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EFFECT OF TEMPERATURE ON CHARPY IMPACT RESPONSE OF LAMINATED GLASS STRUCTURES

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Abstract. For the structural purpose, the usage of laminated glass units in the modern construction industry is becoming widespread. Laminated glass units are manufactured using glass layers bonded together with interlayer materials. When the laminated unit is shattered, the interlayer prevents large and sharp pieces. This property makes laminated glass a safety glass, which prevents injury and even death of people. The current study is about the effect of temperature on the impact behavior of laminated glass, which has different interlayer materials and interlayer thickness. Experiments are conducted for the analysis of the impact behavior of the laminated glass units. Also, a finite element model is developed using a commercial package program ABAQUS. Comparison of impact response of laminated glass units for different interlayer thicknesses, different temperature values, and for different interlayer materials, PVB and EVA, are given as a result of the study.

Keywords: laminated glass, impact, PVB, temperature, EVA, Charpy impact test

1. Introduction

Laminated glass is produced by pasting an interlayer between glass layers at a specific heat and pressure. The most common interlayer used in a lamination process is polyvinyl butyral. Laminated glass provides safety in the event of breaking. When the glass unit breaks, the fragments of the unit keep connected because of the adhesion property of the interlayer. In the moment of fracture, the outer glass layer fractures while the inner one remains unfractured. This property of laminated glass prevents injury and even death of people. Because of mentioned high safety features, laminated glass is finding wider application in the building industry day by day. Depend on the increasing usage of a laminated glass units, analyzing its breakage mechanism under impact loading and determining the effect of impact on the safety of it becomes an intriguing phenomenon for the researchers.

A failure is an undesirable event for engineering materials because of safety and economic reasons. Impact behavior and fracture toughness of materials are very important parameters used for design. Therefore, tests on the impact behavior of materials were established to define the fracture characteristics of the material and to prevent brittle failure of materials under dynamic loadings. Performing impact analysis provides much convenience about choosing materials for designers. The general purpose of the impact tests is to artificially apply the stress accumulation that will cause a brittle fracture in the materials to the base of the material during impact and to determine the resistance of the material against dynamic forces. The impact test gives information about the amount of energy required to break the sample under dynamic stress. For engineers, the amount of absorbed energy during ductile or brittle fractures is an important parameter used in the material selection process. Researchers perform Charpy impact test to determine the maximum fracture energies that the

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materials can withstand under dynamic loads or obtain information about the ductile or brittle behavior of the material by determining the amount of energy that can be absorbed at the moment of sudden impact. Charpy impact test which is one of the most common impact tests, is a reliable and low-cost test method. It provides information about energy consumed in the breakage of material when it is hammered by a swinging pendulum.

2. Previous research

In the architectural and automotive industry, the application of laminated glass units as a glazing material has been dominated especially in the last few decades. Due to its common usage, in civil, mechanical, and material engineering areas many studies have been carried about the behavior of laminated glass [22]. Studies about the dynamic behavior of laminated glasses have an important place among these studies. Therefore to analyze the dynamic behavior of laminated glass and to satisfy its safe and effective usage in building applications, many studies have been carried by researchers. Experimental and numerical studies about linear and nonlinear analysis of laminated glass subjected to blast [1-3] and impact loading [4-8] were performed by scientific researchers.

Timmel et al. [2] improved the explicit finite element model to investigate the attitude of laminated glass units under impact loading. To confirm the results of the finite element method model they conducted experiments.

Dharani et al. conducted numerical studies regarding the effect of glass ply geometry on the impact resistance of laminated glass [6] and nonlinear dynamic behavior of laminated glass units subjected to low velocity small hard missile impact [11].

Beason et al. [8] observed that outside glass ply in laminated units serves as an impact shield in the moment of impact. In their analysis, the outer ply is modeled as frangible while the inner ply is modeled as infrangible to provide enough strength.

Pelfrene et al. [9] applied the Hillerborg model to simulate the cracking of glass by element deletion. They observed that the hardness of the material decreased with the decrease in energy. Wang et al. [10] analyzed fracture stages of brittle glass units using four different numerical techniques based on discontinuum and continuum categories. They explained the restriction and applicability of low-velocity impact model developed for brittle materials. They used the results of conducted experiments to verify their results.

