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INFLUENCE OF POLYMERIC INTERLAYERS ON THE STRESS DISTRIBUTION IN LAMINATED GLASS PANES

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Abstract: *Glass is nowadays one of the most progressive materials in civil engineering. It is used not only as a filling material but also as a material for load-bearing structures. Unlike widely-used materials (steel, aluminium, etc.), glass behaves elastically until it breaks by a brittle fracture without any warning. The insufficient tensile strength of float glass is solved by using a tempering process that enables the production of heat-strengthened or heat-toughened glass. However, increased tensile strength is not the only requirement for safe design. Laminated glass panels should be used in the reliable and effective design of glass elements as parts of a load-bearing system. The composite action of laminated glass under loading is influenced mainly by the shear modulus of the interlayers, which is dependent on time and on temperature. This paper presents experimental research performed at the Klokner Institute of CTU in Prague on the material properties of visco-elastic interlayers under various temperatures and under various load rates.*

Keywords: Glass, Interlayers, Shear modulus, Lamination, Visco-elastic material, Polymer.

1. Introduction

Modern trends in materials and in production technologies have been emerging in civil engineering. Glass is a material that has been used for a long time in windows as a filling material. It has much to offer for this purpose, due to its very high compressive strength and its transparency. There is now a growing trend to extend the use of glass sheets to load-carrying elements. These sheets are used for floors, staircases, beams, columns and shear panels that are not loaded only by self-weight but that are also able to transfer wind or snow loads and service loads. Laminated glass needs to be used, in order to achieve sufficient ultimate resistance of structural glass elements and also residual resistance.

At the present time, there is a lack of information, design rules and procedures for considering the potential mechanical participation of various interlayers for glass elements under loading. The safety considerations and the really conservative approaches that are widely adopted in practical applications are based on the assumption that the laminated glass is considered without any composite action. This leads to conservative tensile stress values, and therefore to the use of expensive, thick glass panes. To improve the design process, it is necessary to determine the real shear modulus of the interlayers that are used, because the material properties are generally unknown. The main issue in the experimental research presented in this paper has been to define the influence of temperature and load duration on the shear modulus of the transparent interlayers that are widely used for laminated glass panes.

2. Laminated glass

Laminated glass consists of at least two glass panes, which are connected by transparent interlayers. Various kinds of polymers and other plastics are used as materials for the interlayers. Widely-used interlayers are poly-vinyl-butyral (PVB), ionoplast (SentryGlass), ethylene vinyl-acetate (EVA), polyethylene (PE) and thermoplastic polyurethane (TPU). Full surface connection offers many ways to

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modify the mechanical properties of laminated glass, depending on the component layers that are selected, their thickness and the sequence of the layers. The main consideration for load-bearing glass elements is their post-breakage behaviour. After failure of one or all of the glass layers, the pieces of glass remain on the interlayer. Following significant improvements in load-bearing behaviour, post fracture integrity and robustness, laminated glass also acts under loading as a composite element. The full load-bearing capacity and the residual load-bearing capacity of laminated glass are influenced by the strength of the individual layers, and above all by the composite action effect of the interlayers. The behaviour of the interlayer is strongly influenced by temperature and by load duration, Fig. 1. This means that under high temperatures laminated glass has no composite action, because the polymer materials are not able to transfer the shear forces, and the shear modulus will be close to zero. However, temperatures below 20°C lead to hardening of the material and to higher shear modulus values. The second crucial factor influencing the shear modulus is load duration. Typically, there is creeping of the polymer interlayers under long-term loading, and the shear modulus value decreases (Wurm 2007).

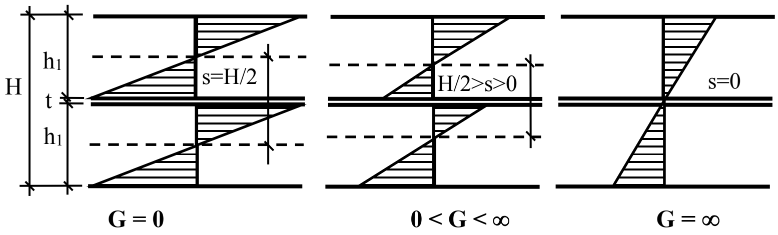

Fig. 1: Normal stress distribution of laminated glass, depending on the shear modulus G of the interlayer.

