TEMPERATURE EFFECTS ON THE STRUCTURAL BEHAVIOR OF LAMINATED SAFETY GLASS

ZUM EINFLUSS DER TEMPERATUR AUF DAS TRAGVERHALTEN VON VERBUNDSICHERHEITSGLAS

A L'INFLUENCE DE LA TEMPERATURE AU COMPORTEMENT PORTANT DU VERRE FEUILLETE DE SECURITE

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SUMMARY

Shear and bending tests were performed in the temperature range from -20°C to +40°C to investigate the characteristic viscoelastic properties of polyvinyl butyral-resin (PVB), mostly used in laminated safety glass for architectural applications. A temperature dependent coupling parameter is used to describe the structural behavior of laminated safety glass subjected to bending stresses in comparison to a monolithic plate of the same thickness.

ZUSAMMENFASSUNG

Zur Bestimmung der viscoelastischen Materialkennwerte von Polyvinyl-Butyral Folie (PVB), die in Verbundsicherheitsglas (VSG) verwendet wird, wurden Scher- und Biegeversuche im Temperaturbereich von -20°C bis +40°C durchgeführt. Mit Hilfe eines temperaturabhängigen Kopplungsparameters kann das Tragverhalten von VSG bei Biegebeanspruchung im Vergleich zu einer monolithischen Scheibe gleicher Dicke beschrieben werden.

RESUME

Des essais en cisaillement et en flexion ont été effectués à la température de -20°C à +40°C afin de déterminer des valeurs caractéristiques visco-élastiques de feuille faite en polyvinyl-butyral (PVB), appliquée en verre feuilleté de sécurité. A l'aide d'un paramètre de couplage dépendant de la température, on

peut décrire le comportement portant de verre feuilleté de sécurité en flexion en comparaison avec une vitre monolithique de même épaisseur.

KEYWORDS: Laminated Safety Glass, PVB, Temperature, Shear Stress, Creep

1. INTRODUCTION

The use of laminated safety glass has considerably enlarged the bounds of possibility for construction with glass in architectural applications, in particular for safety and overhead glazings. Laminated safety glass consists of a sandwich with two (or more) sheets of glass bonded to a thin layer of a marcomolecular polymer, usually polyvinyl butyral (PVB). In comparison to monolithic glass, it has an improved impact resistance and provides substantial safety in accidents. In the case of failure laminated safety glass preserves a residual load-carrying capacity, the tough interlayer has the ability hold glass fragments in place.

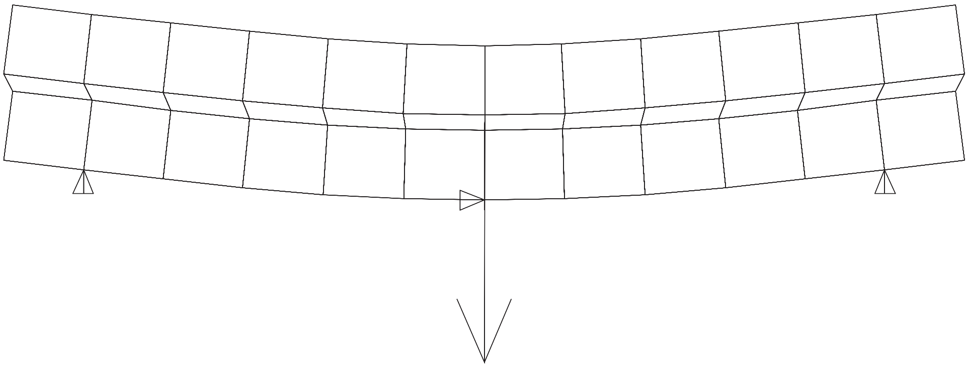

Fig. 1: *Schematic representation of laminated safety glass subjected to bending stresses.*

The structural behavior of laminated safety glass subjected to bending stresses is considerably determined by the shear transfer in the interlayer. Fig. 1 exemplary shows the deformation of a sandwich beam with rigid faces (glass plates) and a thin, low modulus core (PVB). Flexural moments are mainly carried by the glass plates. The stiffness of the core determines the amount of shear transfered between the glass plates.

Since PVB shows a distinctive temperature dependence of its mechanical properties, the consideration of a favourite shear transfer in structural design calculations is not permitted in Germany [DIBt, 1998]. At a temperature T=23° C the PVB resin for achitectural applications requires a tensile strength of ≥20 N/mm^2 and an elongation at break of ≥ 250%.