Researchers have conducted many efforts to acquire knowledge about the effect of interlayer type and thickness on the bending behavior of laminated glass units and develop glass lamination technology.[4,16-19]

Yuan et al. [4] conducted researches on the nonlinear behavior of rectangular laminated glass units subjected to low-velocity impact by applying first-order shear deformation theory. In addition, they carried out experiments on laminated glass units bonded by two different interlayers (PVB and SPG). As a result of their experiment, they concluded that as the interlayer material gets stiffer the contact force increases while the transverse displacement is decreasing.

In 2017 Castori and Speranzini [19] conducted four-point bending tests to determine bending behavior for elastic and post-critical phases in combination with finite element model to examine the structural behavior of laminated glass plate with PVB, SPG, EVA, and XLAB interlayers.

Vedrtnam and Pawar's research [18] consist in achieving both experimental and numerical studies to analyze the bending strength of laminated glass with different interlayer material and interlayer thickness. They observed that bending samples show maximum strength of laminated glass strongly depends on the interlayer type and interlayer thickness.

Wang et al. [17] conducted tests to analyze the impact behavior of SentryGlas®Plus subjected to low-velocity impact of a hard body. They observed while the effect of panel size has a limited effect on breakage energy, the interlayer thickness and the glass types used in the lamination process affect the impact behavior of the unit.

Zhang et al. [16] carried out experiments at different impact velocities to investigate low-velocity hard impact performance and the impact resistance properties of laminated glass bonded by four different interlayers.

Alsaed O. and Jalham I.S. [20] conducted theoretical and practical studies about the failure strength of laminated glass bonded with different interlayer thicknesses and materials as PVB or EVA.

Studies regarding glass thickness, interlayer type, and interlayer thickness on the amount of absorbed energy and load capacity were carried by Jalham I.S. and Alsead O. [21]. They observed that as the thickness of interlayer was increasing the load capacity of laminated glass units bonded by different interlayers decreased. Also the load capacity of laminated glass units bonded by EVA was observed as greater than that of bonded by PVB. It was also observed that as the thickness of the interlayer and glass plate was increasing the amount of absorbed energy increased.

Studies of the effect of temperature on the behavior of laminated glass units are limited [12,13,14]. Samieian et al. [12] conducted experiments on laminated glass units at a high strain rate to analyze the effect of temperature on their post cracking response. Tests are conducted between 0-60°C considering different interlayer thicknesses as 0.76mm, 1.52 mm, and 2.28mm. They came to the conclusion that the post-cracking behavior of laminated unit depends on the interlayer thickness and temperature. According to the knowledge of the author there is a gap in the literature about the effect of temperature on the impact behavior of laminated glass. Hooper et al. [13] analyzed dynamic behavior PVB and observed glassy behavior of it under 5-10°C. Bermbach et al. [14] performed a shock tube experiment on laminated glass units 13 and 30°C and obtained a higher strain and strain rate at 13°C.

It is clear from the above-mentioned studies that researchers focused on studies about the strength and impact behavior of laminated glasses with different bonding interlayer material and different geometries. Furthermore, the main bonding material in these studies is PVB. This investigation differs from the above-mentioned ones in that it concentrates on how the temperature affects the impact behavior of laminated glass. The aim of the study is to examine the influence of temperature on the impact energy absorption of laminated glass samples with different interlayer geometry and interlayer material. For this purpose, experimental tests were performed on samples subjected to different temperatures. Then, in the light of the experimental data obtained, the impact absorption energies of the samples with different glass ply geometries were calculated numerically. In addition, von Mises stress distributions and the amount of deformation depending on the time are presented in graphs. In numerical analysis, samples and supports were modeled in three dimensions in ABAQUS package program. After the necessary boundary conditions and contact parameters were defined, the analysis was carried out and the results were given in graphics in comparison with the experimental data.

In the following sections, the detailed representation of carried experiments are presented and the results of experiments are discussed in detail.

