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RESEARCH ARTICLE

Temperature dependent load bearing capacity of laminated glass panes

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Abstract

An experimental programme with numerous single and laminated glass specimens was carried out to study the temperature dependent behaviour of laminated glasses. The difference of load bearing capacities between the laminate manufactured from ordinary float (laminated glass) or tempered glass layers (safety laminated glass) were also studied in four-point bending. When glass laminate fractures, the interlayer can keep the fragments in place. Different types of interlayer materials, both resin and foil (type EVA) were studied in safety and non safety laminated glass specimens. Glasses are used not only in the interior but also in exterior places. Therefore, the effect of temperature of -20˚C, +23˚C and +60˚C were investigated on bending characteristics of glasses. The main influencing factors on the load bearing capacity and bending characteristics of the glass specimens were investigated e.g. tempering, laminating and temperature.

Keywords

glass · laminated glass · temperature · delamination · EVA · interlayer

Acknowledgement

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Fig. 1. Glass separation wall

1 Introduction

Tendency of architecture is to use larger size glass panes or to expose it to carry high loads e.g. glass slabs with carry loads of cars. Therefore, appropriate laminated glass panes should be selected in order to avoid excessive deflections, and the effect of temperature – especially at outdoor conditions – has to be taken into account to the calculations. Glass is often used as a construction material to create load bearing structures where the bending strength of the material plays an important role in the load bearing capacity.

For safety glazing applications, heat-strengthened or heat-tempered glass should be used. Only the lamination of glass layers does not make it *safe*. Therefore, the layers of laminated safety glass should be consisting of heat-strengthened or heat-tempered glass layers. Tempering increases the price of the glass (about 1.5 times), therefore, sometimes people try to use ordinary float glass where the use of heat-strengthened or tempered glass would be necessary. Fig. 1 indicates that non-safety glass was used in glass separation wall and the failure stared by about 120 panes. The use of float glass in point fixed glazing is especially dangerous, because it is not resistant to high stress concentrations e.g. which develop around holes [1].

EN ISO 12543-1:2000 [2] differentiates between laminated and laminated safety glasses. Laminated safety glass is generally used with kind of foil. But for larger sizes and curved shapes or bent laminated glass is usually available with a resin interlayer. The interlayer has two functions [3]: (i) to keep in place the glass splinters during the fracture process to reduce the risk of injury and (ii) to increase residual load bearing capacity.

Until recently, some national standards explicitly stipulated

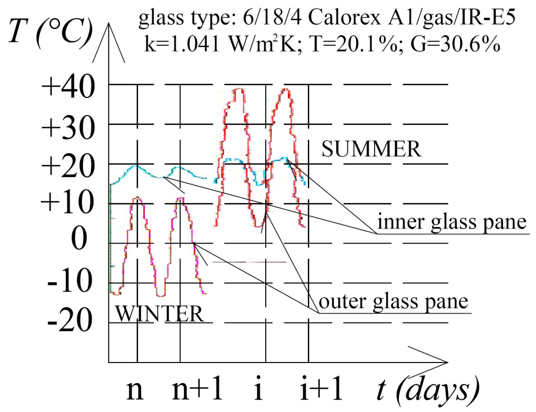

Fig. 2. Effect of ambient temperature on the temperature of an insulating window glazing [6]

the composition of the interlayer, usually within the standard definition of laminated glass. As a result, interlayer materials are not explicitly specified for composition or fields of application e.g. use in commercial or public buildings in outdoor or indoor conditions. The new European standards (*EN 356:1999* [4]) also focus on performance (e.g. tensile strength, ultimate elongation) rather than composition. As a result, those foil and resin interlayer materials or others are acceptable, which are determined to be acceptable for use in laminated glass by the manufacturer of interlayer materials.

When using laminated glass on external surfaces (facades, roofing, etc.), the temperature can reach about 60°C in summer or -20°C in winter [5]. Fig. 2 indicates the change of temperature of an insulating glass in summer and in winter, calculated with Helios software [6], when the room temperature is regulated and it is +20°C. In case of an insulating glass unit the outer glass layer is more affected by the temperature of the environment. The question araises – especially in the case of load bearing glass constructions exposed to a wide range of temperatures (depends on the climatic region of the countries) – how the temperature affects the load bearing capacity of single or laminated glasses.

The aims were to study the bending characteristics of laminated soda lime silicate glasses including: force and deflections, strains in two different regions as well as the residual load bearing capacity.

2 Materials and test programme

An experimental programme was carried out to analyse the load bearing capacity of single and laminated glass panes. Specimens were tested in four-point bending. Specimens were manufactured from soda-lime silicate float glass with polished edges. Tempering induces a pre-determined amount of stress into the glass. *ASTM C1048-85:1985* defines the required surface and also edge compression stresses. Required compressive stress for heat tempered glass is at least 69 N/mm^2 on the surface and at least 67 N/mm^2 at the edges [7]. In the case of tempered glass, the stress must first exceed the built-in compression stresses before tension develops [8]. The influence of edge strength also influences the strength of glass pane. Therefore, the strains in middle of pane and in the edge regions were also studied. The results of tempered glass specimens were compared to those of non heat treated float glass specimens.

2.1 Test parameters and test programme

Test parameters of laminated glass specimens were the following [9]:

- Constants: test arrangement, width and length, thickness, rate of loading (20 mm/min), edgework.
- Variables: number of glass layers: two or three, type of laminate (non safety or safety laminate), type of interlayer material (resin or EVA foil or without interlayer), temperature of specimens.

Tests were based on glass panes with a thickness of 6 mm. The chosen thickness allows the study of large deflections of the glass specimens in bending. Single glass specimens with thickness of 12 and 19 mm were also investigated, to compare the monolithic *upper layered limit* of 2×6 mm and of 3×6 mm laminated glass specimens. To determine the *lower layered limit*, laminated glasses layers without use of interlayer material (with use of only spacer at the edges) were tested.

The schematic diagram of the test programme for laminated glass specimens is illustrated in Fig. 3.

Simplified symbols were used in this paper to distinguish the studied specimens, these are e.g. E_2_R. The meaning of the symbols are as follows: at first place is the type of glass: (E_) tempered, (F_) float; at the second place is the number of applied glass layers (_2_,_3_); at third place is the type of interlayer material (_R) resin, (_F) EVA foil, or (_D) non bonded glass layers. In the case of single glasses the used symbols indicate the type of glass and the nominal thickness e.g. E_12 mm means single layer tempered glass with nominal thickness of 12 mm.