This kind of behavior influences the stress distribution in real structures, e.g. glass floors or roofs which are exposed to temperatures between 0° and 80°C. According to the temperature and the load duration, the connection between the glass panes is semi-rigid. The relation between the maximal normal stress σ and the shear modulus G of the interlayer is shown in Fig. 2. The study was performed for a squared pane simply supported along four sides made from double-layered laminated glass. Curve σ_h shows the normal stress on the tensile side of the upper pane, while curve σ_d demonstrates the normal stress on the tensile side of the bottom pane. It is obvious that full composite action between glass panes occurs if the shear modulus G is close to 10 MPa. In this case, the normal stress σ_h on the tensile side of the upper pane is equal to zero, see the picture on the right in Fig. 1.

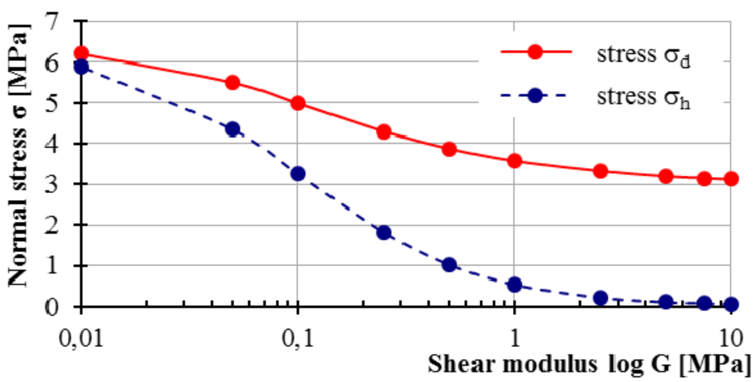

Fig. 2: The relation between normal stress and shear modulus in the middle of glass pane.

The influence of the shear modulus on the stress redistribution also depends on the boundary conditions. In case of glass panes simply supported along two sides, the differences between the full composite action and the composite action without a connection (e.g. due to high temperature) are more significant than when the panes are simply supported along four sides. The relation between the maximal normal stress σ_d on the tensile side of the bottom pane and the shear modulus G is shown in Fig. 3. Results were compared for squared pane from double-layered glass simply supported along four, three or two sides.

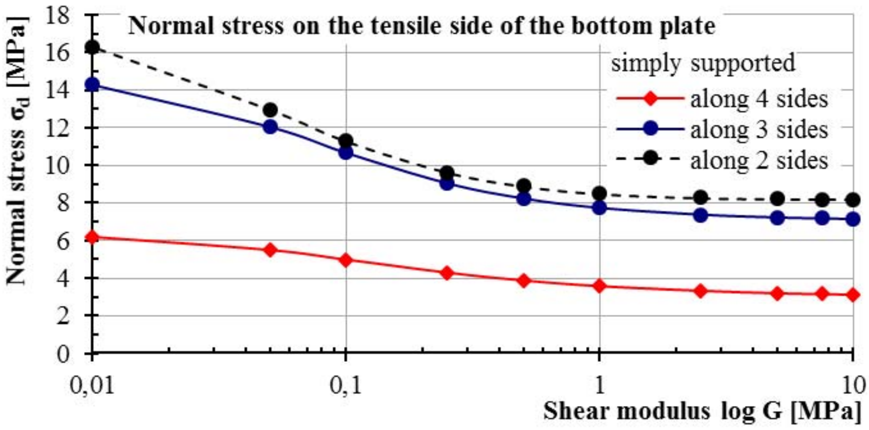

Fig. 3: The relation between normal stress and shear modulus in the middle of glass pane for various boundary conditions.

The same behavior under the loading can be observed in case of vertical deformation δ in the middle of the laminated glass panes. Relation between the maximal vertical deflection δ and the shear modulus G for squared pane from double layered glass pane and for various boundary conditions is shown in Fig. 4.