3. Experimental investigation. Charpy impact test.

The amount of absorbed energy may be obtained as a result of the impact test and it may be defined as the failure behavior of materials under high-velocity impact loading, which leads to sudden fracture and toughness. Since toughness or in other words the area under the stress-strain diagram is small for brittle material it may be concluded that the amount of absorbed energy is small for brittle materials. Due to the viscoelastic behavior and brittle-polymer composite structure of laminated glass, its mechanical attitude, especially under applied dynamic loadings, is reasonably complicated. So, experimental analyzes are very significant for the dynamic analysis of laminated glass units.

In the current study, a dynamic three-point bending experiment is conducted using Charpy device. Used Charpy device has 4 different pendulums at 4 different energy levels as 7.5J, 15J, 25J, and 50J. Pendulum speed is 3.8m / s. and starting angle is 150°. Pendulum moments measured for 7.5J, 15J, 25J, and 50J are 4.0192, 8.0385, 13.397, and 26.795 Nm, respectively. The device operates with 220 V energy and complies with ISO179, GB / T1043, GB1834, JB / T8762, ASTM D6110, ASTM 5942, and ISO9854 Standards. Before starting the experiment, samples were exposed to 3 hours standby temperatures at -5, -1.1, 10, 32.2, 48.9, and 60°C. A temperature cabin is used to bring the samples to the desired temperatures. It is Nuve branded and has a usable volume of 120 lt. Its temperature range is between -10°C and + 60°C and its humidity range is between 20-95% RH.

The experimental setup comprises the test specimen supported by the anvils and pendulum which is attached to a pinned rotating arm. The pendulum, which has a defined mass, hits the middle of the laminated glass test specimen following a circular path and transfers its kinetic energy to the specimen. In the current investigation, the mass of the pendulum hammer is 1.045 kg, the length of the swing arm is 30 cm and the impact velocity is 3.8 m/s. The laminated glass units consists of two glass sheets with a thickness of 5 mm and a polyvinyl butyral interlayer connects them. Two different interlayer thicknesses are investigated namely 1.52 mm and 0.76 mm. The length and width of specimens are 55 mm and 10 mm, respectively. The laminated glass units are given in Fig. 1. Tests are digitally recorded using a high-speed camera with a resolution of 1080×2240 pixels. Two laminated glass panels were supplied by Mutlu Cam Factory with glass thicknesses of 11.52 mm and 10.76 mm. The cutting of hundred test specimens, which are going to be used in the experimental investigation, is carried out by a high-pressure water jet from each panel.

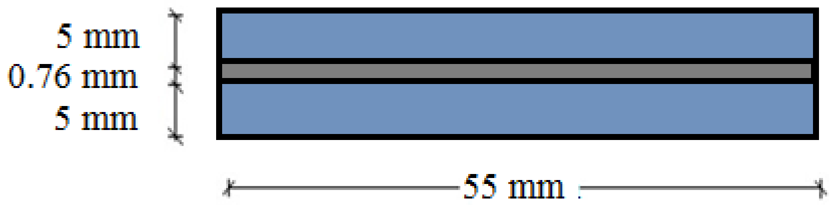


Fig. 1. Laminated glass units

The experiments are conducted at Adnan Menderes University Civil Engineering Laboratory at 22-23 degrees Celsius. The experimental setup is shown in Fig. 2. Before starting the experiment, the device was operated once or twice and it was checked whether there was any energy loss during the experiment. The correct placement of the samples in the experiment is very important. During the experiment, the pendulum is first raised to a height where it will have the potential energy detected earlier. After placing the sample, the material dimensions are arranged on the screen where the readings are, and made the indicator is brought to the initial state. In general, the impact value of the materials varies with temperature. Therefore, the ambient temperature is an important parameter in the experiment.

Fig. 2. Experimental setup

The 7.5 Joule pendulum is the swing from a fixed height and strikes the test specimen to show how brittle the laminated unit is. To apply simply supported boundary conditions the specimen is supported at its two ends on an anvil. The physical properties of specimens are given in Table 1. To start the experiment the pendulum is set up to its original position to have 300J. Then the specimen is placed in the support at the base of the tester. After placing the test specimen, the hammer is released and swung following its clear path. When the pendulum hits the specimen, it breaks. After each hit, the energy data from the dial is recorded to obtain the energy value which caused the specimen to break. The same procedure is applied with the test specimen having different interlayer thicknesses and of the temperatures -5, -1.1, 10, 32.2, 48.9, and 60°C.

