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Four-Point Bending Tests of PVB Double Laminated Glass Panels – Experiments and Numerical Analysis

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Current architecture uses glass even for load bearing structural elements. Typical example is perpendicularly loaded laminated glass panel as a part of balustrade, staircase, or canopy. Laminated glass is a composition of two or more glass plies bonded by polymeric interlayer which enables the shear transfer between the individual plies in a laminated panel. The shear transfer depends on the shear stiffness of a certain interlayer as a time and temperature dependent parameter. Shear stiffness in time and temperature domain can be numerically described by a discrete Maxwell model whose Prony parameters may be obtained by Dynamic mechanical thermal analysis (DMTA) of a certain interlayer. There are various techniques of DMTA as well as various Prony parameters fitting methods. As soon as shear stiffness given by Maxwell model is quantified, it is desirable to verify its credibility by experiment. This paper compares the experimental data from displacement-controlled four-point bending tests in various loading rates and from four point bending long-term creep experiments of double laminated glass panels with PVB interlayer Trosifol®BG R20 to the numerical analysis performed in ANSYS® 18.0. The interlayer was modelled as a viscoelastic material by two discrete Maxwell models. Prony parameters of the first Maxwell model were based on DMTA results performed on small scale specimens in single lap shear mode and Prony parameters of the second Maxwell model were based on combined DMTA results performed on small scale specimens in single lap shear mode and torsion mode. Results show that Maxwell model based only on single lap shear tests enabled to describe the long-term response of a panel while that based on single lap shear and torsion tests was more precise in task of displacement-controlled test. All experiments and analyses were performed at CTU in Prague.

Keywords: Laminated glass, Loading ratio, Temperature, Shear stiffness, Polymeric interlayer, DMTA, Creep test

1. Introduction

Laminated glass gets extensively popular in a current architecture due to its transparency, aesthetical impression and subtle appearance. It is a composition of two or more glass plies bonded with polymeric interlayer. Laminated structural elements such as roof panels, balustrades, or stairs actually act as load bearing elements thus there is a need of safe and economical design. Shear stiffness of polymeric interlayer significantly affects shear interaction of the individual glass plies. To be economical, consideration of interlayer´s shear stiffness in the design of laminated glass panel in bending is appropriate. Experimental investigation of this quantity can be basically divided into two groups: (i) static long-term creep or relaxation experiments or (ii) dynamic tests called Dynamic mechanical thermal analysis (DMTA). Static tests can be performed on a single interlayer (Botz and Wilhelm et al. 2019) or on laminated glass specimens (Callewaert and Depaepe et al. 2008; Botz and Kraus et al. 2018). These require simple evaluation methods but cannot be basically performed in broad time and temperature range. Usual results are values of shear modulus in time domain. DMTA is more complicated experimental method, it requires advanced testing apparatus and software. Interlayer in laminated glass specimens can be subjected to oscillatory loading in shear mode (Vokáč and Hána et al. 2019) or in torsion mode (Andreozzi and Bricolli Bati et al. 2014). Usual result is a Master curve of tested interlayer which can be described by generalized Maxwell model (Kraus and Schuster et al. 2017). Once the Maxwell model fits DMTA data, it enables to express shear modulus of an interlayer in broad time and temperature range. Unfortunately, both shear and torsion modes are affected by a certain error (Hána and Janda et al. 2019) thus there is a need to verify fitted mechanical models of a certain interlayer by experiments. One way is considering simple shear modulus in analytical calculations (Galuppi and Manara et al. 2013) or using full viscoelastic solution (FVS) based on Maxwell model implemented in FE software (Kuntsche and Schuster et al. 2019) to calculate the response of laminated glass panel in certain boundary conditions and to compare obtained results with experiment. FVS is more time consuming, but it includes the entire loading history which is an important parameter. This paper compares the experimental data from four-point bending creep tests and from displacement-controlled four-point bending tests of double laminated glass panels with PVB interlayer Trosifol®BG R20 to the numerical results gained from ANSYS® Mechanical 18.0. Emphasis is placed primarily on the credibility of interlayer´s material model as an input into numerical model, with regard to the method of its experimental investigation. The interlayer was modelled as an isotropic homogeneous viscoelastic material by two Maxwell models based on (i) DMTA results in shear mode (Vokáč and Hána et al. 2019), and (ii) combined DMTA results in shear and torsion mode (Hána and Janda et al. 2019). All experiments and analyses were performed at CTU in Prague.

2. Experimental programme

2.1. Materials and equipment

Six double laminated glass panels were tested in displacement-controlled four-point bending tests and one double laminated glass panel in four-point bending creep tests. Panels were laminated with 0.76 mm thick interlayer Trosifol®BG R20 and they were made of heat toughened glass. Nominal dimensions of panels were 1100 x 360 mm, 10.10.2. Displacement-controlled tests were performed in MTS 100 kN loading device, see Fig. 1a, and creep tests were performed in the climatic chamber, see Fig. 1b. Static schema of all bending tests is shown in Fig. 2. To measure the normal stress at midspan, there were totally six strain gauges LY 11-10/120 attached to the glass surface – three gauges in tension (lower surface) and three in compression (upper surface), see Fig. 3. Vertical deflection at the midspan was measured by two displacement sensors I and II located near the edge of the panel, see Fig. 4. In creep tests, temperature of each glass surface was measured by two TE Connectivity Pt 100 sensors stuck directly to the glass and the temperature in the climatic chamber was measured by RS 3 wire Pt 100 sensor. In displacement-controlled tests, the temperature was measured by contact thermometer. Tested interlayer belongs among interlayers made of polyvinyl butyral which is an amorphous thermoplastic polymer soluble in organic solvents. Good adhesion between PVB based interlayer and glass is mainly generated by the formation of hydrogen bonds between hydroxyl groups of these two materials (Schuster and Kraus et al. 2018). Material data of tested PVB interlayer Trosifol®BG R20 is shown in Table 1.

Table 1: Material data of tested PVB interlayer Trosifol®BG R20.