At room temperature PVB behaves viscoelasic. Relaxation and a dependence on the duration of loading is observed. Under long-term loading PVB has the tendency to creep. With falling temperature the shear moduls increases. Below the glass transition temperature the material becomes elastic with low damping and high tensile strength at break.

The experimental investigations reported in this paper, provide the temperature dependence of the material data of PVB and the structural behavior of laminated safety glass required as input data for calculations and for practical engineering purposes.

2. TESTS

2.1 Creep Tests in Simple Shear

The test setup is schematically shown in fig. 2. The test specimem with a cross-sectional area of 12mm*20mm was cut from a laminated safety glass with the construction 4 mm glass / 0.76 mm PVB / 4 mm glass. For a time period of 1000 s a load F = 50 N produced a constant shear stress τ = 0.2 N/mm^2 in the interlayer. The displacement $u(t)$ between the glass plates was measured with a LVDT during the load was applied and during further 1000 s of free relaxation after the load was released. The time-dependent shear $\gamma(t)$ was calculated with the nominal thickness t_f = 0.76 mm of the PVB resin.

[DIBt, 1998] Technische Regeln für die Verwendung von linienförmig gelagerten Verglasungen, Entwurfsfassung August 1998

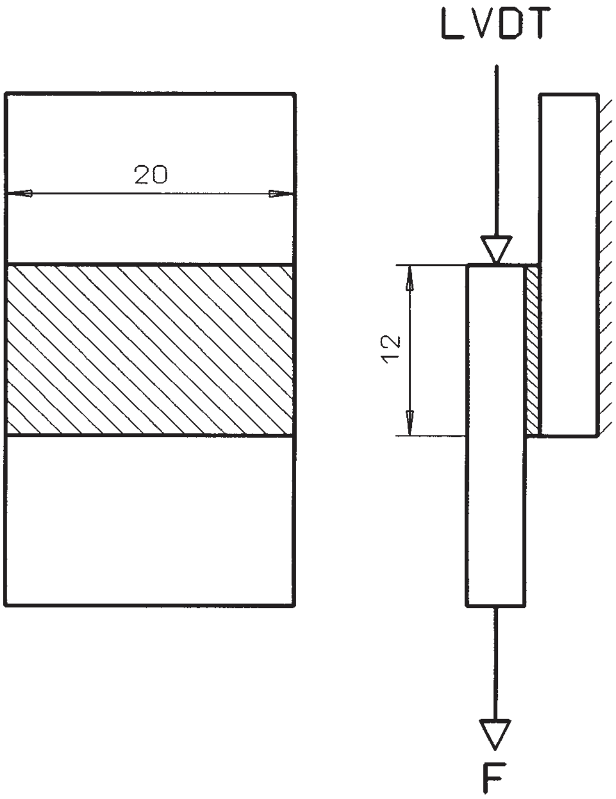

Fig. 2: *Shear test.*

The decrease of the shear stiffness during the load F is applied (time interval $0 \leq t \leq 1000$ s) can be described by

$$\gamma(t) = \tau \cdot f(t) \tag{1}$$

with the 4-parameter creep function

$$f(t) = a + b \cdot t + c \cdot [1 - exp(-\lambda \cdot t)] \tag{2}$$

The parameter a represents the time independent elastic part of the shear that follows instantaneously the external load. The shear modulus resulting from this pure elastic deformation is given by $G = \tau/a$.

The linear term describes irreversible creep with a creep velocity $v = b/\tau$. The relaxation time $t = 1/\lambda$ gives the time span within the reversible part of the shear deformation recovers. A dependence on the load level is not concerned by equ. 1.

