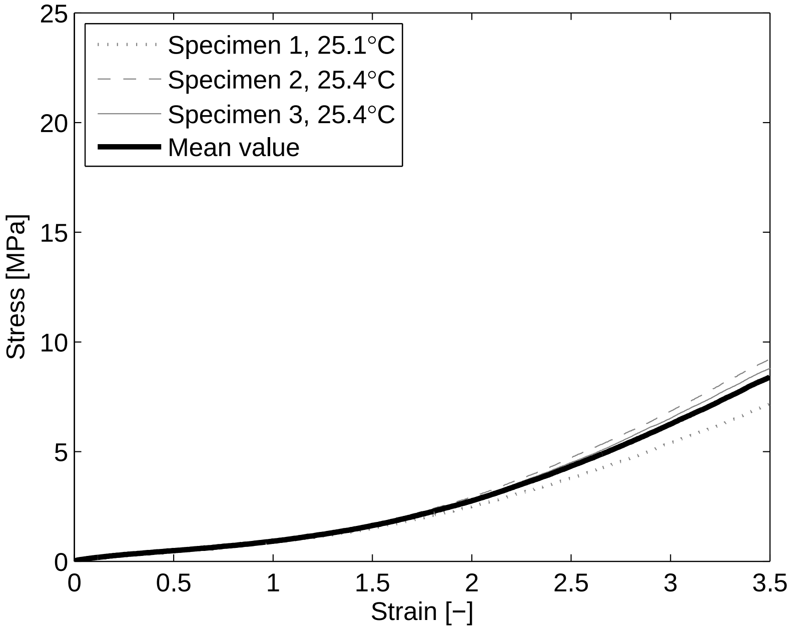

Figure A.13: PVB 0.38 mm, 10 mm/min

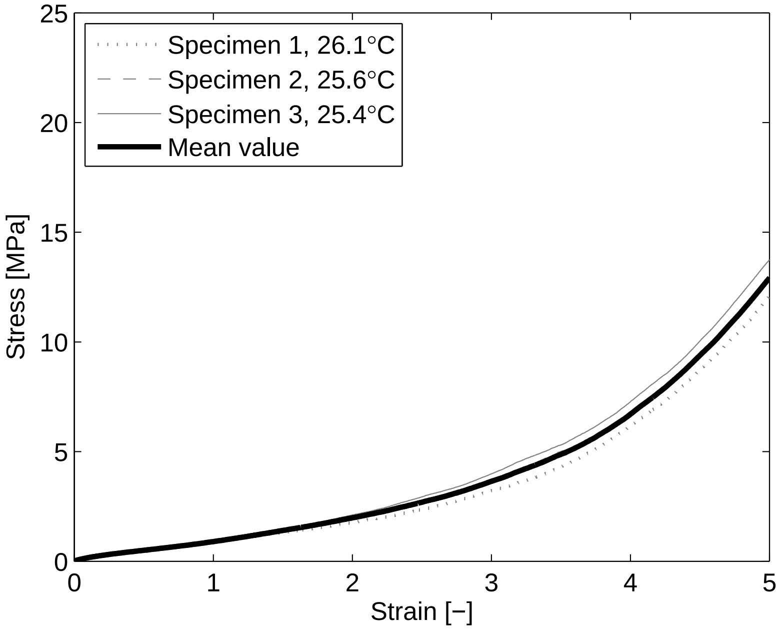

Figure A.14: PVB 0.76 mm, 10 mm/min

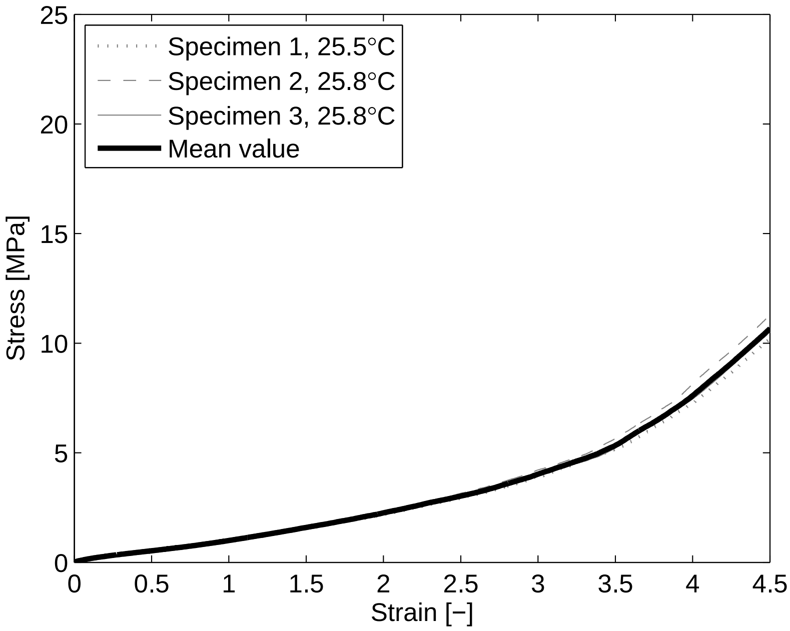

Figure A.15: PVB Acoustic 0.76 mm, 10 mm/min

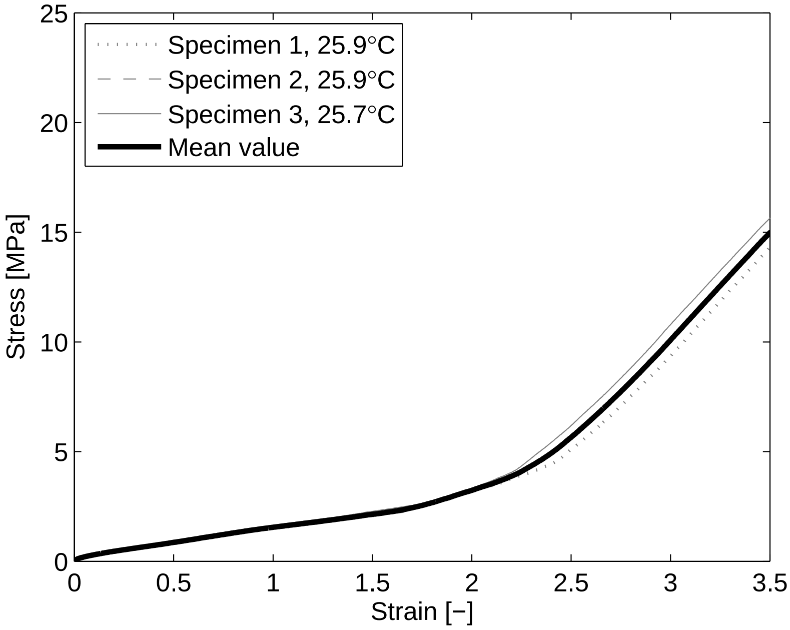

Figure A.16: DMJ1, 10 mm/min

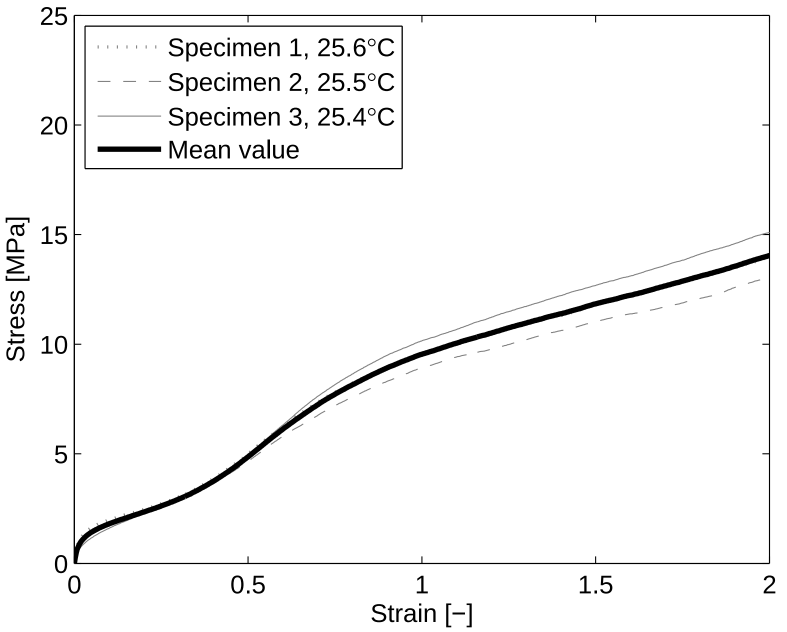

Figure A.17: VS02, 10 mm/min

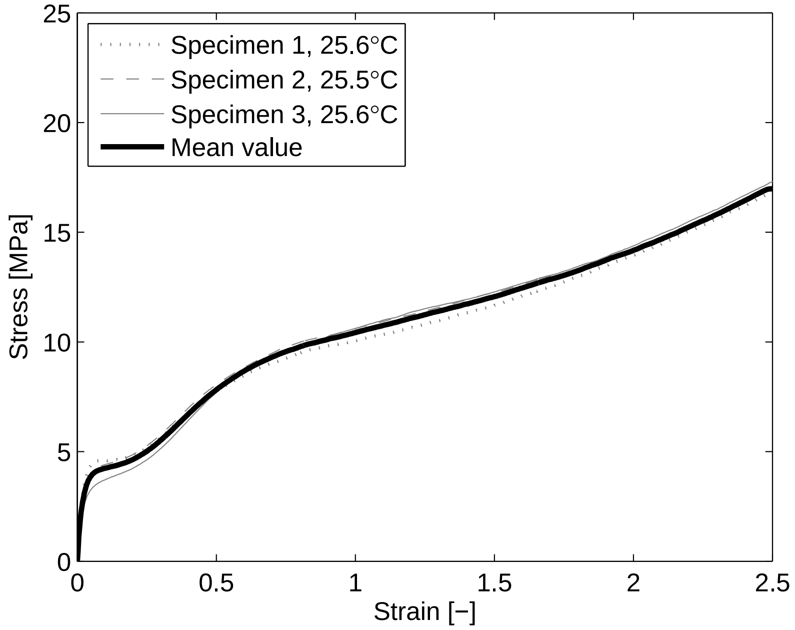