Interlayer	Density	Thermal conductivity	Tensile strength	Nominal thickness	Glass transition temperature
	[g/cm^3]	[W/mK]	[MPa]	[mm]	[°C]
Trosifol BG R20	1.065	0.2	23.0	0.76; 1.52	+26

Fig. 1a) MTS loading device for displacement-controlled tests, b) Closed climatic chamber for creep tests ensures climatic conditions.

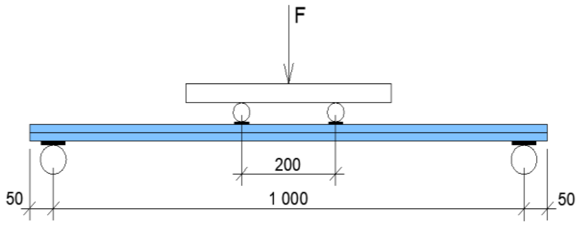


Fig. 2 Static schema of all bending tests.

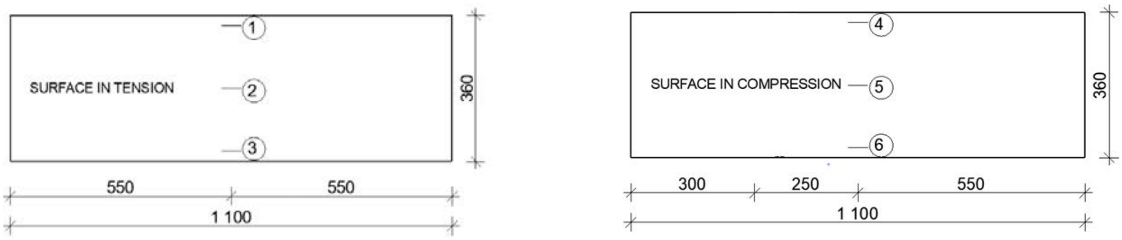
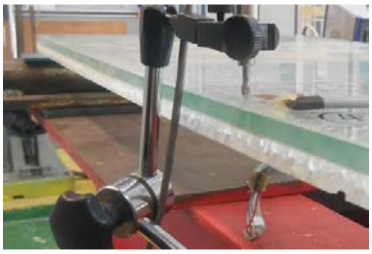


Fig. 3 Position of strain gauges on lower and upper surface of laminated glass panel at all tests.



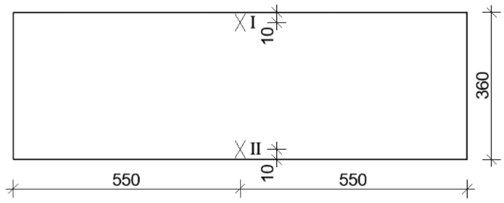
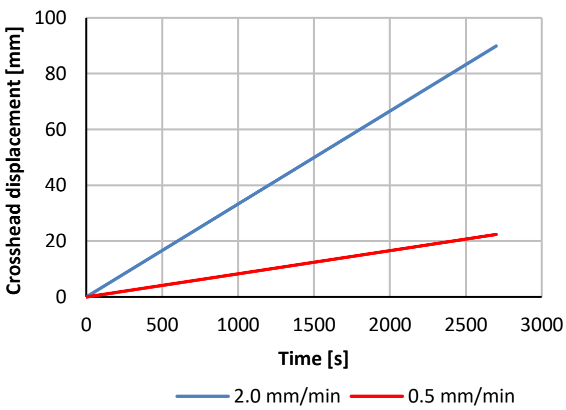


Fig. 4a) Detail of displacement sensor, b) Position of displacement sensors on glass panel at all tests.

2.2. Test set-up

Three panels in displacement-controlled tests were loaded by MTS cross head speed 2.0 mm/min, and three panels by cross head speed 0.5 mm/min to find the influence of the loading rate on their response. The tests were destructive and each panel was loaded until breakage of lower glass ply. Loading rate was kept constant during the entire loading phase. Temperature during the experiments was measured in the range of +19 °C and +22 °C. Modes of MTS cross head displacement in time are schematically shown in Fig. 5a and detail of MTS loading apparatus is shown in Fig. 6a.

In creep tests, the panel had been conditioned at the testing temperature in the closed climatic chamber for at least 24 hours before applying the load. The chamber was then opened, laminated panel was loaded by constant force 1.12 kN as fast as possible, and the chamber was closed. The load was applied in the range of 117 hours to 164 hours. Then, the chamber was opened, the panel was unloaded as fast as possible, the chamber was closed again, and the response of the panel was further monitored for at least 24 hours. The example of force-time relation is in Fig. 5b. Loading force was achieved by self weight of four steel weights and loading apparatus. Steel weights were positioned on the loading apparatus, see the apparatus in Fig. 6b, to load the panel as much symetrically as possible. Static schema of the creep test was identical with displacement-controlled tests, i.e. four-point bending tests in both cases. Temperature was kept constant during the entire creep measurement. Totally 3 temperatures were tested: +30 °C, +40 °C, and +50 °C. The positions of glass temperature sensors TE Connectivity Pt100 glued on both glass surfaces and example of their temperature record at 40 °C during the entire experiment are in Fig. 7. Loading of panels in both types of experiments is shown in Fig. 8.



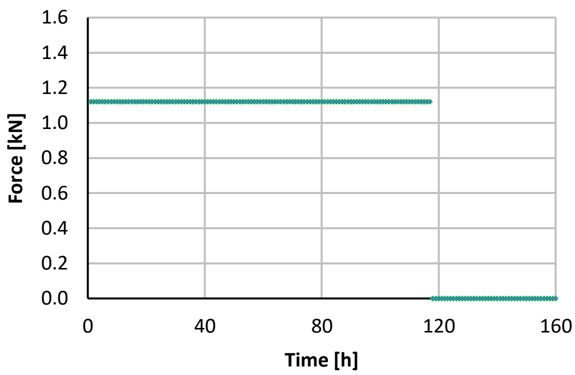


Fig. 5a) Modes of cross head displacement in time in displacement-controlled tests, b) Example of applied load in time in creep test.