The photos of laminated glass samples tested at 60°C are given in Fig. 3. The cracks can be observed close to the midpoint of samples. However, as can be seen from the photos, the adhesive interlayer keeps the glass layers together and does not break into pieces.

Fig. 3. Laminated glass specimens after impact

The geometry of unit, interlayer type, and temperature are considered to be the most important factors which have influence the attitude of laminated glass units under impact. In this study, the effect of interlayer thickness, interlayer type, and temperature are investigated. The experiments are conducted for two different interlayer thicknesses at six different temperatures in a range from -1.1°C to 60°C. Ten test specimens are used for each case. The mean and standard deviations of measurements are given in Figs. 4 and 5 for different interlayer thicknesses. The figures show that as the temperature increases the amount of energy decreases.

Table 1. Physical properties of laminated glass units and impactor

	Dimensions (mm)		Modulus	
	Thickness	Width	E	G
Glass 1	5	100	70 GPa	28.8 GPa
PVB	1.52	100	3000 kPa	1000 kPa
Glass 2	5	100	70 GPa	28.8 GPa

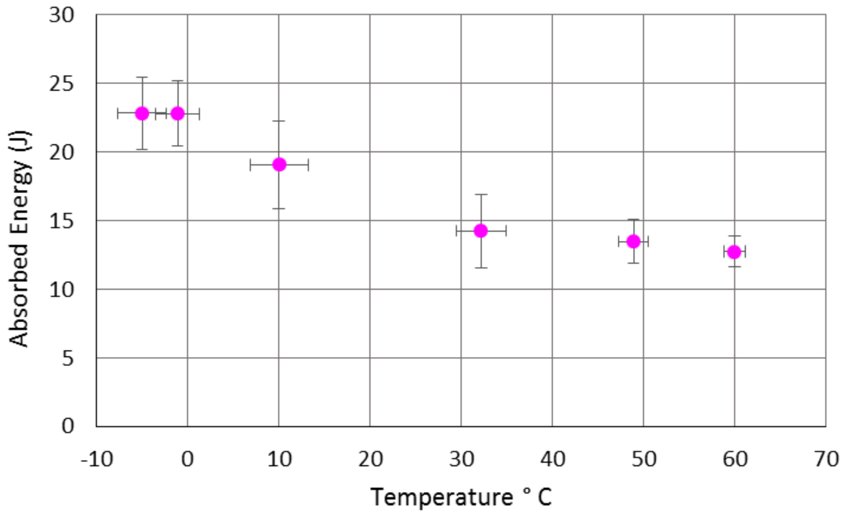


Fig. 4 Experimental results for 0.76 mm interlayer thickness

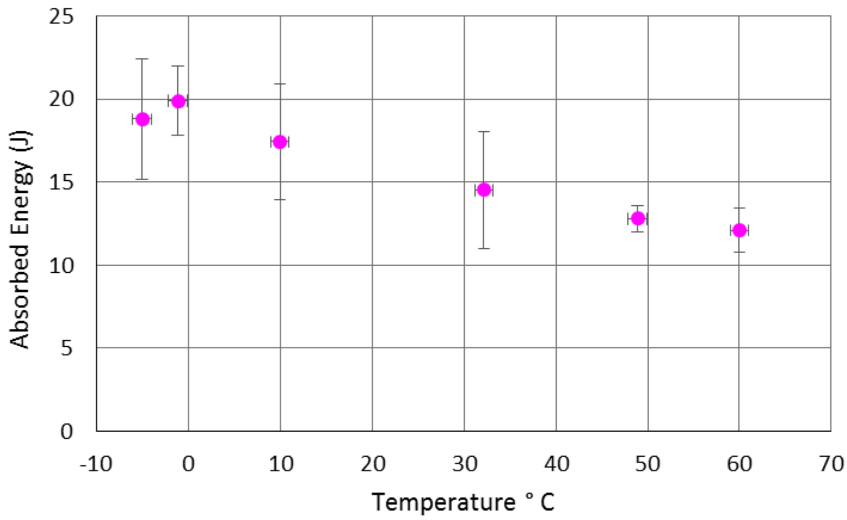


Fig. 5 Experimental results for 1.52 mm interlayer thickness

4. Finite element investigation

In order to compare the experimental results, the same problem is modeled using the finite element method. The three-dimensional finite element model is developed and solved with the finite element package program ABAQUS version 6.13-4. Time is an important parameter in impact problems since displacement, stress, force, energy dissipation and damage vary with time. For this reason, an explicit dynamic solution (ABAQUS/Explicit) strategy is selected. The model contains four parts as outer glass layer, inner glass layer, interlayer, and impactor.

Each of the parts is modeled separately. While the glass layers and interlayer are modeled as deformable; the impactor is modeled as rigid. A reference point is created on the impactor to assign the mass and velocity. The mass of the impactor is taken as 1.045 kg as in the experimental setup. To create boundary conditions of the impactor, translations of it in x and z directions are restricted and only the vertical translation is considered. The length of the laminated glass units is 550 mm and its width is 10 mm. Two different thicknesses are considered