Interlayer materials used in laminated glasses were resin (cast in place, unsaturated polyester resin based on ortho-phthalic acid with stryrol content, pre-accelerated, light stabilised) and EVA (ethyl-vinyl-acetate) foil. While PVB (polyvinyl-butyral) foil is widely used in laminated glass, EVA foil is a new generation of foils (product of Bridgestone). EVA interlayer was first used in Hungary in 2005 by *Rákosy Glass Ltd.*

The main properties of the tested interlayer materials in more details are summarised in [9]. The glass transition temperature and melting temperature ranges were not available for cured resin. These data were only available for EVA foil. In order to determine the glass transition- and melting temperature ranges, DSC (Differential Scanning Calorimetric) tests were carried out at Faculty of Chemical Technology and Biotechnology, Department of Plastics and Rubber Technology, BME. The determined glass transition temperature, T_g, was -42 to -38°C and melting temperature, T_m, was +109°C (80°C to 140°C) for cured resin.

The average values were determined for each test combination from at least three measurements in the case of laminated

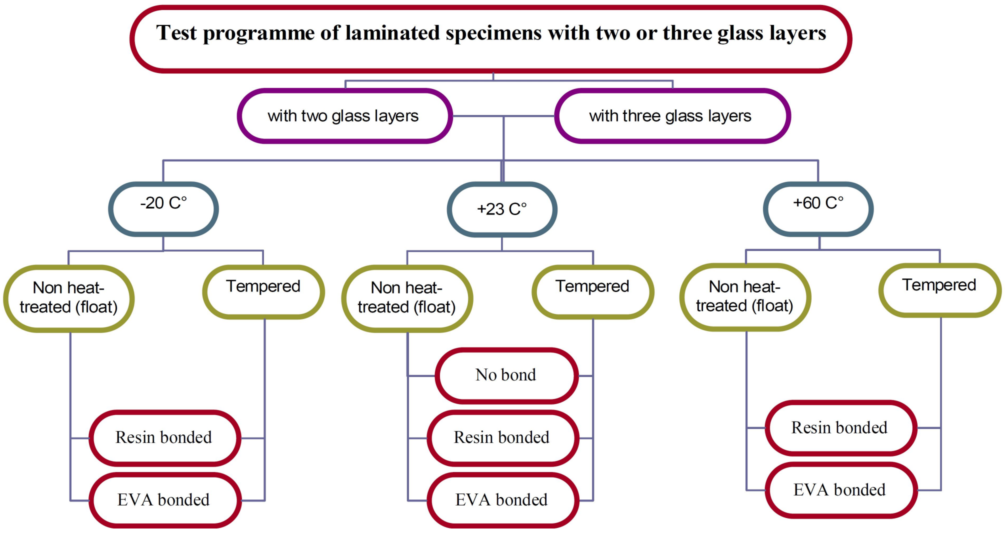

Fig. 3. Schematic diagram of test programme for laminated specimens [9, 10]

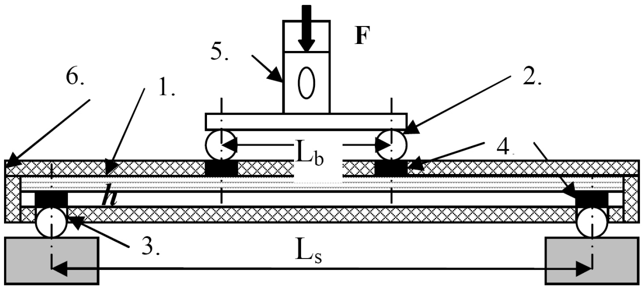

Fig. 4. Test method for four-point bending (*EN 1288-3:2000* [11]) where, 1.: specimen: 1100×360 mm, 2.: bending roller, 3.: supporting roller, 4.: rubber strips (3 mm thick, according to ISO 48 [12]), 5.: self-designed transducer, 6.: custom-made insulation (40 mm thick), L_s: 1000 mm, L_b: 200 mm, h: thickness of the specimen (6 mm, 12 mm, 19 mm or 2×6, 3×6 mm) [9].

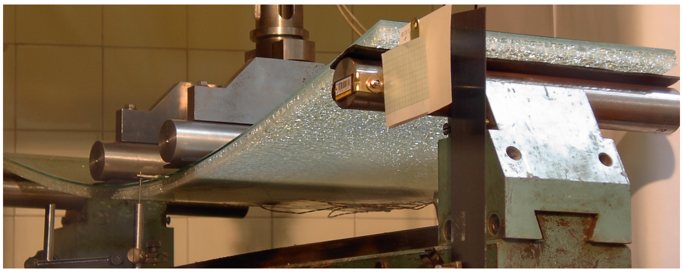

Fig. 5. Test of laminated safety glass specimen

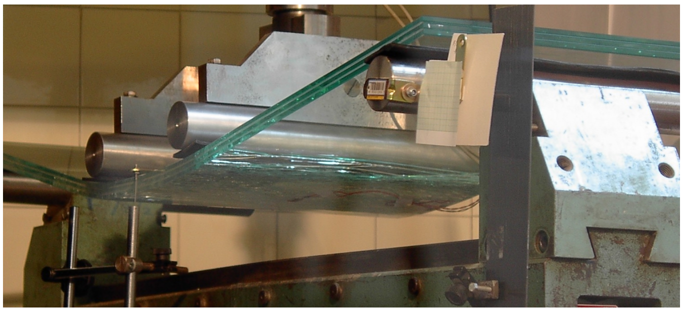

Fig. 6. Test of non safety laminated glass specimen

glasses and four measurements in the case of single glasses. The standard deviation of the test results was lower than 10% of the average of measured values.

3 Experimental procedure

3.1 Force measurements

All glass specimens with a constant span of L_s = 1000 mm and supported at a width of b = 360 mm were tested in four-point bending. The deflection at mid-span of the glass panes were measured with displacement transducer in all tests. The test procedure was a semi-dynamic short-term test. The tests were carried out at a specimen temperature of +23˚C. Further specimens were heated to +60 ˚C or cooled to -20˚C. The temperature of the specimens and the room temperature were continuously measured during the tests. The specimens were mounted as shown in Fig. 4.

The temperature was kept constant during the test with ± 1˚C in order to avoid the development of thermal stresses. The temperature of insulated specimens was measured on their surface during tests. Load was measured with a self-designed force transducer, developed by the authors [1, 9] for *Instron Type 1197* testing instrument. Values measured during the tests were simultaneously recorded by computer. The fracture process and crack pattern of glass specimens were recorded with digital optical methods. The specimens were tested until fracture Figs. 5 and 6.