Fig. 6a) Loading apparatus in displacement-controlled test, b) Loading apparatus in creep tests.

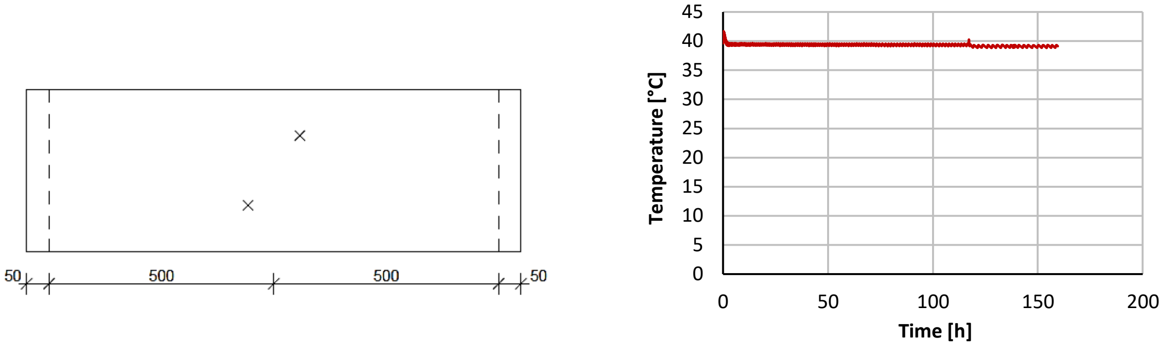


Fig. 7a) Position of sensors Pt 100 on glass surfaces in creep test, b) Temperature record on glass by sensor Pt 100 at set 40 °C in creep test.

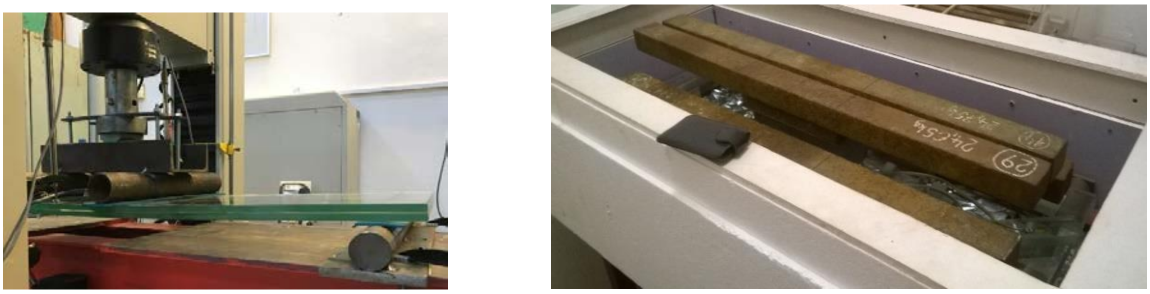


Fig. 8a) Panel loaded in displacement controlled bending test, b) Panel loaded in bending creep test – opened chamber right after loading

Polymeric interlayer was in the numerical model considered as a viscoelastic material through Maxwell models based on DMTA performed on small-scale laminated glass specimens. First Maxwell model was based on DMTA results from shear mode (SH) (Vokáč and Hána et al. 2019), second was based on combined DMTA results from shear and torsion mode (SH+TS) (Hána and Janda et al. 2019). DMTA in shear mode was performed on single lap specimens in hydraulic testing system MTS with climatic chamber TIRA TEST T250/1. Temperature of glass was also measured by sensors Pt 100. Testing temperatures and frequencies were kept in range -5 °C to +40 °C and 0.05 Hz to 4.95 Hz, respectively. Tests were displacement-controlled. DMTA in torsion mode was performed on small, double laminated, cylindrical specimens glued by stiff epoxy to rotating plates of dynamic shear rheometer HAAKE MARS. Bottom plate served as a heat source. Torsion tests were performed in range of frequencies 0.001 Hz to 50 Hz and temperatures +10 °C to +60 °C, and they were controlled by torsional moment. Both testing methods, displayed in Fig. 9a, should theoretically provide the same value of interlayer´s shear modulus *G* which can be used as a material parameter into analysis of laminated glass in bending, but both methods are loaded by certain errors causing the noise of the data. This means, they practically provide the values of *G* by constructed Maxwell models which do not coincide (Hána and Janda et al. 2019) and the need of their experimental investigation using large scale specimens is desirable.

Fig. 9 a) DMTA of single lap laminated glass specimen in MTS, b) DMTA of double laminated glass specimen in rheometer HAAKE MARS.

3. Numerical model of bending tests in ANSYS

Numerical analysis of bending tests was performed in ANSYS® 18.0. Nominal dimensions of glass and interlayer were used in the analysis, i.e. 10 + 0.76 + 10 mm thickness, 360 mm width, and 1000 mm span of the panel. Glass was considered as linear elastic isotropic material with Young´s modulus $E = 70$ GPa and Poisson´s ratio $\upsilon = 0.23$ according to DIN 18008-1. Viscoelastic interlayer is characterized by a combination of elastic and viscous behaviour. Stress function of an interlayer for variable load is in ANSYS defined by Boltzmann superposition principle as (Lakes 2009; Martynenko 2017)

$$\boldsymbol{\sigma}(t) = \int_0^t 2\boldsymbol{G}(t-s)\frac{d\boldsymbol{e}}{ds}ds + \boldsymbol{I}\int_0^t \boldsymbol{K}(t-s)\frac{d\boldsymbol{\xi}}{ds}ds, \tag{1}$$

where e denotes deviatoric part of strain, ξ represents volumetric part of strain, G(t) represents shear relaxation tensor, K(t) is bulk relaxation tensor, t is current time, s lies in interval <0; t>, and I is unit tensor. Relaxation functions are in ANSYS represented in terms of Maxwell Prony series according to the equation 2, where G_0 and K_0 represent instantaneous shear and volumetric stiffness of Maxwell as $G_0 = \sum_i G_i + G_\infty$ and $K_0 = \sum_i K_i + K_\infty$, and a_i are the relative shear or bulk moduli of individual elements defined as $a_i^G = G_i / G_o$ and $a_i^K = K_i / K_o$. Symbols τ_i^G and τ_i^K represent relaxation times of elements as a ratio of dashpot viscosity and spring stiffness as $\tau_i^G = \eta_i^G / G_i$, $\tau_i^K = \eta_i^K / K_i$.