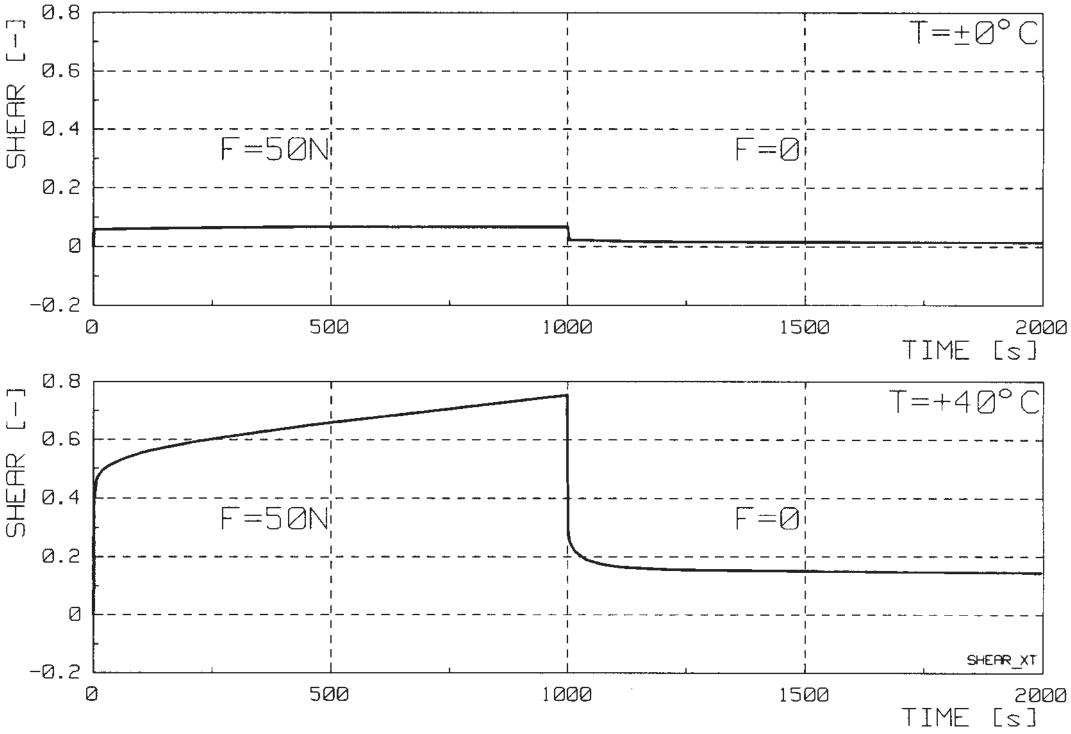

Fig. 3: *Measured shear $\gamma(t)$ as a function of time.*

Fig. 3 demonstrates the quite different behavior of PVB at temperatures T = ±0°C and T = +40°C. With increasing temperature the shear stiffness decreases rapidely and creep becomes more significant. The parameters a, b and λ were evaluated by a fit of equ. 1 to the exerimental data in the interval $0 \leq t \leq 1000$ s. Although the tests are not suitable for a precise determination of the shear modulus, the principal tendency as a function of temperature can be evaluated.

The shear modulus decreases about two orders of magnitude in the considered temperature range (fig.4), while the creep velocity $v(T)$ increases (fig. 5) from $v \approx 0$ to the about of 10^{-3} mm^3/Ns. The relaxation time $t = 1/\lambda$ was about 50 s to 200 s.