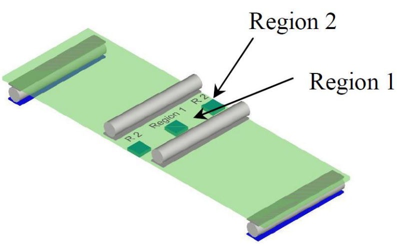

Fig. 7. Region 1 and Region 2 of glass surface strain measurements [9, 13]

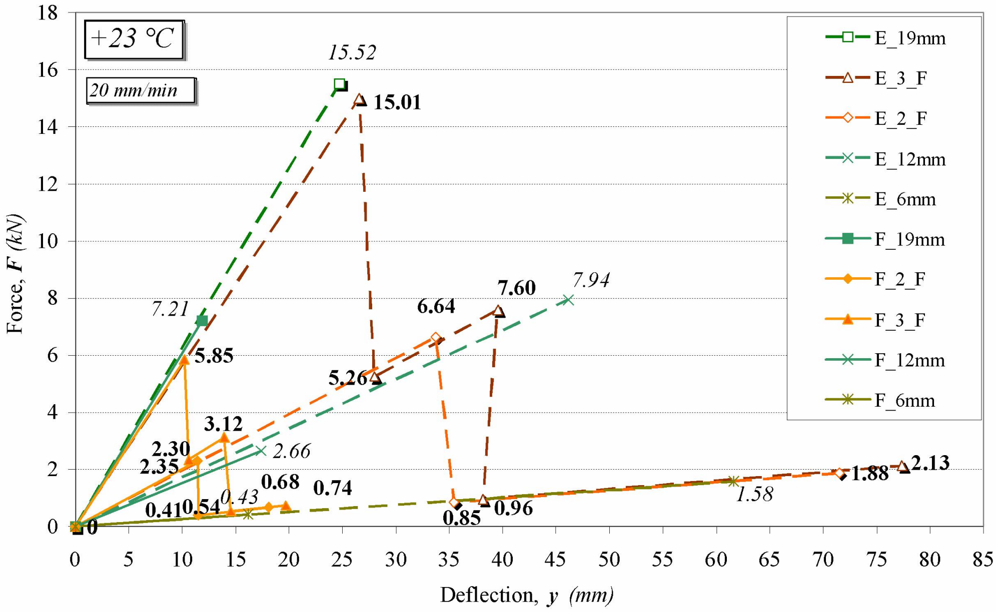

Fig. 8. Force vs. deflection diagram of non heat-treated float (F_) and tempered (E_) laminated glass (with 3×6 mm and 2×6 mm glass layers) specimens, laminated with EVA foil (_F); also single glass specimens with thicknesses of 6, 12 as well as 19 mm are illustrated. Dashed lines illustrate the tempered, continuous lines, the float specimens.

3.1.1 Strain measurements

Strains at selected points on the surface (in R 1 and R 2 Region) of the glass panes were measured with Type *HBM LY11-10/120* strain gauges (Fig. 7). For temperature compensation, another glass specimen had strain gauges applied on its surface and was stored at the same condition as the tested specimens. Stresses at glass surface may be calculated with *Hooke's* law for linear elastic materials.

4 Test results and discussion

4.1 Stages of fracture process of laminated glass

Fig. 8 indicates the force vs. deflection in four-point bending of laminated glass specimens consisting of three glass layers and EVA interlayer.

Three different stages (*Stages A, B* and *C*) of the fracture can be identified in the laminate (Fig. 9).

Stage A: When the laminated glass is unbroken, the hypotheses of Bernoulli can be adopted for the glass layers. The modulus of elasticity of the laminate depends on the service temperature, loading rate, etc. Fracture occurs when the ultimate strength of the bottom glass layer under highest strain is reached, then the force drops to the lower level e.g. F_{u23} immediately.

Stage B: The load has to be carried by the non-fractured layers of laminated glass.

Stage C: The interlayer material serves two purposes: (1) the adhesion of the fragments of the fractured glass layer to the non-fractured glass layer and (2) to transfer forces between the glass layers. Therefore, the force starts to increase until the ultimate strength of the next layer is reached again. When two glass layers are fractured and the interlayer material remains unbroken, it can help as *reinforcement* for the last non-fractured glass layer in the case of laminated glass consisting of three glass layers.

The measured values for fracture process of laminated glass specimens in more details is available in [9, 10].

4.2 The effectiveness of tempering of laminated glasses

It is suggested to introduce the definition *effectiveness of tempering* (heat treatment). The effectiveness of tempering shows the proportion of load bearing properties (e.g. maximal force) of tempered glasses to non heat treated float glasses with the same thickness. The authors have experimentally shown that the effectiveness of tempering depends on the glass thickness in the case of single glasses and the number of applied numbers of glass layers in the case of laminated glasses. Based on the laboratory results in four-point bending the effectiveness of tempering decreases with the increase of thickness in the case of single glasses, and it also decreases with increase of applied number of glass layers in the case of appropriate bond (Fig. 10).

Fig. 10 indicates the effectiveness of tempering as a function of the number of glass layers and as a function of the thickness of a single glass layer. The higher the number of glass layers, the lower is the effectiveness of tempering in laminate with appropriate bonded glass layers. In the case of laminate without bonded glass layers (as lower limit), the load bearing capacity is influenced by the ultimate force of each individual glass layer and there is no significant change in the ratio by increasing the number of glass layers from two to three (Fig. 10). With an increase of thickness (from 6 to 12 and 19 mm) of monolithic single glass layers (as upper limit), the ratio decreases. With an increase of the number of glass layers, the number of defects on the surfaces also increases, which affects the load bearing capacity of the laminate. In the case of relatively thick glass layers ($h > 10$ mm) or with increase of number of layers, the strength is considerably influenced by the size effect. The reason for the size effect is the stochastic distribution of the defects in the glass pane (Weibull type size effect, otherwise called statistical size effect [14]).

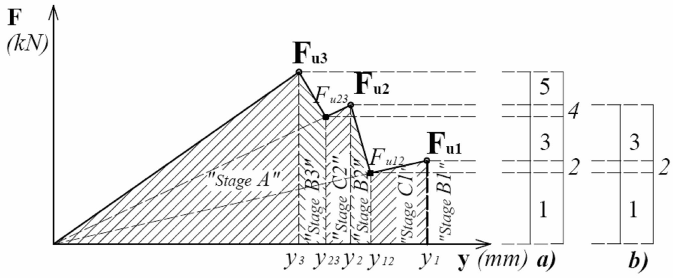

Fig. 9. Stages during fracture process of laminated glass and numbering of stages of change in force a) consisting of three glass layers, b) consisting of two glass layers

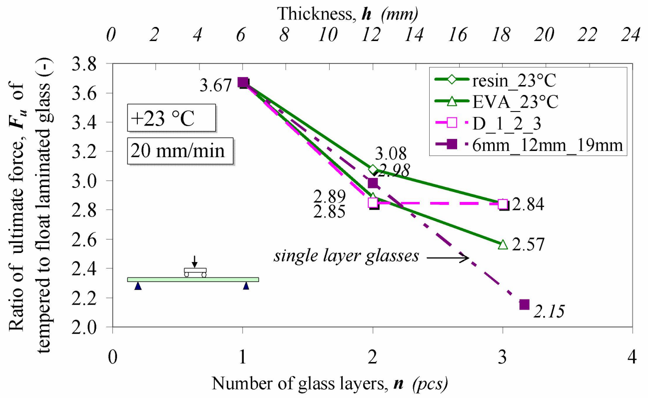

Fig. 10. Effectiveness of tempering vs. number of glass layers of laminated glasses at 23 °C, where symbols mean: D_ without bonded layers, 6 mm, 12 mm, 19 mm are the single layer glass specimens

Most of glass strengthening methods are used to introduce residual compressive stresses into the outer layers by physical or chemical tempering [9, 13]. With increase of number of tempered glass layers of safety laminated glasses, it will contain more compressed layers, which help to close cracks initiated on the surface and can stop crack propagation as well as can increase the load bearing capacity.