$$G(t) = G_0[a_\infty^G + \sum_{i=1}^{n} a_i^G \exp(-t/\tau_i^G)];\ K(t) = K_0[a_\infty^K + \sum_{i=1}^{n} a_i^K \exp(-t/\tau_i^K)] \tag{2}$$

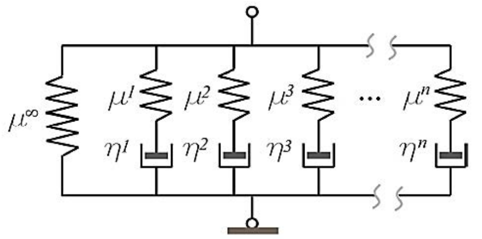


Fig. 10 Prony series of Maxell model – μ_i as shear modulus G_i or bulk modulus K_i of elastic spring, η_i as viscosity of a dashpot.

General structure of Maxwell model is in Fig. 10. According to prEN 16613, most interlayers are isotropic materials. Viscoelasticity is characterized by time and temperature dependence thus ordinary relations for homogeneous isotropic materials between shear modulus G, Young´s modulus E, and bulk modulus K were considered for each elastic spring in Maxwell models. This results into the relation between fitted shear modulus G_i of each spring and calculated bulk modulus K_i as $K_i = 2G_i(1+\upsilon)/3(1-2\upsilon)$. Poisson´s ratio for PVB interlayer Trosifol®BG R20 was considered as $\upsilon = 0.49$ (Botz and Wilhelm et al. 2019). Relaxation times τ_i^G and τ_i^K for deviatoric and volumetric relaxation were considered identical. To show the example of input Prony parameters, those of Maxwell model based on combined DMTA results from shear and torsion mode (SH+TS) for reference temperature 20 °C are shown in Table 2. In fact, only the set of $\{E_0, a_i^{G,K}, \tau_i\}$ for viscoelastic isotropic interlayer in ANSYS needs to be user defined. Input Prony parameters of Maxwell model based on DMTA in shear mode (SH) can be similarly obtained from a set of given $\{G_\infty, G_i, \tau_i\}$ series (Vokáč and Hána et al. 2019). Both models suppose tested PVB interlayer to be thermorheologically simple thus extrapolation of relaxation times to other temperatures T is performed as $\tau(T) = \tau(T_{ref})\cdot\alpha(T)$ (Brinson and Brinson 2015) where $\alpha(T)$ is obtained through Williams-Landel-Ferry equation suggested by Williams et al. (Williams and Landel et al. 1995) using WLF constants C_1 and C_2. For displacement-controlled tests, temperature of 20 °C was considered. In creep tests, relaxation times in Maxwell model were modified according to tested temperature.

Table 2: Maxwell Prony parameters of Trosifol®BG R20 based on combined shear and torsion DMTA results.

T_{ref}	20 °C	C_1	8.635	C_2	42.422
E_0 [MPa]	9196.230	G_0 [MPa]	3085.983	K_0 [MPa]	153270.487
E_∞ [MPa]	0.692	G_∞ [MPa]	0.232	K_∞ [MPa]	11.536
E_i [MPa]	G_i [MPa]	a_i^G [-]	K_i [MPa]	a_i^K [-]	$\tau_i^K = \tau_i^G$ [s]
5310.730116	1782.124	0.5774	88512.169	0.5775	1.00E-05
1547.241926	519.209	0.1682	25787.365	0.1682	1.00E-04
1627.606864	546.177	0.1770	27126.781	0.1770	1.00E-03

E_i [MPa]	G_i [MPa]	a_i^G [-]	K_i [MPa]	a_i^K [-]	$\tau_i^K = \tau_i^G$ [s]
646.341736	216.893	0.0703	10772.362	0.0703	1.00E-02
40.582534	13.618	0.0044	676.376	0.0044	1.00E-01
14.865134	4.988	0.0016	247.752	0.0016	1.00E+00
4.958124	1.664	0.0005	82.635	0.0005	1.00E+01
1.749856	0.587	0.0002	29.164	0.0002	1.00E+02
0.76884	0.258	8.360E-05	12.814	8.360E-05	1.00E+03
0.190124	0.064	2.067E-05	3.169	2.067E-05	1.00E+04
0.501832	0.168	5.457E-05	8.364	5.457E-05	1.00E+05

FE mesh was modelled using 20 node hexahedrons SOLID 186 with quadratic shape functions. Using higher order elements reduces possible volumetric locking of incompressible materials (Rohan and Lobos et al. 2014) thus using second order element is justified (υ_{PVB} = 0.49). Every node has 3 degrees of freedom, hence the corresponding dimension of element stiffness matrix is 60 x 60. Used element is shown in Fig. 11a. Basic step of the mesh was 10 mm. Glass was modelled with two elements and interlayer with one element in a vertical sense, see the detail of the mesh in Fig. 11b. Vertical support was modelled on both 360 mm long edges of the panel as in real experiment, see Fig. 1a. Based on obtained experimental values of displacement, linear geometrical equations were applied. Non-linearity consisted in constitutive equations, thus the problem was solved using full Newton-Raphson iteration. In displacement-controlled tests, the model was loaded by vertical displacement of nodes which were in contact with MTS loading apparatus, see Fig. 6a. Totally 56 loading steps were applied. The ratio of displacement increment and time increment $\delta w/\delta t$ respected prescribed loading rate 2.0 mm/min, or 0.5 mm/min. Creep tests were simulated by applying constant force 1.12 kN uniformly distributed along the width of the panel. It means, the uniform load 1.55 kN/m acted on the upper ply in both contacts with loading apparatus, see Fig. 6b. Loading period was divided into 88 steps. The length of time steps was shortened up to 1 h after loading and unloading to catch the variable stiffness of interlayer.