in the current study as 5+0.76+5 mm and 5+1.52+5 mm. The tie option is used to bond the layers of the unit perfectly. Modulus of elasticity of glass is taken to be 70 GPa and the Poisson's ratio of it is taken as 0.25. The density of the glass unit is 2500 kg / m2, the breaking stress is 30 MPa and Mode 1 breaking energy is 4 J. The density of the polyvinyl butyral intermediate layer is $1070\ kg/m^2$ while its Poisson ratio is 0.45. The interlayer is modeled viscoelastic. Viscoelastic material properties are given in Table 2.

Table 2. Viscoelasticity parameters of PVB

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

The temperature affects the behavior of the interlayer. The shear modulus of polyvinyl butyral increases as the temperature decreasing and decreases as the temperature increasing. The value of temperature which mechanical properties of materials show a vast amount of change may be defined as transition temperature, Tg. For polyvinyl butyral, the transition temperature is between 49 and 70°C. Below the transition temperature, the polymers are stiff, hard, and glassy while they are rubbery above the transition range. At room temperature, the PVB interlayer is hard, stiff, and glassy therefore the laminated unit is too brittle. Impact resistance and adherence of laminated unit increase by adding the plasticizers to the interlayer. Adding plasticizers to the interlayer causes to decrease transition temperature of it which is between -150°C and -50°C. The transition temperature is an important factor affecting the behavior of laminated glass since the stiffness of the interlayer experiences enormous change over the transition temperature. The behavior of the interlayer shows the vast amount of change over the transition and this affects the response of the laminated unit. Hooper [15] obtained temperature-shear modulus relations of polyvinyl butyral given in Table 3 and Fig. 6.

Table 3. Shear modulus of PVB with respect to temperature

T (°C)	G (MPa)
-1.1	45
4.4	25
10	8
15.6	2.5
21.1	1
26.7	0.57
32.2	0.52
37.8	0.47
43.3	0.42
48.9	0.37

To apply boundary conditions to the ends of the laminated unit the vertical displacement on all nodes along the end is set to be zero. The nonlinearity of the model is defined using large deformation analysis. To create mesh eight-node plane stress element (CPS8R) is used.

This meshing technique ensures faster convergence and more accurate results for large deformation analysis. The mesh size for the laminated glass units is 0.239 mm.