In the case of resin laminated specimens, the tempering is more effective than in the case of EVA laminated specimens with an increase of the number of glass layers. The resin interlayer (cured liquid resin) material can fill out the surface unevenness of tempered glass more effectively than EVA foil interlayer. Therefore, it influences the effectiveness of the tempering. Bonding between the resin and the glass *(chemical bond)* is extremely strong because of the chemical link between the resin and the silol (SiOH) groups on the glass surface. These chemical bonds which are formed during and after curing are highly stable and resistant. Laminates with a resin interlayer sometimes offer better humidity resistance than foil-laminated glasses [15].

4.3 The effect of temperature on maximal force of laminated glasses consisting of different number of glass layers

The experimental results showed that the behaviour of laminated glass is influenced by the temperature both for non heat treated laminated glass and for tempered laminated glass [9]. With the increase of temperature, the deflection increases while the ultimate force decreases. This behaviour is more pronounced in the case of resin interlayer material than in the case of EVA foil interlayer material. Comparing maximal force of laminated glass specimens vs. ratio of total thickness of interlayer material to total thickness of specimen, (Fig. 11) indicates that the load bearing capacity of laminated glass with EVA interlayer is less affected by the change of temperature compared to resin laminated specimens.

The laboratory results indicate that the temperature sensitivity is more pronounced in the case of resin interlayer compared to EVA interlayer. EVA interlayer material is more effective in varying temperature conditions in the case of load bearing safety glass applications, where high ultimate forces have to be resisted. The load bearing capacity of laminated glass can be increased with increase of thickness of interlayer material in the case of appropriate bond. Research results of Behr et al. [16], Vallabhan et al. [17], Norville [18] indicated that the increase of PVB interlayer thickness the load bearing capacity of laminated glass increases at room temperature.

At high temperatures, resin interlayer material will soften with a decrease of bond strength, therefore, the ultimate force of laminated glass significantly decreases. Hussein, et. al (2005) studied the vinyl acetate content of EVA on the rheology of polymer modified asphalt and suggested that the tested type of EVA1 of low VA content would show higher modulus (G') at high temperature, which is preferred for hot climates [19]. The reduction of the flow activation energy [20] reduces the degree of temperature sensitivity, hence, reduces the change of viscosity due to temperature changes. Therefore, in the case of applying EVA foil in laminated glass as an interlayer material, it is preferred to investigate EVA foils with low VA content.

The effect of temperature on load bearing capacity and on deflections, especially in the case of load bearing laminated glasses, should not be neglected. The interlayer thickness can be optimalised in the case of known service temperature or *exposure class* of laminated glass.

4.4 The effect of temperature on strains of laminated glasses in different regions of glass surface

Glass strength in the Region 2 (edge region) is mainly influenced by the edgework [8–10, 13]. The strength of laminated glass is further influenced by the condition of the interlayer material near the edges. The edge region of laminated glass is the area most affected by humidity, temperature or contact with other materials, such as silicon in sealing. If delamination would occur at the edges, the bond strength in the Region 2 would decrease, therefore, the stresses of Region 2 increase, which af-

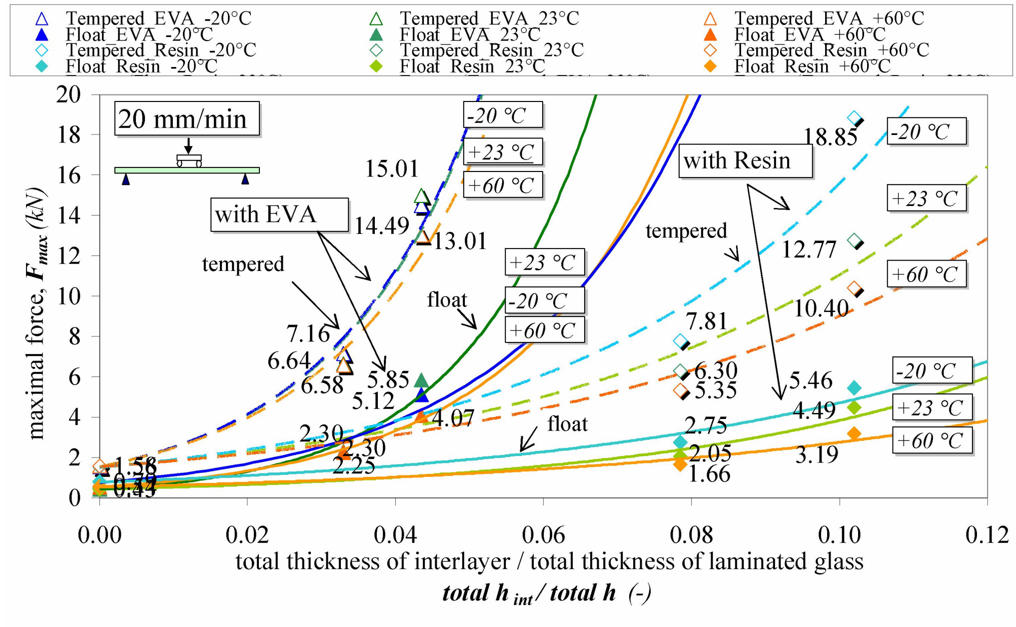

Fig. 11. Change of ultimate force at "Stage A" of laminated glass specimens laminated with resin or EVA foil interlayer materials at temperatures of -20°C, +23°C and +60°C (values are average of thee measurements)

fects the strength of the overall laminate. The increase of strains of glass layers in Region 2 highlighted that mainly this area of laminated glasses are temperature sensitive (Fig. 12).

The strains in the Region 2 of laminated glass without bonded layers can be 19% higher than in the Region 1 at 23°C. By increasing the temperature from 23°C up to 60°C of float laminated glass consisting of two glass layers with resin interlayer material indicated that the surface strains at bottom surface in the Region 2 can increase up to about the strain value of laminated glass without use of interlayer material. Therefore, there is no appropriate bond between the glass surfaces at 60°C of resin laminated glasses. In the case of EVA interlayer material the strains in the Region 2 at 60°C remain about 7-8% higher than of Region 1, like at 23°C.