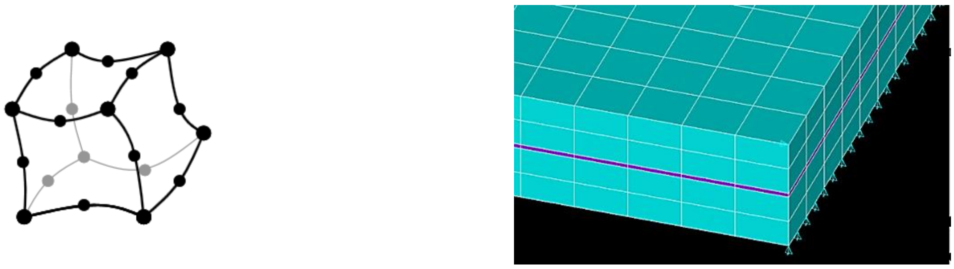


Fig. 11 a) SOLID 186 used in FE model, b) Detail of FE mesh on the panel´s corner.

4. Results and discussion

The folowing text refers to the experimental and numerical results of two representative panels in displacement-controlled tests and to one panel in a creep tests. In order to illustrate the shear relaxation moduli of Trosifol®BG R20 given by both investigated Maxwell models, their time dependence is given in Fig. 12. It should be stated that Maxwell model based only on shear (SH) gives higher relaxation modulus and is more temperature sensitive than that based on combination of shear and torsion results (SH+TS). Shear stiffness of interlayer in the range 0.1 – 1.0 MPa significantly influences the response of laminated panel in bending (Galuppi and Royer-Carfagni 2013). It might be expected, that numerical results of creep test based on Maxwell model in shear will be temperature sensitive in longer time interval.

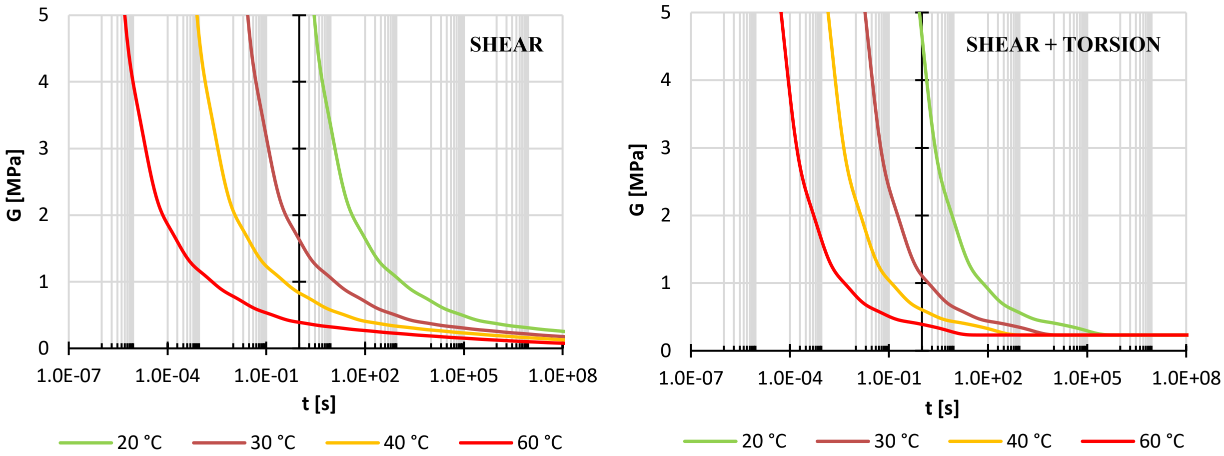


Fig. 12 a) Shear modulus based on DMTA results in shear, b) Shear modulus based on combined DMTA results in shear and torsion.

4.1. Displacement-controlled four-point bending tests

Comparison of experimental vertical deflection measured by displacement sensor I (DS I, see Fig. 4) and normal stress on the lower surface of the panel measured by strain gauge 3 (SG3, see Fig. 3) with numerical values given by both Maxwell models is shown in Fig. 13 and Fig. 14. All experimental and numerical results react to the rate of displacement. Lower the rate, higher vertical experimental deflections and normal stresses for a certain force are obtained. It corresponds to a decrease of interlayer´s shear stiffness. Maxwell model is also loading rate sensitive and gives reduced stiffness for lower loading rates (Vokáč and Hána et al. 2019) which corresponds to the ratio of numerical results at presented loading rates. Experimental relations are, more or less, linear and show nearly constant shear stiffness of tested interlayer. Numerical relations confirm this fact. Maxwell model based on combined results in shear and torsion (FE: SH+TS) is in good correlation with all experimental results – maximal deviation of experimental and numerical results is up to 6%. Maxwell model based on results in shear (FE: SH) shows stiffer response of modelled panels in both loading rates – deviation from experimental and numerical results is up to 20%. It means, the model provided higher values of interlayer´s shear stiffness. This statement corresponds to the comparison of shear relaxation moduli between this Maxwell model (in SH) with that based on shear and torsion (SH+TS) at 20 °C, see Fig. 12. Similar relations were also obtained for other tested panels.