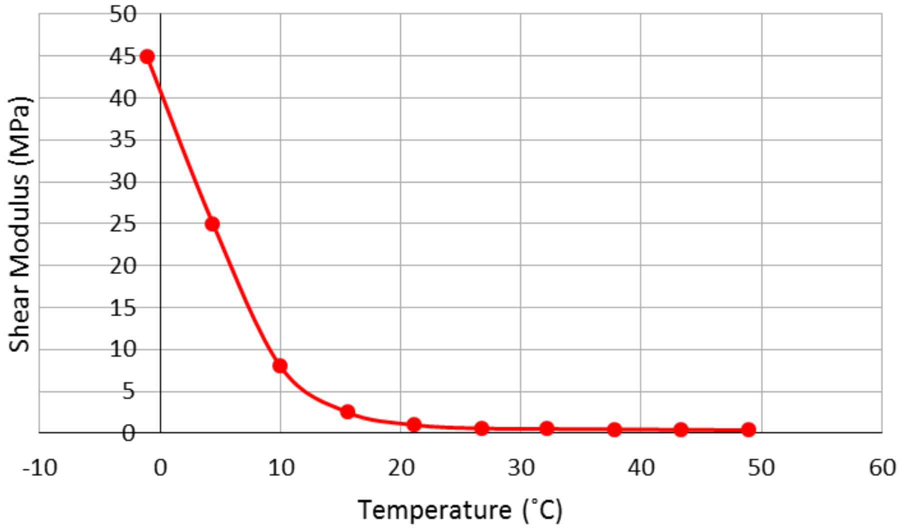


Fig. 6. Shear modulus versus temperature for PVB interlayer

To model the contact of beam and impactor, the surface to surface contact algorithm with penalty is chosen. The friction coefficient is chosen as 0.4. The impactor is assumed as the master surface while the glass surface is modeled as slave surface.

A comparison of experimental and finite element model results for laminated glass units are presented in Table 4 and Figs. 7 and 8 for 0.76 mm and 1.52 mm interlayer thickness, respectively. It is observed from Table 4 that no fundamental differences were found between the experimental and the numerical results. Maximum error (difference) between the amount of absorbed energies; is about 8.326 % for 0.76 mm interlayer thickness while it is about 7.752 % for 1.52 mm interlayer thickness. Experimental results are slightly higher than the numerical ones. A comparison of absorbed energy is presented in Fig. 7 for the considered 0.76 mm interlayer thickness. It is observed from the figure that except -1.1°C the absorbed energy in the experiment is higher than those in the finite element model. The absorbed energy values obtained from the experiment are slightly higher than those of developed finite element solutions. As can be seen from Figs. 7 and 8 the results are quite close to each other.

Table 4. Laminated glass absorbed energy values

Interlayer thickness=0.76 mm			
Temperature (°C)	Experimental Results(J)	ABAQUS Results(J)	Error (%)
-5	22.8425	21.751	4.778
-1.1	21.997	20.198	8.179
10	19.077	18.349	3.814
30	14.260	13,073	8.326
48.9	13.488	12.532	7.092
60	12.757	12.479	2.177
Interlayer thickness=1.52 mm			
Temperature	Experimental Results(J)	ABAQUS Results(J)	Error(%)
-5	18.794	18.712	0.434
-1.1	19.902	18.892	5.073
10	17.446	16.335	6.369
30	14.515	13.390	7.752
48.9	12.873	12.200	5.226
60	12.864	12.751	0.875