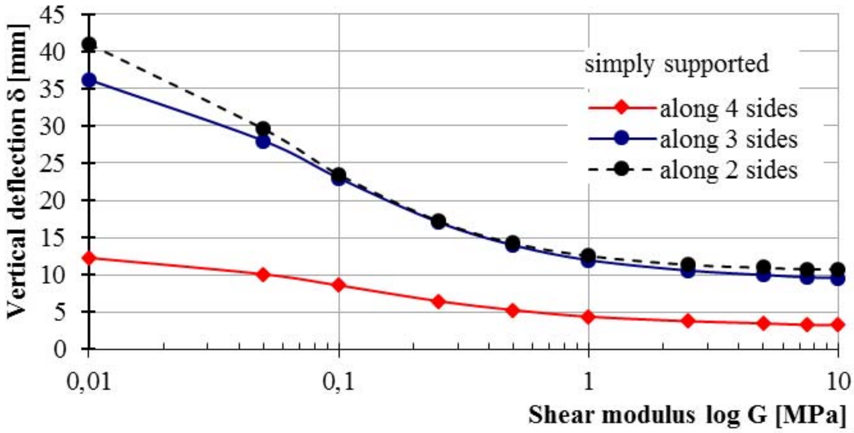

Fig. 4: The relation between vertical deflection and shear modulus in the middle of glass pane for various boundary conditions.

3. Experimental programme

As a pilot phase of the research project, small-scale tests aimed at determining the shear modulus of transparent foils were carried out at the Klokner Institute, CTU in Prague, in 2015. Laminated glass test specimens were tested under various boundary conditions – at temperature levels of 0°C, 20°C, 40°C and 60°C and at a load rate of 2 mm/min, 0.5 mm/min and 0.125 mm/min. Two types of EVA interlayers (EVALAM-80-120, EVASAFE), two types of PVB foils (TROSIFOL-BG-R-20, TROSIFOL-ES) and TPU (KRYSTALFLEX PE399) were chosen for the experimental programme. A total of 315 test specimens were tested.

3.1. Test set-up

Test specimens with geometrical dimensions of 50 x 150 mm, were produced from double layered laminated float glass 10 + 10 mm with thickness of the interlayer 0.76 mm, Fig. 5a). The tested area of 50 x 50 mm in the middle of the specimen was subjected to shear. A special steel frame, Fig. 5b), was used for introducing the appropriate load.

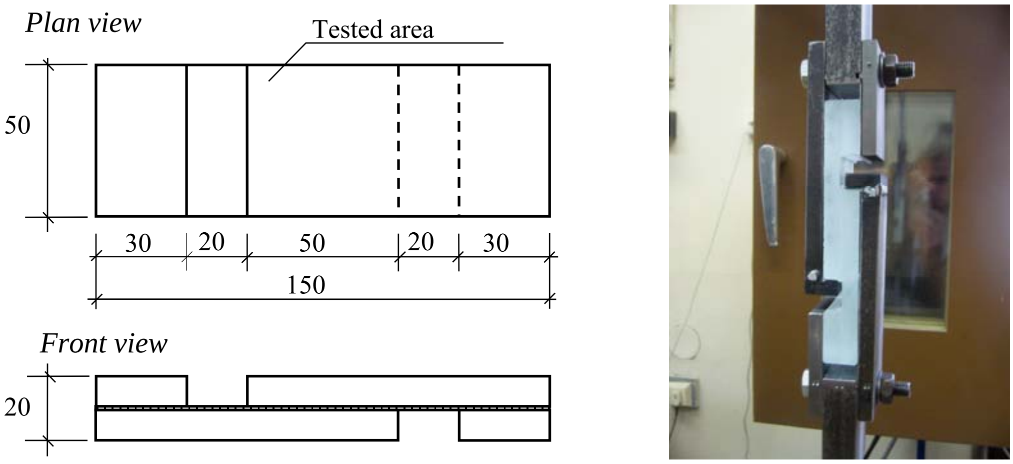

Fig. 5: a) Geometrical dimensions of the test specimens, b) Steel frame for introducing the load.

All experiments were carried out in the laboratory of the Klokner Institute, using the TIRA testing machine, which was supplemented by a climatic chamber for experiments at above and below room temperature 20°C. Additionally, the displacements of each test specimen were measured by two potentiometers. A total of 10 test specimens are planned for each type of interlayer, temperature and load rate.