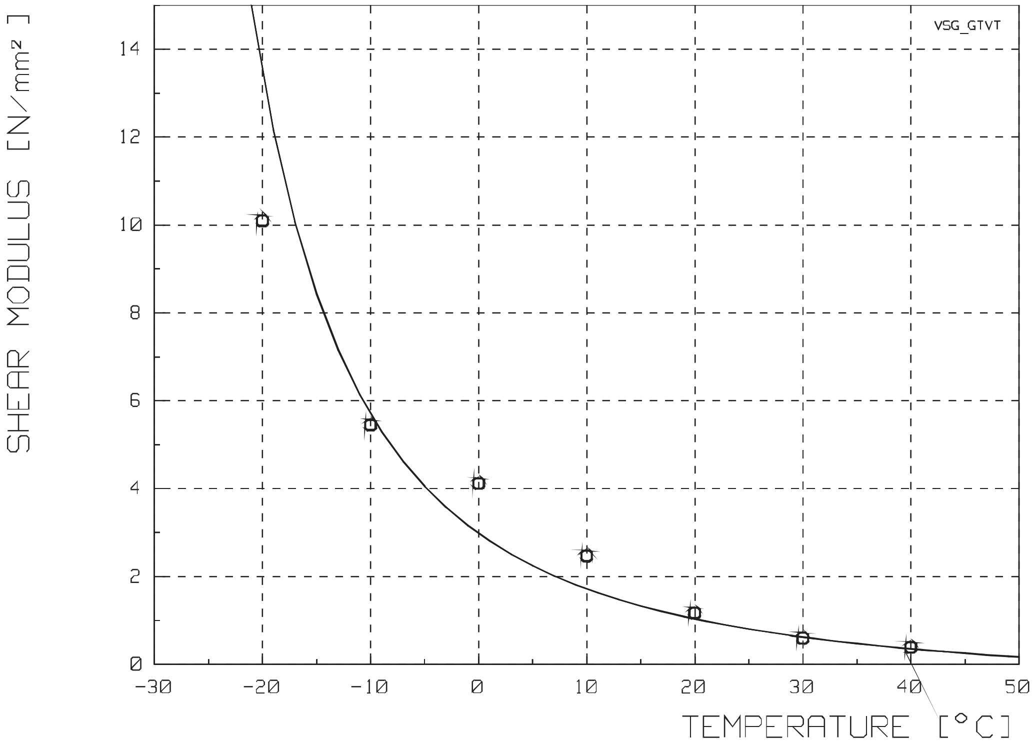

Fig. 4: *Shear modulus G(T)*

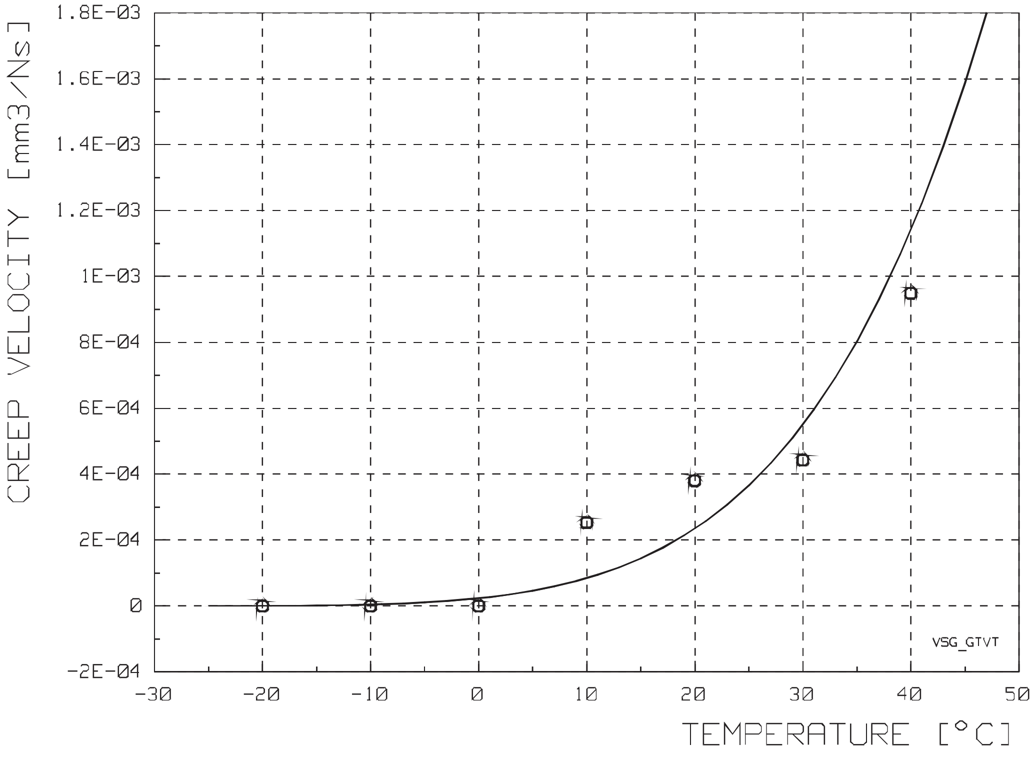

Fig. 5: *Creep velocity v(T)*

2.2 Bending Test

Fig. 6 shows the test setup for 3-point bending. A concentrated load F=20 N was applied at the midspan if a beam (span L=400 mm, width B=30 mm) consisting of laminated glass (4 mm glass / 0.76 mm PVB / 4 mm glass). The center deflection $u(t)$ was measured by a LVDT. The temporal procedure was the same as described in cap. 2.1.