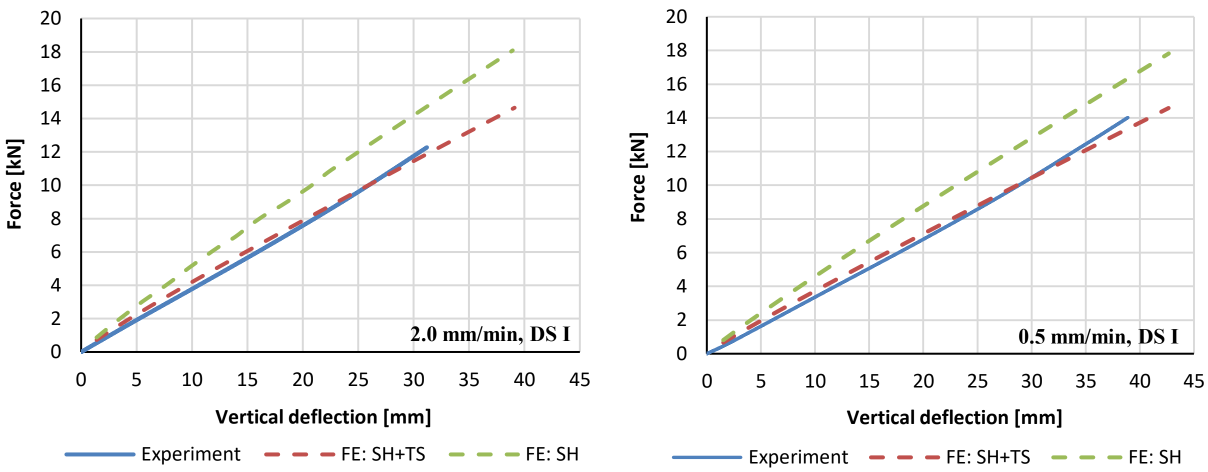


Fig. 13 Comparison of experimental and numerical midspan displacements by DS I of representative panel in displacement controlled test.

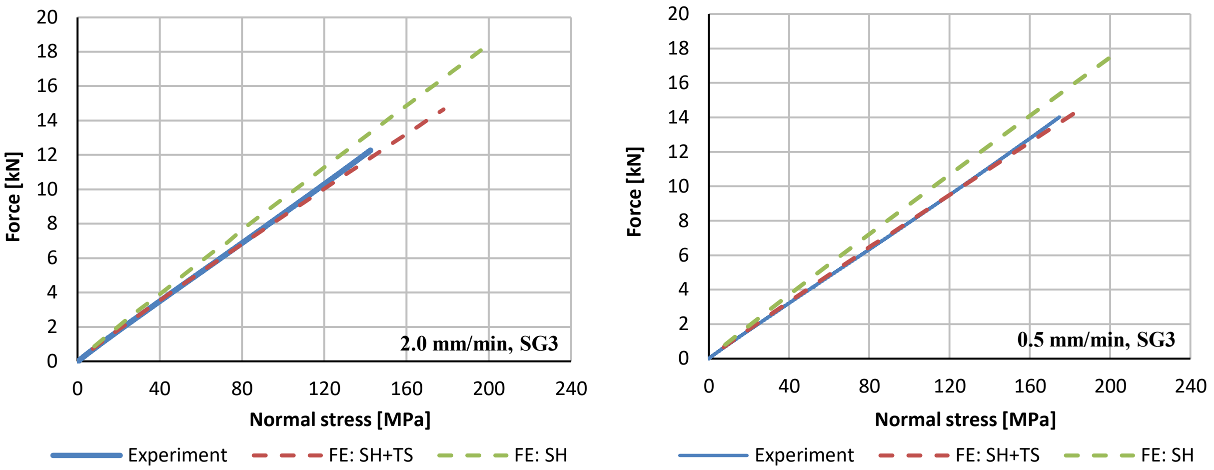


Fig. 14 Comparison of experimental and numerical tensile stress by SG3 of representative panel in displacement controlled test.

4.2. Creep four-point bending tests

The following figures present experimental and numerical results of tested panel in the creep test. Particularly, vertical deflections given by displacement sensor I (DS I) and normal stress on the lower surface measured by strain gauge 2 (SG2, see Fig. 3) at midspan are illustrated. All experimental relations are temperature and time sensitive. As loading time or temperature increases, growth of measured quantities is observed. This is well documented in Table 3 which shows the experimental data at loading (in time 0.01 h) and right before unloading. Measured values at loading also increase with increasing temperature. Since the load duration at 30 °C and 40 °C was similar, data before unloading in Table 3 can be compared – growth of measured values at 40 °C is obvious. To illustrate the influence of boarder temperatures 30 °C and 50 °C at 117 h of load duration, vertical deflection measured by DS I increased for 12.5% and normal stress measured by SG2 increased for 13.5% at 50 °C. Considering the fact that Young´s modulus of glass is constant in these conditions, the variety of measured data in temperature and time is caused by variable shear stiffness of interlayer. The highest increase of measured data in time is observed at 30 °C. This is consistent with relaxation functions of Trosifol®BG R20 at 30 °C in Fig. 12. Experimental relations in Fig. 15 - Fig. 17 do not generally converge at loading phase. This reminds the response of thermoplastic polymers in a creep test (Brinson and Brinson 2015) among which tested PVB belongs.

Shear relaxation function given by Maxwell in SH+TS approaches residual shear stiffness $G_\infty = 0.23$ MPa after 10^4 s ≈ 2.7 h at 30 °C. For higher temperatures, this time is shorter, as shown in Fig. 12b. Therefore, the numerical values of stress and deflection at loading in Fig. 15 - Fig. 17 given by FE: SH+TS are nearly identical. While unloading, the residual stress and deflection drop rapidly and turn to zero at all temperatures. Contrary, numerical results in Fig. 15 - Fig. 17 based on Maxwell in SH are time and temperature sensitive. Shear modulus given by this model for 30 °C to 50 °C changes smoothly between 1 s and 10^6 s from 1.7 MPa to 0.1 MPa, see the chart in Fig. 12a. To remind, the stress and deflection of laminated glass panels in bending change rapidly in the interval of interlayer´s shear stiffness $G = 1.0 – 0.1$ MPa (Galuppi and Royer-Carfagni 2013) thus time and temperature sensitivity of obtained relations is justified. To illustrate the example of time sensitivity given by FE: SH at 30 °C at loading (in 0.01 h) and before unloading (in 120 h), midspan vertical deflection at DS I increased for 42% and tensile stress at SG2 increased for 22%. The influence of temperature is illustrated as an increase of the same quatities at 117 h of loading at boarder temperatures 30 °C and 50 °C: vertical deflection increased for 10.5% and normal stress increased for 6.5%. To discuss the correlation between numerical and experimental relations before unloading, results provided by FE: SH cover the experimental data with higher accuracy and are mostly conservative than those by FE: SH+TS. Experimental data after unloading is also in better corellation with FE: SH but experimental residual values are a bit higher.