Delamination of laminated glass can happen due to chemical reactions e.g. aging of interlayer material or due to physical phenomenon e.g. considerably decrease of bond strength (change of viscosity or adhesion of interlayer material) [10]. Delamination can occur (i) partially in edge region with locally decoupling of glass layers, but the interlayer remains relatively stiff and functions as a spacer between the glass layers, or (ii) it can occur globally when the overall surface is affected by high temperature and the interlayer material considerably softens and the laminate transforms to an "oil laminate".

If temperature of laminated glass can reach (dependent on the exposure) the melting temperature (or Heat Deformation Temperature) range of the interlayer material, it behaves like an "oil laminate", because the interlayer is not able to transfer shear forces. Therefore, overall decoupling (or debonding) can occur, and to the load bearing glass calculations only the resistance of individual glass layers should be taken into account, although physically the delamination as a phenomenon can not be indicated directly. Partially delamination can occur mainly around the edges due to chemical reactions (e.g. incompatibility of materials) also or loss in adhesion properties by moisture absorption of the interlayer material, etc. Without inspection, it can propagate into the overall laminate and the delamination can be physically shown. Research results of Van Duser et al., (1999) indicated that the water content of PVB interlayer above the optimum value of around 0.45% can reduce both the adhesion to the glass surface and the rigidity of the bond [21]. In previous studies [22, 23], moisture penetration and retention was observed in laminated glasses. That moisture condensation occurred in the laminated glasses around the edges. In the former laminates, the originally clear and transparent EVA layer would become white or opaque which gradually can disappear in time by displacing the laminates to dry air conditions [22, 23]. If delamination occurs in the case of resin laminated glass pane, the process is irreversible (Fig. 13).

Therefore, it is important to study the bond capacity of interlayer material, especially in those regions where the edges of interlayer are exposed to outdoor conditions. Protection of the highlighted regions is needed.

The ultimate strain is higher in Region 2 compared to Region 1 especially in case of non-bonded layers. Interlayer materials can reduce the difference between the ultimate strain of Region 2 and Region 1. With increasing temperature this reducing effect decreases more in the case of resin than in the case of EVA interlayer material. The adhesion increases in the case of EVA with increase of temperature, although the material softens. In the case of resin the chemical bond between the interlayer and the glass surface is less effective at temperature of +60°C than at -20°C. The temperature dependent behaviour of laminated glass should be studied on the whole laminated material. It is not enough to study the temperature dependent behaviour of the interlayer material.

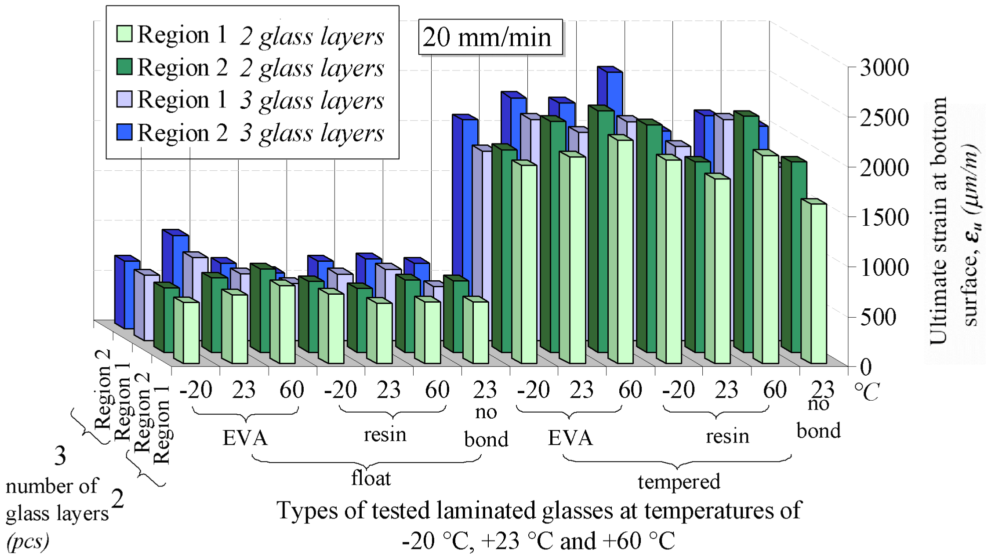

Fig. 12. Strain at maximal force on bottom surface of laminated glass in R 1 and R 2 regions, consisting of two or three float or tempered glass layers, laminated with resin or EVA foil at temperatures of -20 °C, +23°C and +60°C, loading rate of 20 mm/min.

Fig. 13. Delamination of resin laminated glass pane a) one month after finishing, b) three months after finishing

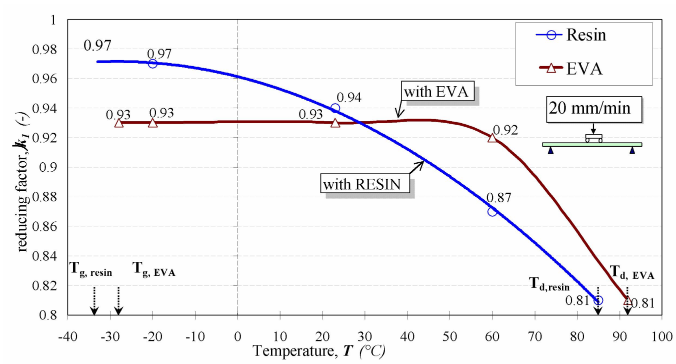

Fig. 14. Reducing factor k_1 vs. temperature of laminated glass with EVA and resin interlayer materials

Reducing factors should be applied to the calculations of glass strength for different regions (Fig. 14 indicates the suggested values for k_1). Therefore, it is not preferred to use an overall design strength, especially for load bearing glass applications in outdoor conditions or for lifetime predictions. A k_e factor to calculate the edge strength for single glasses in *EN 1288-3:2000* was already determined [11]. In the case of laminated glass, the strength of the edge region (Region 2) is influenced by the bond behaviour at service temperature of the interlayer material. Based on the laboratory results k_1 reducing factor as function of temperature was determined for laminated glasses with resin and EVA foil interlayer materials (Fig. 14).