Figure A.18: DG41, 10 mm/min

A.4 Load Rate 2 mm/min and 0.5 mm/min

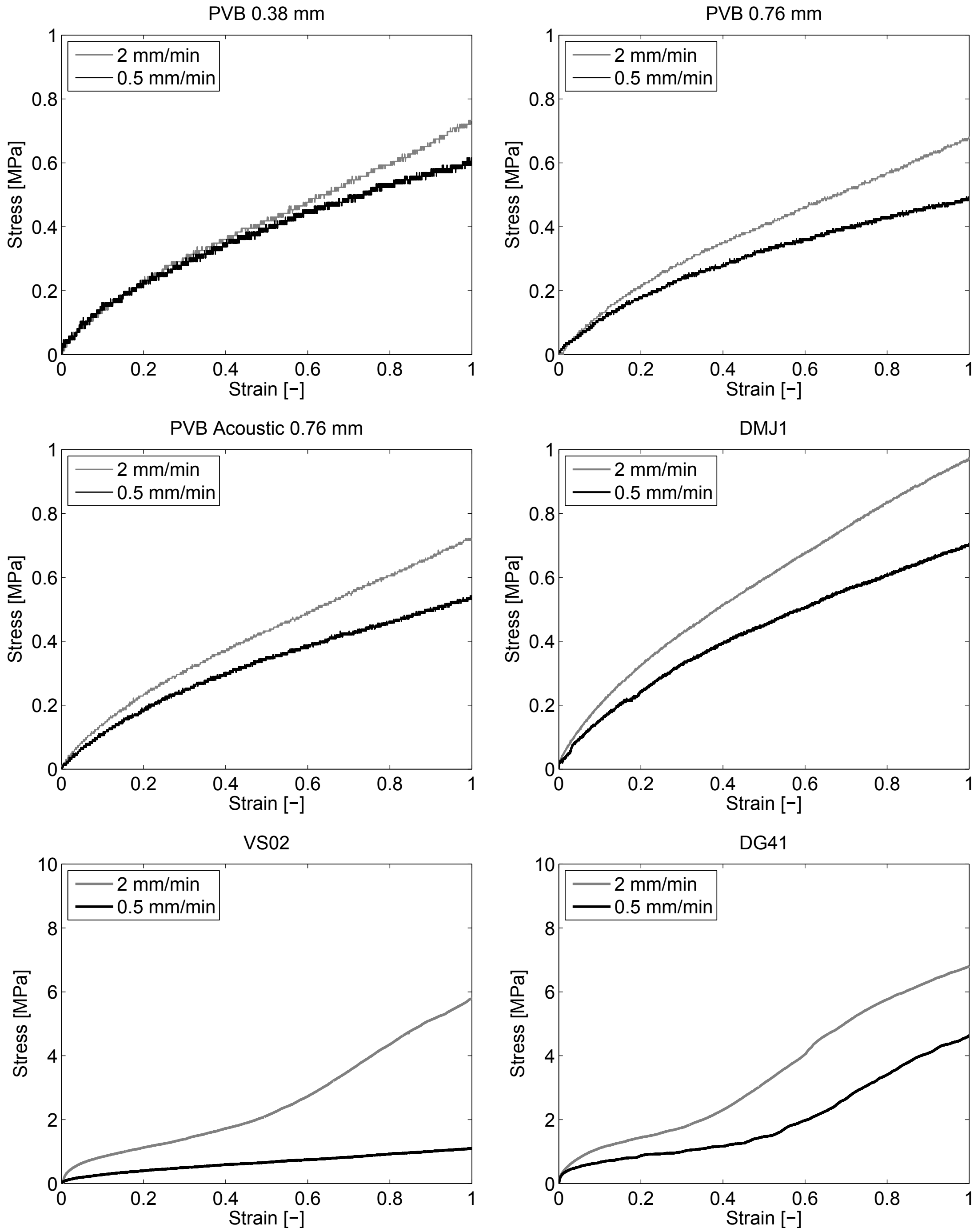

Figure A.19: Load rate 2 mm/min and 0.5 mm/min for every type of interlayer

Appendix B

Loads

The loads are calculated according to Eurocode, SS-EN 1991-1-3.

B.1 Snow Load

The snow load is calculated according to Eurocode 1: Actions on structures - Part 1-3: General actions - Snow loads (SS-EN1991-1-3).

$$s = \mu_i C e C_t s_k \tag{B.1}$$

where

μ_i is the form factor for the snow load, assumed $\mu_1 = 0.8$ (Table 5.2, 0°$\leq \alpha \leq$ 30°)

s_k is the characteristic value of ground snow load, assumed $s_k = 1.5$ kN/m^2 (Appendix NB, Lund)

C_e is the exposure factor, assumed $C_e = 1.0$ (Table 5.1, Normal Topography)

C_t is the thermal coefficient, assumed $C_t = 1.0$

The snow load used in simulation is

$$s = 0.8 \cdot 1.5 \cdot 1.0 \cdot 1.0 = 1200 \text{ Pa} \tag{B.2}$$

A typical value for the duration of snow load is 3 Months.

B.2 Wind Load

The wind load is assumed to be 1200 Pa as well. A typical value for the duration of wind load is 10 Minutes. Otherwise, how to calculate the magnitude of wind loads can be seen in Eurocode 1: Actions on structures - Part 1-4: General actions - Wind actions (SS-EN 1991-1-4).