Table 3: Midspan displacement measured by DS I and normal stress measured by SG2 at loading and right before unloading in creep test.

Temperature [°C]	Quantity	Loading (in time [h])	Before unloading (in time [h])	Increase [%]
30	Displacement [mm]	2.62 (in 0.01)	3.87 (in 117.1)	47.5
	Stress [MPa]	11.45 (in 0.01)	14.62 (in 117.1)	28.0
40	Displacement [mm]	3.30 (in 0.01)	4.21 (in 117.3)	28.0
	Stress [MPa]	13.20 (in 0.01)	15.49 (in 117.3)	17.5
50	Displacement [mm]	3.31 (in 0.01)	4.34 (in 163.5)	31.0
	Stress [MPa]	13.21 (in 0.1)	16.70 (in 163.5)	26.5

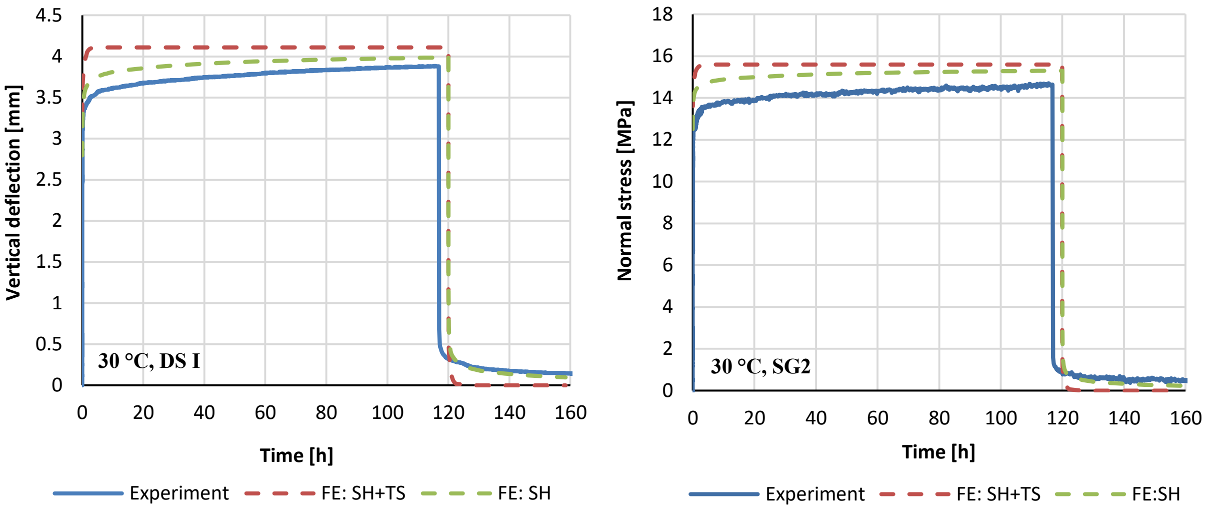


Fig. 15 Comparison of experimental and numerical midspan displacements by DS I and normal stresses by SG2 at 30 °C.

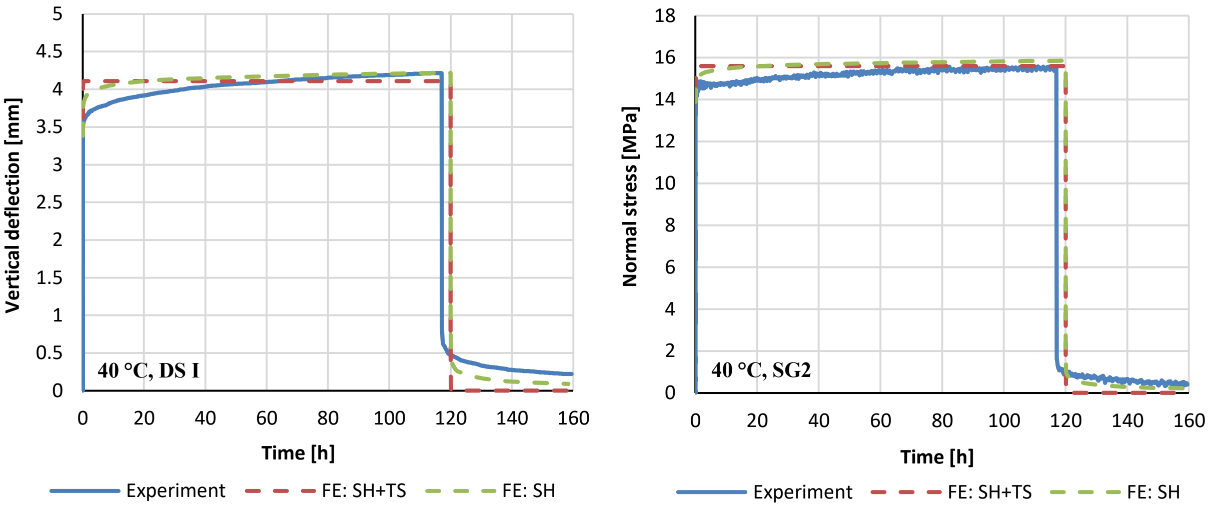


Fig. 16 Comparison of experimental and numerical midspan displacements by DS I and normal stresses by SG2 at 40 °C.