The authors proposes the definition of *delamination temperature*, T_d, of laminated glass. This temperature can be predicted when the interlayer is not able to transfer shear forces between the glass layers (non-bonded glass layers). It is suggested the determination of k_1 between temperature range of glass transition temperature, T_g, and delamination temperature, T_d, of the interlayer material. The delamination temperature is influenced by the type of applied interlayer material. The delamination temperature is about 85-100°C in the case of resin interlayer

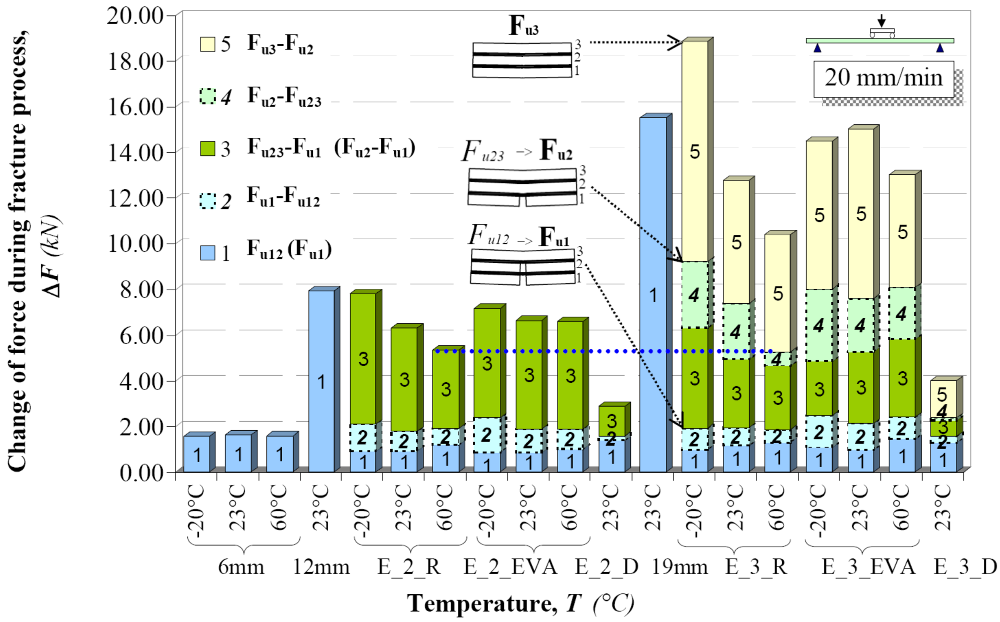

Fig. 15. Change of forces during fracture process of laminated *tempered* glasses at temperatures of -20°C, +23°C and +60°C, symbols are: E_ – tempered glass, numbers: -number of glass layers; _EVA-EVA foil, _R-resin interlayer material, _D – without interlayer material

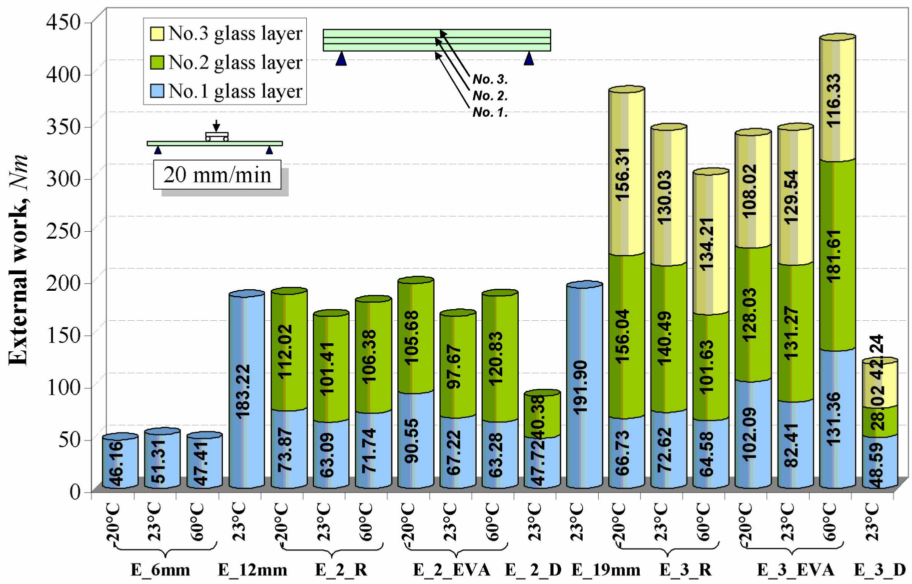

Fig. 16. External work during fracture process of laminated *tempered* glasses at temperatures of -20°C, +23°C and +60°C, symbols are: F_ – float glass; numbers: -number of glass layers; _EVA- EVA foil, _R- resin interlayer material, _D – without use of interlayer material as well as single layer glasses with thickness of 6 mm, 12 mm, 19 mm are indicated.

laminated glasses. The delamination temperature is about 92-96˚C in the case of EVA interlayer laminated glasses by applied loading rate of 20 mm/min. In the case of increase of number of glass layers in laminated glass or with the increase of interlayer thicknesses, the delamination temperature decreases. The delamination temperature is influenced by the rate and type of loading (e.g. static or cyclic), therefore, further investigations are needed, especially in the case of load bearing glasses.

4.5 Residual load bearing capacity of laminated glasses at different temperatures

A glazing element can fail during its service life due to various impacts. An interesting aspect is the residual load bearing capacity after failure of one or more glass layers of multi-layered laminated glass (post-failure behaviour), especially when it is used in overhead areas e.g. roofing or in canopies as well as in slabs, where safety demands are.

The residual load bearing capacity of laminated glass during the fracture process is influenced by the temperature sensitivity of the interlayer material. Fig. 15 indicates the decrease of bond capacity of the interlayer material (parts *No. 4* and *No. 2* of columns, see also Fig. 15).

If one glass layer of laminated glass consisting of n glass layers and with a temperature of 23˚C fractures, the residual load bearing capacity is higher than that of laminated glass consisting of $n-1$ glass layers. The interlayer on the top of the fractured glass layer works as a kind of strengthening (see Fig. 12, dotted line and columns E_2_R and E_3_R at +60˚C).

The drop in load bearing of laminated glasses with resin interlayer is significant with the increase of the temperature from −20˚C to +60˚C. However, the temperature sensitivity of laminated glasses with EVA interlayer is less pronounced. There are small drops in load bearing both by reducing the temperature from +23˚C to −20˚C and increasing the temperature from +23˚C to +60˚C in the case of EVA interlayer. The effect of temperature on the residual load bearing capacity of laminated glass decreases during the fracture process.

Single float glass has limited capability for energy absorption and thus contributes little to the energy absorption of the laminate structure which therefore, is governed by the properties of the interlayer. Single float glass can fail due to a critical crack, while in case of tempered glass the statistical distribution (Weibull distribution [14]) of cracks influences mainly the load bearing capacity. In the case of large deflections and during fracture process of laminated glass, the elongation behaviour, adhesion properties, tear strength of interlayer material is important. Laminated glass with EVA interlayer material need higher external work than resin laminated glass during fracture at higher temperatures. In the case of resin laminated specimens with decrease of temperature from + 60 ˚C to -20˚C the efficiency of interlayer material increases. In the case of increase of ultimate force, the external work increases, but at low temperature the ultimate elongation decreases. In the case of large deflections and low temperature, cracks can form in the interlayer, therefore, the energy absorption property decreases. The energy absorption property of the interlayer is also important by impact resistance of laminated glass.