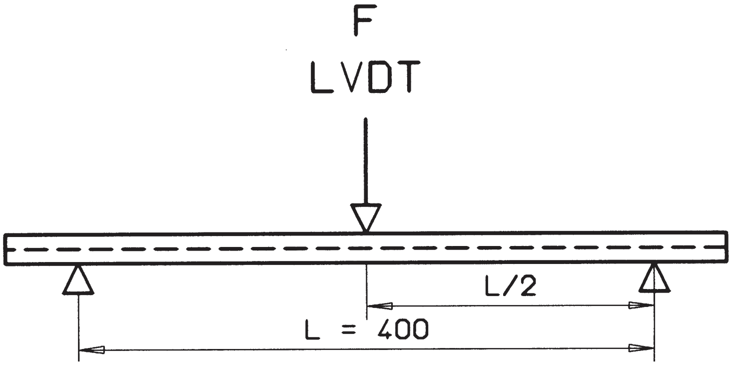

Fig. 6: *Bending Test.*

The center deflection can be calculated by

$$u = \frac{F}{48 \cdot (E \cdot I)_{beam}} \cdot L^3 \tag{3}$$

E and I are the Young's modulus and the moment of inertia of the beam. The moments of inertia of the glass plates I_g, of the core I_f and the coupling term I_c contribute to the total amount of the moment inertia I. The cross section area of the beam is shown in fig.6.

$$(E \cdot I)_{beam} = E_g \cdot I_g + E_f \cdot I_f + E_c \cdot I_c \approx E_g \cdot I_g + E_c \cdot I_c \tag{4}$$

$$I_g = 2 \cdot B \cdot t_g^3/12, \; I_f = B \cdot t_f^3/12, \; I_c = \kappa \cdot B \cdot t_g \cdot (t_g + t_f) \tag{5}$$

Since $I_f \ll I_g$, the moment of inertia of the core can be neglected. The amount of coupling by the core is given by the parameter κ with $0 \leq \kappa \leq 1$. In the limiting case $\kappa = 1$ the total moment of inertia becomes equal that of a monolithic beam with the thickness $t = 2 \cdot t_g + t_f$. $\kappa = 0$ describes the case of zero coupling with $I = I_g$.

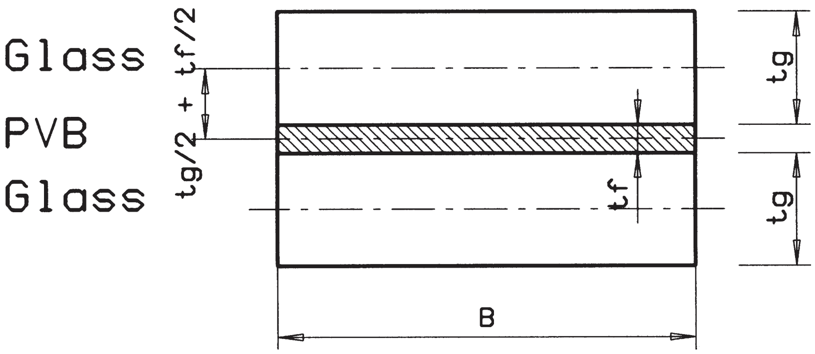

Fig. 7: *Cross section*

The measured displacements u(t) at temperatures T = ±0°C, +10°C, +20°C and +40°C are given in fig. 8. At low temperatures PVB and from that laminated glass behaves mostly elastic. Due to the decrease of the shear stiffness of the PVB interlayer with rising temperature the displacement u(t) increases.

At temperatures above 40°C the coupling between the glass plates is very small and the deformation of the laminated glass beam is determined mainly by the elastic deformation of the glass plates. It is obviously that creep becomes mostly significant at mid tempertures about +10°C to 20°C. Due to this, the bending stiffness of laminated glass is mostly influenced by the duration of loading in this temperature range.