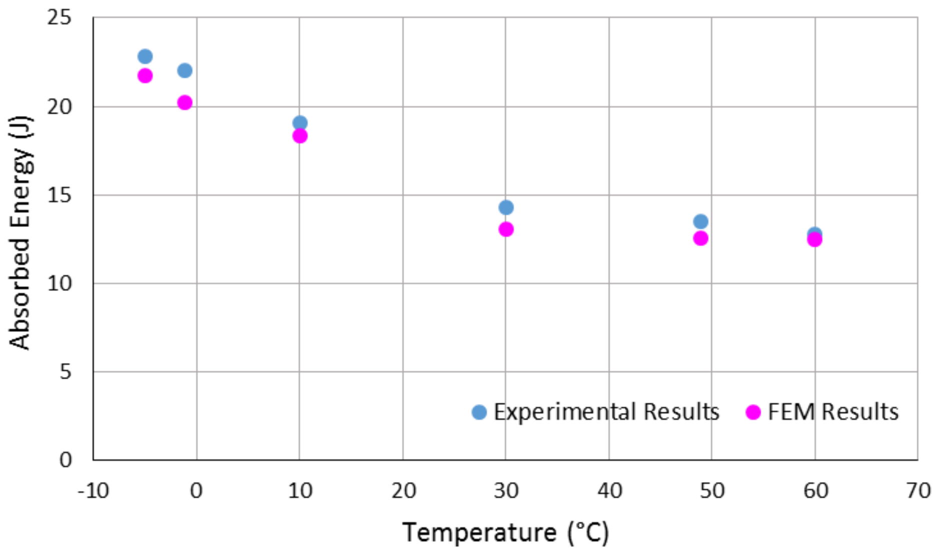


Fig. 7. Comparison of Experimental and FEM results for 0.76 mm interlayer thickness

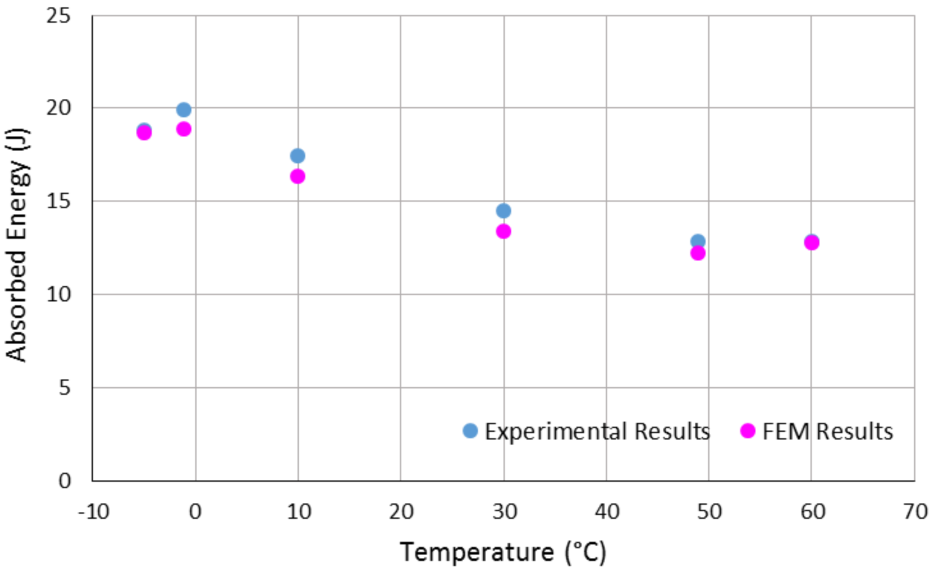


Fig. 8. Comparison of Experimental and FEM results for 1.52 mm interlayer thickness

There are different types of interlayers used in the laminated glass industry. To compare the effect of interlayer material on the dynamic behavior of laminated glass units two different types of the interlayer, ethylene-vinyl acetate film (EVA) and polyvinyl butyral (PVB), are analyzed in the current study. The density of EVA interlayer is 943 kg/m. While Poisson's ratio of EVA is 0.48, its Young Modulus is 15.7 MPa. The interlayer is modeled viscoelastic. Viscoelastic material properties are given in k1=g1=0.195, tau1=0.95. To consider the effect of interlayer thickness on the impact behavior of laminated glass units the finite element analysis is conducted for laminated glass units with interlayer thickness 0.76 and 1.52 mm. Figures 9 and 10 illustrate the comparison of absorbed energy amounts for the laminated unit with EVA (LG-EVA) and PVB (LG-EVA) interlayer. It is observed from the below figures that absorbed energy of 10.76 mm thick laminated glass unit which contains PVB as binding material are greater than those of containing EVA as binding material. In the case of 11.52 mm thick laminated glass, the situation is the opposite. Figures 11 and 12 present a comparison of interlayer thickness for LG-EVA and LG-PVB, respectively. It can be clearly seen that for both cases the amount of absorbed energy of laminated glass with a thickness of 10.76 mm is higher than that of 11.52 mm thick unit.

Strain energy versus velocity of laminated glass with different interlayer material and interlayer thickness is illustrated in Fig. 13. Strain energy values of laminated glass with 0.76 mm interlayer thickness are higher than those have 1.52 mm interlayer thickness.