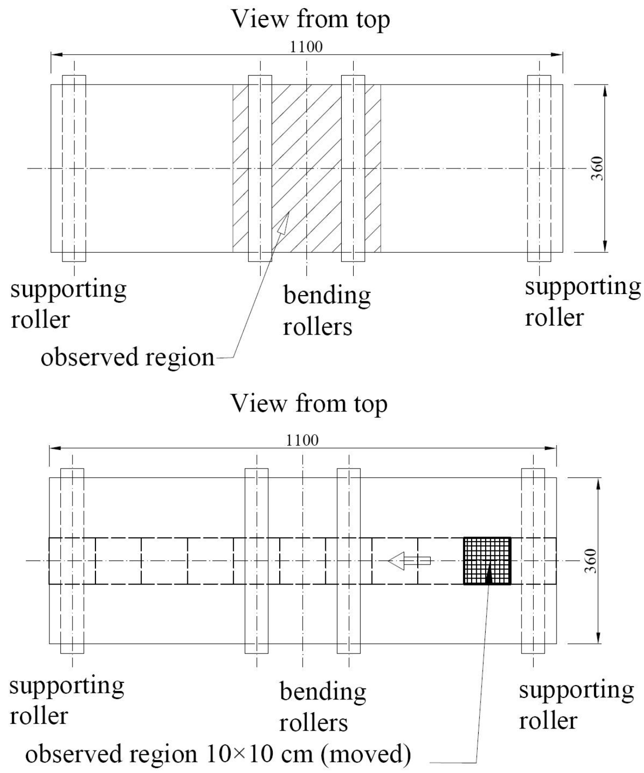

Fig. 17. Schematic views of observation locations of fractured area of a) float and of b) tempered glass panes

Fig. 16 indicates that the residual load bearing capacity increases with the increase of the number of glass layers from two to three layers, if appropriate bond is ensured. Based on the experimental results, the *relative external work* (external work at different temperatures compared to temperature of +23˚C) decreases with the increase of temperature and the number of glass layers in the case of resin laminated glass, but it increases in the case of EVA. At a temperature of -20˚C resin laminated glass behaves more rigidly which leads to smaller deflections and formation of larger "*islands*" of fractured specimens. The drop of the external work during fracture of one glass layer is also higher at lower temperatures (-20˚C) in the case of resin interlayer.

Fig. 16 indicates also the external work values for laminated glasses without bonded layers. In the case of non bonded glass layers the values are low and external work increases proportional to the number of applied glass layers. The comparison of values of non bonded glass layers and appropriate bonded glass layers indicates the importance of interlayer materials in load bearing capacity of laminated glasses.

4.6 Effect of fracture pattern on load bearing capacity of laminated glasses at different temperatures

Photos were taken during and after testing. Figs. 17a, b illustrate the observed areas of fractured laminated glass specimens.

To study the fragmentation pattern of tempered laminated

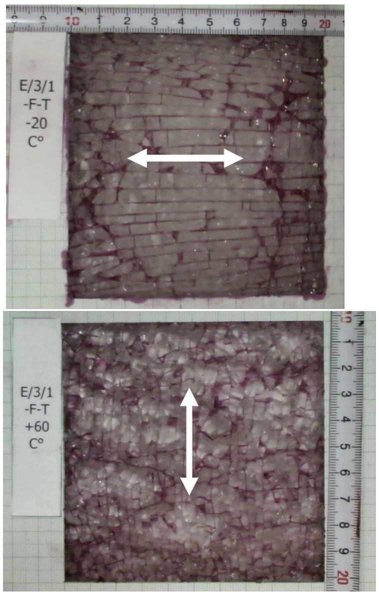

Fig. 18. Fractured regions (10×10 cm) of EVA foil laminated tempered glass consisting of three glass layers a) at -20°C b) at +60°C (from 10 to 20 cm at centre line, arrow indicate the direction of support locations

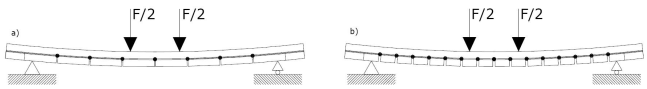

Fig. 19. Schematic representation of fracture pattern of laminated glass a) at -20°C, b) at +60°C

glass the surfaces of fractured specimens were painted to better observe the contour lines. The painted fragmentation pattern indicated that it differs with temperature, Figs. 18a, b.

In the case of glass temperature with a temperature of + 60°C, the fragments *islands*, Figs. 19a, b) were smaller than in the case of glass with a temperature of -20°C.

At temperature of -20°C resin laminated glass behaves more rigidly than at room temperature, which is also indicated by the larger *islands* of fractured specimens.

The distance of cracks and size of fractured regions (islands) influence the bond capacity of the interlayer material, therefore, residual load bearing capacity of laminated glass is influenced by the fracture pattern. In the case of resin laminated float glasses, the width of the fractured zone (in the region of the bending rollers) decreases with the decrease of temperature from +60°C to -20°C. Therefore, the interlayer can transfer forces of larger non fractured regions between glass layer surfaces. In the case of EVA interlayer material, the width of the fractured zone is not significantly influenced by temperature. The bonded *islands* of fractured glass layers influence the bending stiffness of laminated glass during the fracture process.

When the ultimate strain of the glass layer is reached and it fractures into several fragments, cracks appear. The distances between the cracks, called the crack spacing, s_r, will vary. When the crack formation phase ends (it is more dynamic in case of tempered glass, than in case of float glass), the stabilized cracking phase begins. In this case no more cracks appear in

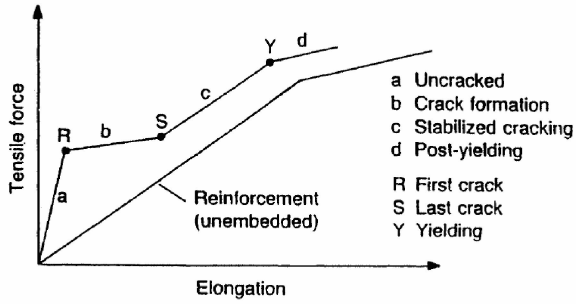

Fig. 20. Idealised behaviour of a reinforced concrete tie for tension-stiffening effect [26]

the glass layer with increased loading, especially in tempered glass. However, the width of the existing cracks will increase with increased load [24,25] and crack can not form at a distance less than the transmission zone, $l_{t,max}$ (fragment length). The reason for that is: the distance (size of fragment) is too short to build up stresses in glass layer to overcome the strength of the glass fragment, (which can be theoretically higher due to the Weibull type size-effect [14] then the strength of the initial non-fractured glass layer). Therefore, the length of the transmission zone is determined by the fracture pattern. In the cracked cross-section the tensile force is resisted by the interlayer. However, between adjacent cracks, tensile forces are transmitted from the interlayer to the remaining glass layer by the bond stresses. This contribution of the glass fragments increases the stiffness of the remaining glass layers in the laminate. Therefore, this effect is called the *tension stiffening effect*, see Fig. 20.