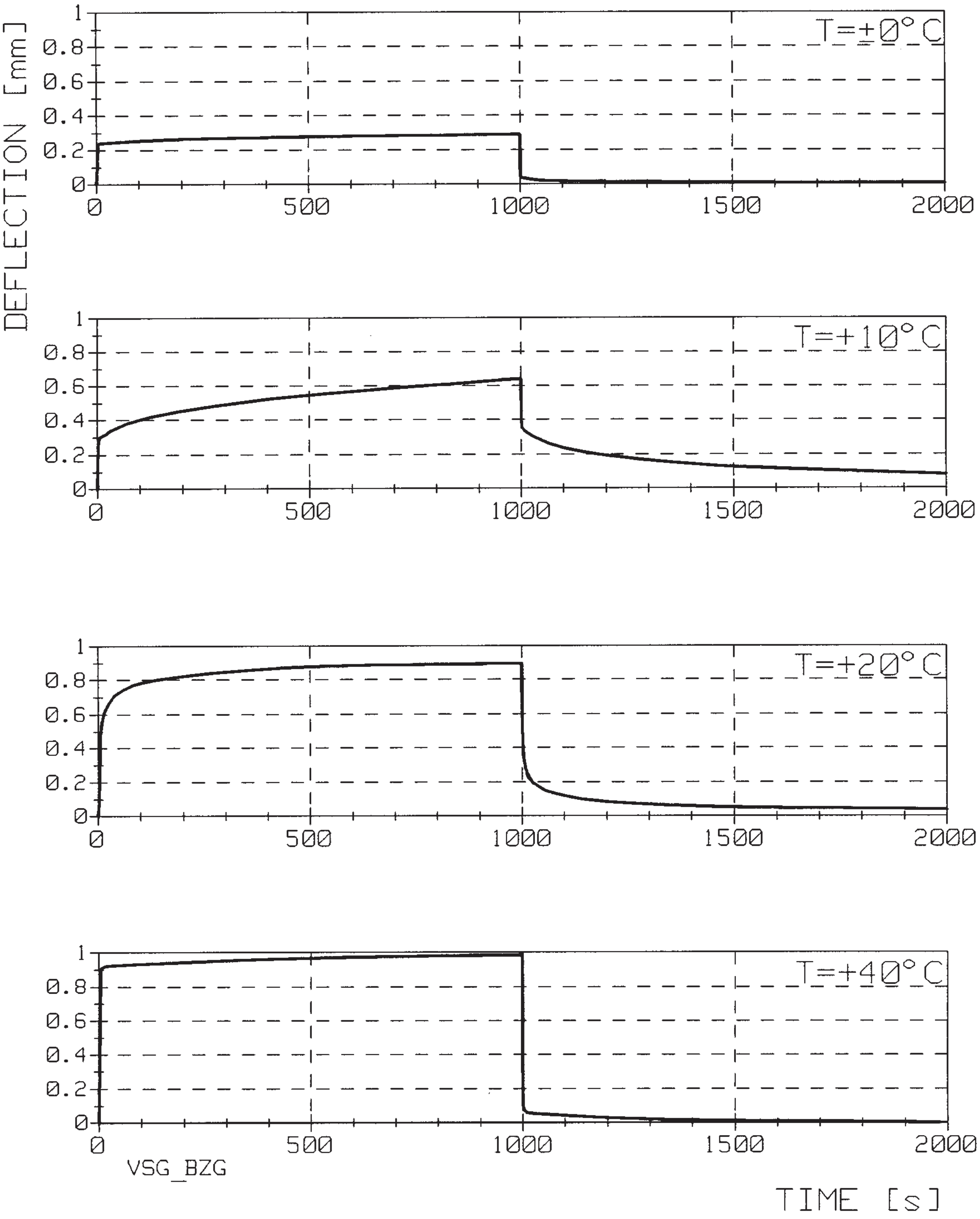

Fig. 8: *Measured center deflection u(t) as a function of time for different temperatures between 0 °C and 40 °C*

The fig. 8 gives the parameter κ(T) that was calculated by means of the equ's. 4 and 6 and the measured displacement $u(t = 10\text{s})$ and $u(t = 1000\text{s})$. Not the nominal, but the actual values of t_g and t_f were used. The actual Young's modulus E_g was determined from a comparative test with a monolithic glass plate.