3.2. Evaluation of the experiments

The first part of the experimental results was evaluated. The number of test samples was sufficient for obtaining the shear modulus of the interlayers under various conditions and for determining the statistical values (average, dispersion, standard deviation). Tab. 1 presents an overview of the specified initial shear modulus *G* for all tested interlayers, temperatures and a one-load rate of 2 mm/min. Shear modulus *G* was determined for each test specimens, values in the table represent the average of 10 test specimens.

Tab. 1: Overview of shear modulus G for a load rate of 2 mm/min.

Type of interlayer	Shear modulus G [MPa]			
	Load rate 2 mm/min			
	0°C	20°C	40°C	60°C
EVA - Evalam	7.31	1.67	0.68	0.32
EVA - Evasafe	-	5.30	2.74	1.48
PVB - Trosifol	-	1.66	0.44	0.26
PVB - Trosifol ES	-	155.34	-	-
TPU - Krystalflex	-	2.56	1.68	0.64

A preliminary summary of the results shows that the strongest interlayer is PVB-Trosifol-ES, which is almost without deformation at a temperature of 20°C. It should be mentioned that the same chemical composition does not mean the same shear modulus (e.g. a comparison between EVA-Evalam and EVA-Evasafe). For high temperatures (60°C), all tested interlayers are much less strong. PVB-Trosifol resisted only a very small force (100-200 N), and there was sliding of the interlayer instead of the usual failure mode. All of the tested interlayers are more resistant with lower temperature and with a higher load rate, see Fig. 6. The load rate has a significant impact on the shear modulus, depending on the type of interlayer. In the case of PVB-Trosifol, we can observe almost the same shear modulus for a load rate of 2 mm/min and for a load rate of 0.5 mm/min, but for a load rate of 0.125 mm/min there is a substantial reduction in the shear modulus. By contrast, EVA-Evalam has the same stiffness for practically all tested load rates. For practical reasons, the load rates were chosen with respect to the testing time, and do not correspond to the long-term behavior under self-weight.

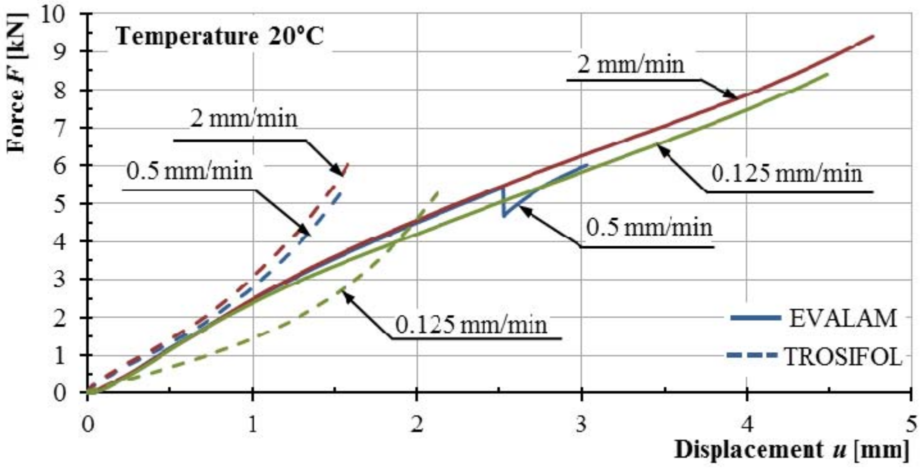

Fig. 6: Force displacement relation of two interlayers for a different load rate.

Comparison of the force displacement relation of two interlayers for different temperatures is shown in Fig. 7. It is obvious that also temperature has a significant impact to the behavior of laminated glass. Shear modulus *G* come close to zero especially in case of the temperature higher than $T = 40°C$, that are common during service-time of structure.