In the case of EVA interlayer material, the width of the fractured zone is not significantly influenced by temperature, therefore also parts *No. 2 No. 4* of columns in Fig. 15 are not significantly influenced.

The temperature sensitivity of interlayer material influences the fracture pattern of laminated glass. Therefore, the fracture characteristics and the secondary cohesion effect (tension-stiffening) of the interlayer during the fracture process should be taken into account to study the residual load bearing capacity of laminated glass at different temperatures.

5 Exposure classes to laminated glasses

For the *exposure class* of laminated glasses the interlayer properties at least with glass transition temperature, T_g and melting temperature, T_m, delamination temperature, T_d, as well as *HDT* (*Heat Deformation Temperature* [20]) should be investigated. The appropriate interlayer material should be chosen for the actual exposure class. The bond capacity of an interlayer material is important. Therefore, further interlayer materials have to be studied and developed with appropriate thermo-mechanical behaviour, with attention of the possible exposure of laminated glasses, especially for load bearing glass application.

The exposure classes of laminated glasses can be determined from the temperature dependent behaviour of interlayer material. It is suggested the determination of exposure classes to

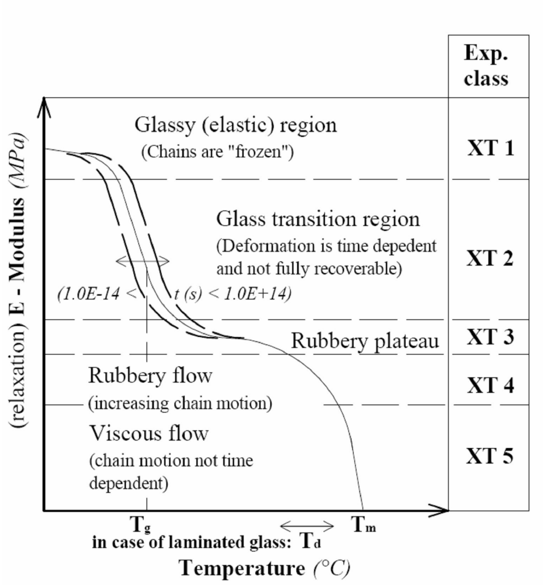

Fig. 21. Preferred exposure classes at service temperature (from XT 1 to XT 5) of laminated glasses dependent on interlayer characteristic [20]

service temperatures (XT 1 to XT 5) as indicated in Fig. 21. To take into account the service temperature and loading condition, e.g. loading rate, the exposure class should be determined. The exposure classes are dependent on the type of polymer e.g. crystalline or amorphous. Note that there is no melting behaviour in the amorphous polymers, therefore, no class *XT 5* exists for it.

The following exposure classes are suggested for the listed conditions:

XT 1: The exposure temperature is below the glass transition temperature, $T<T_g$; short term loads (e.g. wind load, impact); interlayer with the short-time shear modulus, G_0, can be taken into account;

XT 2 to 4: The exposure temperature is between glass transition and melting or delamination temperature, $T_g < T < T_m$ or T_d; semi dynamic loads; interlayer with the stress relaxation modulus $G(t)$ is assumed to be of the form $G(t) = G_\infty + (G_0 - G_\infty)\exp(-\beta t)$ [27], where G_∞ is the long-time shear modulus, G_0 the short-time shear modulus and β the decay factor, t is the time.

XT 5: The exposure temperature is above or equal to the melting and delamination temperature range, $T \geq T_g$; long term loads (self-weight); creep; interlayer with the long-time shear modulus, G_∞, can be taken into account; non-bonded layers (*oil-laminate*).

The testing temperature of laminated glasses should be determined according to the service temperature range.

With known thermo-mechanical behaviour and exposure class the appropriate laminated glass at the "service" or application temperature can be chosen, therefore, the load bearing capacity and durability of it can be determined.

In developing new interlayer materials, [28] also shows the importance of defining properties of laminated glass windshields by determining the interlayer properties with the use of glass transition temperature as an important factor.

EVA foil was used in this research programme, which is a relatively new interlayer material. It was shown to be less temperature sensitive than resin interlayer and is appropriate for outdoor conditions.

6 Conclusions

Based on this experimental study the following conclusions can be drawn for laminated glasses at different temperatures:

- It is suggested the introduction of the definition *effectiveness of tempering* (heat treatment). Based on the laboratory results in four-point bending the effectiveness of tempering decreases with the increase of thickness in the case of single glasses, and it also decreases with increase of applied number of glass layers in the case of appropriate bond.
- The laboratory results indicated that the temperature sensitivity is more pronounced in the case of resin interlayer compared to EVA interlayer. EVA interlayer material is more effective in varying temperature conditions in the case of load bearing safety glass applications, where high ultimate forces have to be resisted.
- The edge strength of the laminate is influenced by the edge strength of the glass layers and it is also influenced by the interlayer properties. By increasing the temperature of laminated glass from 23°C up to 60°C of indicated that the surface strains at bottom surface in the Region 2 can increase up to about the strain value of laminated glass with non-bonded layers. The increase of strains in Region 2 highlighted that mainly this area of laminated glasses are temperature sensitive. Therefore, it is important to study the bond capacity of interlayer material especially in those regions where the edges of interlayer are exposed to outdoor conditions. Protection of the highlighted regions is needed.
- Based on the experimentally results the *delamination temperature*, T_d, of laminated glass can be defined. The delamination temperature indicates the temperature range, when to load bearing glass calculations only the resistance of individual glass layers is preferred to be taken into account, although sometimes physically the delamination as a phenomenon can not be indicated.
- If one glass layer of laminated glass consisting of n glass layers and with a temperature of 23°C fractures, the residual load bearing capacity is higher than that of laminated glass consisting of $n-1$ glass layers. The interlayer on the top of the fractured glass layer works as a kind of strengthening.
- At temperature of -20°C resin laminated glass behaves more rigidly which leads to smaller deflections and formation of larger "*islands*" of fractured specimens. The fracture characteristics and the secondary cohesion effect (tension-stiffening) of the interlayer during the fracture process should be taken

into account to study the residual load bearing capacity of laminated glass at different temperatures.

- It was shown that interlayer materials should be chosen with taken into account the exposure conditions, therefore exposure classes of them should be determined.
- To the *exposure classes* of a laminated glass also the interlayer properties at least with T_g and T_m as well as *thermo-mechanical behaviour* should be investigated. The testing temperature of laminated glasses should be determined according to the service temperature range. Further interlayer materials have to be studied and developed with appropriate thermo-mechanical behaviour with attention of the possible exposure of laminated glasses, especially in case of load bearing glass application.

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