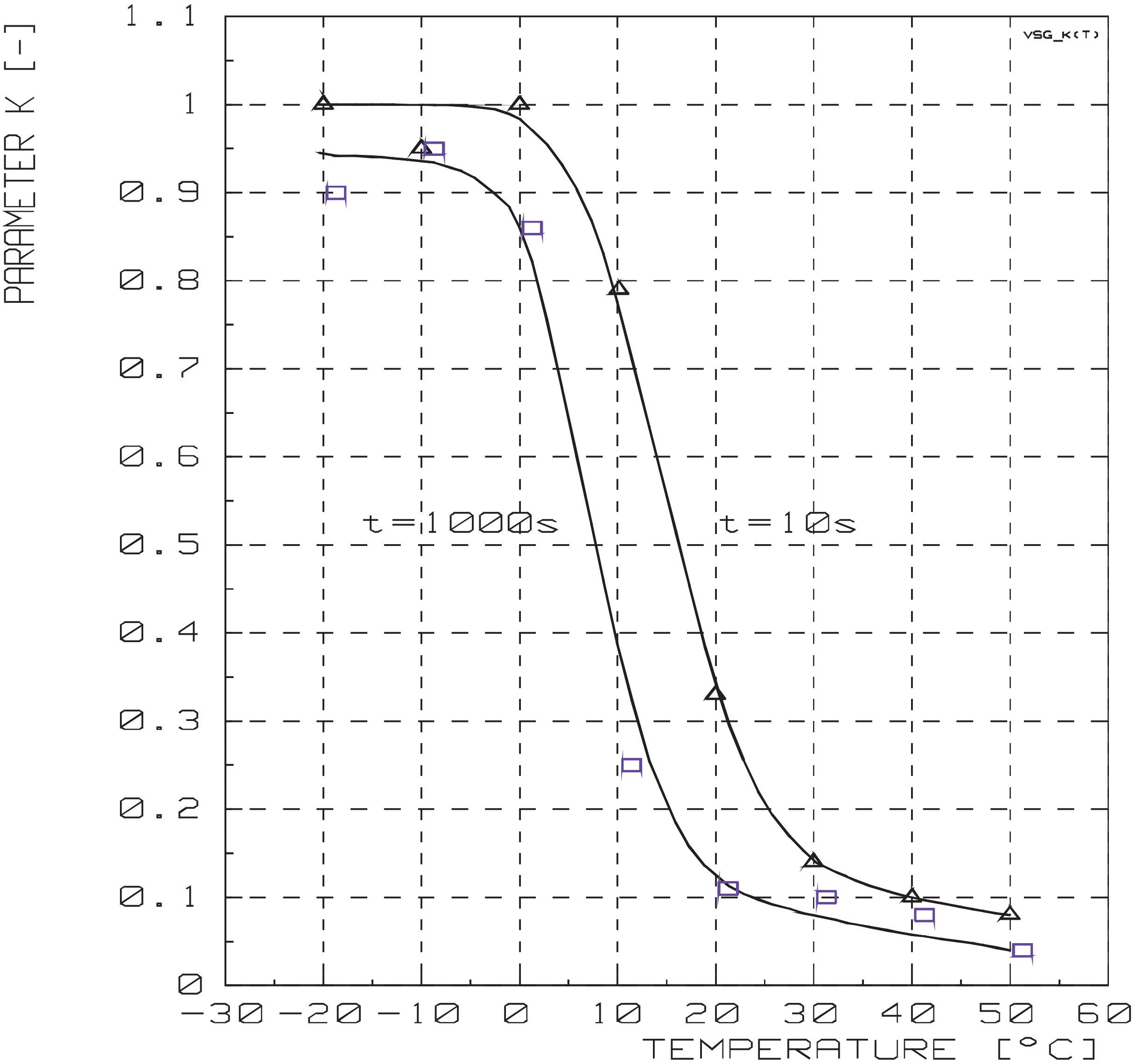

Fig. 9: *Coupling parameter κ(T) for a load duration t = 10 s and t = 1000 s*

CONCLUSIONS

A 4-parameter viscolestic model was used to explain the structural behavior of PVB under long-term loading in simple shear. The shear modulus of PVB evaluated from the exerimental data decreases about two orders of magnitude in the temperature range between -20°C and +40°C. The creep velocity increases with increasing temperature to about 10^{-3} mm^3/Ns at +40°C.

The structural behavior of laminated glass subjected to bending stresses is considerably determined by the shear transfer in the PVB interlayer. According to the temperature dependence of the shear modulus of PVB, laminated safety glass behaves as a monolithic plate at temperatures below ±0°C, at high temperatures above +40°C the behavior comes close to the limiting case with no coupling between the glass plates. Load-duration effects are mostly important at temperatures about 10°C to 20°C.