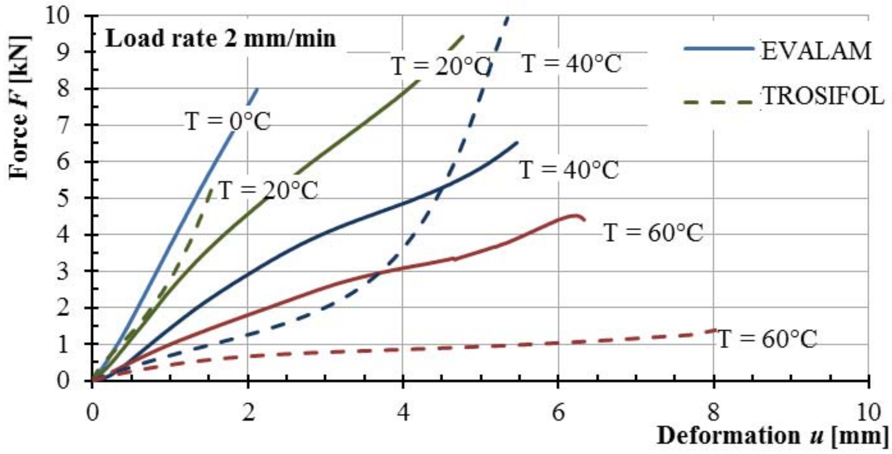

Fig. 7: Force displacement relation of interlayers EVALAM for a different temperature.

4. Design approach based on the effective thickness

Simple design procedure aimed at the laminated glass panes with visco-elatic interlayers, is suggested in the draft of European standard prEN 16612 "Glass in building - Determination of the load resistance of glass panes by calculation and testing" that was prepared by European Committee for Standardization (CEN / TC 129). Design is based on the determination of effective thickness substituting the laminated glass consisted of more than one layer. Following check of ultimate limit state as well as serviceability limit states is executed for single layered glass with effective thickness, which depends on the load duration (permanent load x wind load) and temperature, which is introduced by coefficient ϖ. Such kind of simplification is valid only for the glass panes from laminated glass simply supported along four sides and load by uniform load perpendicular to the plane of the pane.

The effective thickness for calculating vertical deflection is determined by

$$h_{ef,w} = \sqrt[3]{\sum_k h_k^3 + 12\varpi\left(\sum_i h_k h_{m,k}^2\right)} \tag{1}$$

and the effective thickness for calculating the stress of glass ply number j is

$$h_{ef,\sigma,j} = \sqrt{\frac{(h_{ef,w})^3}{(h_j + 2\varpi\, h_{m,j})}}, \qquad (2)$$

where

ϖ is a coefficient between 0 and 1 representing no shear transfer (0) and full shear transfer (1), Tab. 2,

h_k, h_j are the thicknesses of the glass plies, Fig. 8,

$h_{m,k}$, $h_{m;j}$ are the distances of the mid-plane of the glass plies k, j, respectively, from the mid-plane of the laminated glass, Fig. 8.

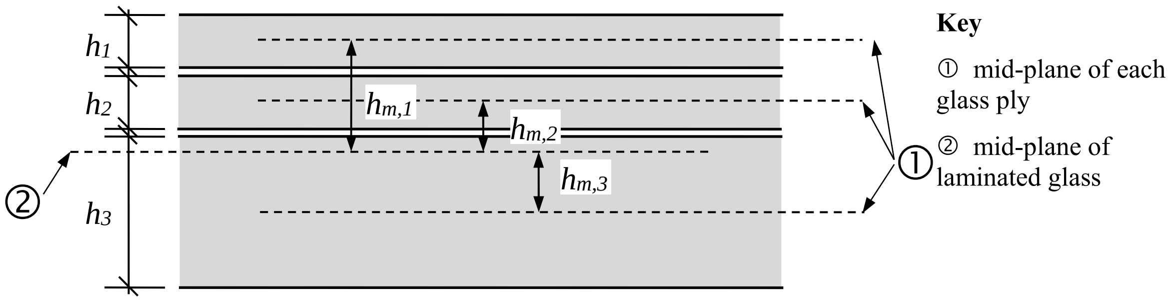

Fig.8: Example of laminated glass

Tab. 2: Value of ϖ associated with interlayer stiffness family and load case

Load case	Family 0	Family 1	Family 2	Family 3
Wind load (Mediterranean areas)	0	0	0.1	0.6
Wind load (other areas)	0	0.1	0.3	0.7
Personal load – normal duty	0	0	0.1	0.5
Personal load – crowds	0	0	0	0.3
Glass for walking on for maintenance	0	0	0	0.1
Snow loads – external canopies	0	0	0.1	0.3
Snow loads – roof	0	0	0	0.1
Permanent loads	0	0	0	0

Stiff foils as (e.g. SentryGlass) belong to the family 3, PVB foils are generally classified as the family 2 however a lot of different producers and insufficient information about the material properties mean that the behavior under the loading is necessary to verified experimentally.