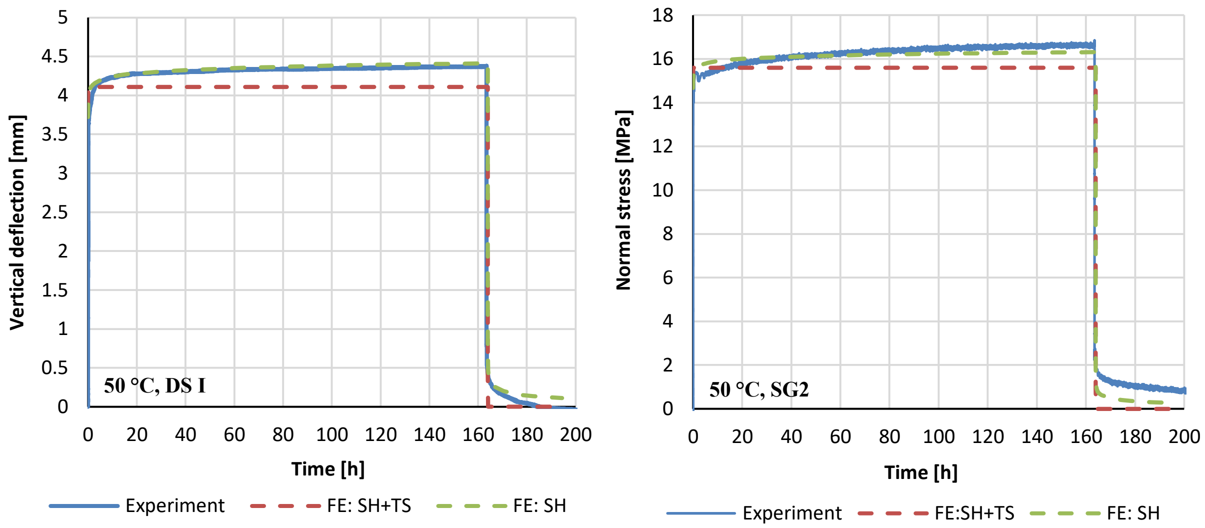
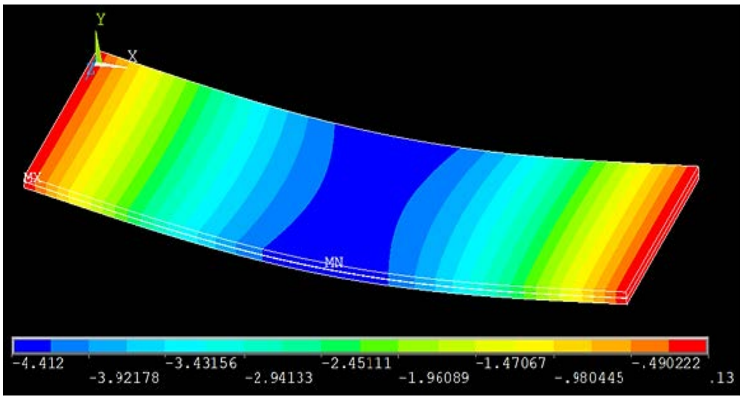


Fig. 17 Comparison of experimental and numerical midspan displacements by DS I and normal stresses by SG2 at 50 °C.

To illustrate the numerical values by FE: SH graphically, deflected shape with the values of vertical deflections at 164 h of load duration at 50 °C and the detail of mutual displacement of glas plies in the panel´s corner are shown in Fig. 18. The deflected shape reminds the deflection curve of monolitic simply supported uniformly loaded panel with maximal midspan deflection 4.41 mm. But the deformed shape of interlayer´s element in Fig. 18b reflects limited shear coupling of the individual glass plies and illustrates in their mutual "slide". Therefore, the model acts actually as a laminated panel.



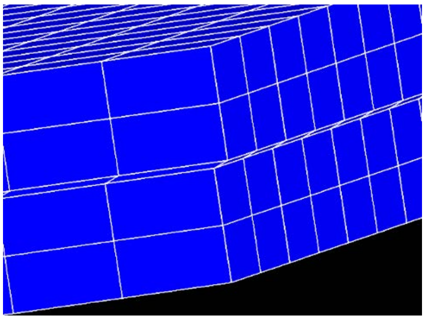


Fig. 18 a) Values of vertical deflection given by FE: SH at 50 °C at 164 hours of loading, b) Detail of glass plies mutual "slide".

5. Conclusion

This paper presented the experimental and numerical results of simply supported, double laminated glass panels 10.10.2 with dimensions of 1100 x 360 mm laminated with PVB interlayer Trosifol®BG-R20. Particularly, representative experimental data from four-point bending displacement-controlled tests at loading rates 2.0 mm/min and 0.5 mm/min performed at room temperature and from long-term four-point bending creep tests performed at +30 °C, +40 °C, and +50 °C in the range of load duration between 117 h and 164 h were compared to the numerical results. Numerical analysis performed in ANSYS® Mechanical 18.0 considered the interlayer as a homogeneous isotropic viscoelastic material modelled by two different Maxwell models. Emphasis was placed on the correlation of experimental and numerical results depending on the type of interlayer´s DMTA testing method (shear vs. torsion) since each of them is loaded by a certain error. Prony series of Maxwell models were based on published results of DMTA in shear mode (SH) and on combined published results of DMTA in shear a torsion mode (SH+TS). Both DMTA were performed on small-scale laminated glass specimens. Experimental data showed the dependence of panels response on time, temperature, and loading rate. Lower rate of prescribed displacement, increase of temperature or increase of loading time resulted in the growth of measured tensile stress in glass and vertical deflections at midspan cross-section. Numerical results using Maxwell model of interlayer based on combined DMTA results in shear and torsion mode (SH+TS) correlated with experimental results of displacement-controlled tests. On the other hand, numerical results using Maxwell model based only on DMTA results in shear mode (SH) were able to describe the response of the panel in the creep test. Therefore, both models are credible. In practical design of laminated glass in bending, the duration of prescribed static load and ambient temperature are the decisive factors, therefore Maxwell model based on DMTA in shear mode (SH) can be considered as more appropriate. In the future, authors further intend to use numerical analysis of laminated glass panels in bending laminated with less common interlayers (made of ionomer, ethylene-vinylacetate, etc., defined by their mechanical models, and compare their numerical and experimental results. This seems to be an appropriate way for the verification of interlayer´s viscoelastic properties.

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