If the information about the shear modulus is known also under different temperature and load duration finite element method and numerical modelling brings more economical design of laminated glass panes.

Comparison between the results using the effective thickness method and numerical model with the shear modulus determined by experiments is shown in the Fig. 9. Normal stress on the tensile side of bottom pane was determined by using above mentioned methods for simply supported glass pane from double layered glass loaded uniformly perpendicular to the surface of the pane. Red dashed lines represent the results of simple method for range of coefficient ϖ from 1.0 till 0. Black continuous lines represents two borders for shear modulus G = 10 MPa and G = 0.01 MPa. Colored lines were established by finite elements method for the real values of shear modulus G obtained from experiments for various conditions (temperature and load rate) of test specimens with interlayer EVALAM.

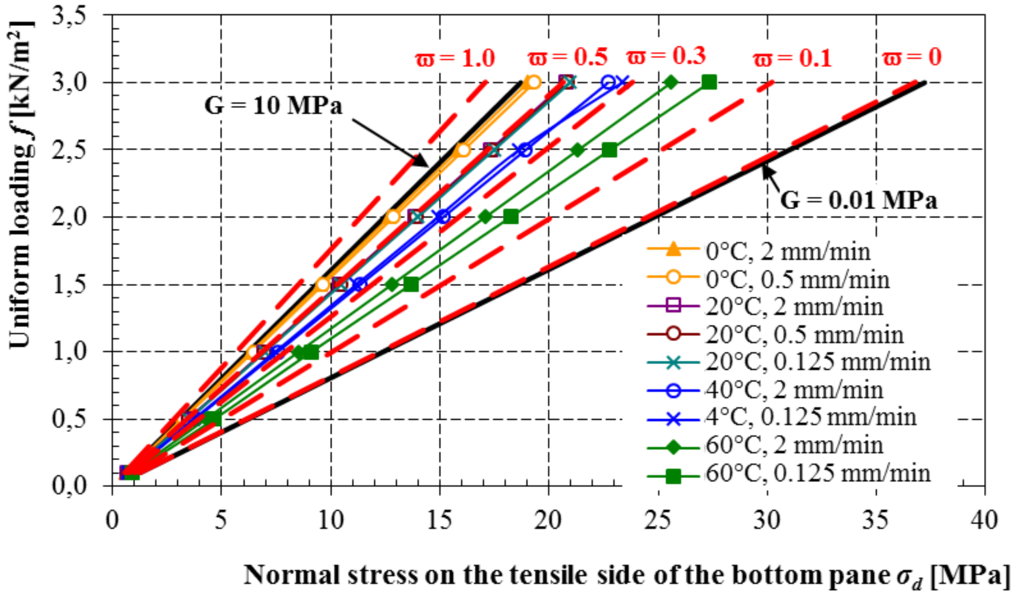

Fig.9: Comparison of the numerical model and simple method using the effective thickness

5. Conclusions

For load-bearing laminated glass panes with a load perpendicular to the surface, the material properties of visco-elastic transparent foils are very important. The composition of the laminated structural elements as a whole needs to be chosen with respect to the static function, the design load and the environmental conditions, e.g. temperature, which affect the shear modulus G of the interlayers and consequently the stress distribution as well as the deflection. This has motivated intensive research in Europe (Galuppi & Royer-Carfagni, 2013).

The shear modulus has different values not only for different interlayer materials but also under different environmental conditions (temperature) and load duration. Under high temperatures, laminated glass generally works without any composite action, because polymer materials are not able to transfer the shear forces, and in this case the shear modulus is close to zero. Temperatures below 20°C lead to stiffening of the material and to higher shear modulus values. Under long-term application of the load there is a creeping effect in the polymer interlayers, which has to be taken into account (e.g. self-weight).

Approaches that are suggested for the design of laminated glass elements, in particular, the method described in Draft prEN 16612 (2013), are based on an evaluation of the effective thickness. These approaches are too simplified and need to be improved. The test results presented here form a small part of a future study under various conditions and for a wider range of interlayer materials in order to obtain all the necessary data (shear modulus values) for the improved design of laminated glass elements.

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