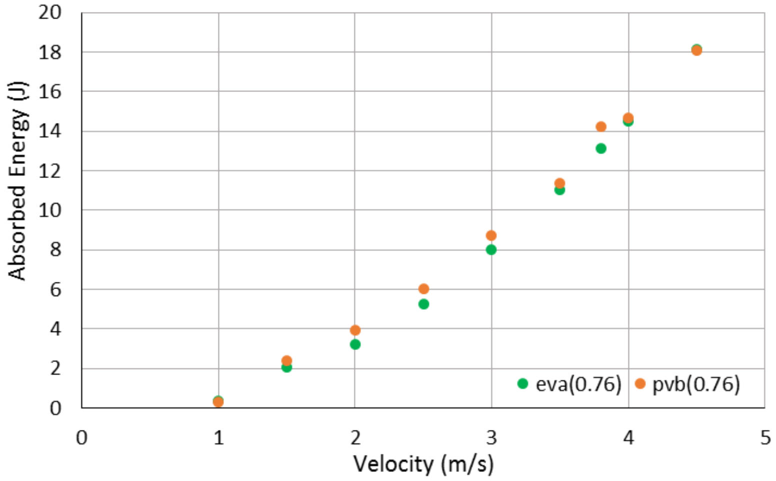


Fig. 9. Comparison of energies for 0.76 mm PVB and EVA interlayer energies

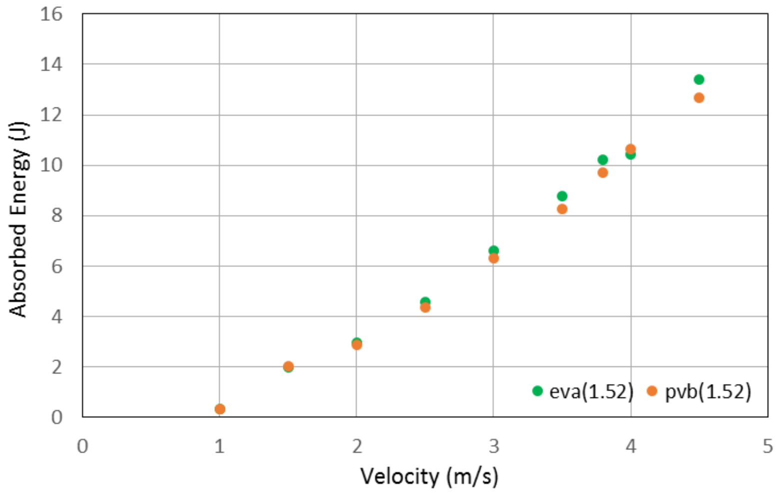


Fig. 10. Comparison of energies for 1.52 mm PVB and EVA interlayer

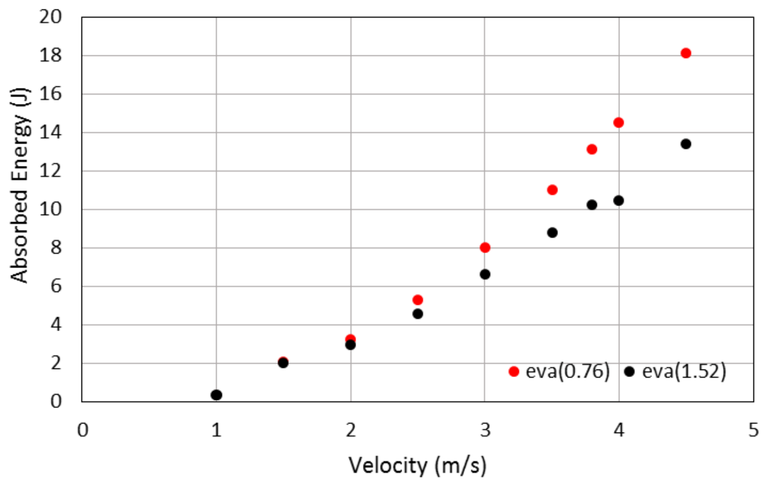


Fig. 11. Comparison of energies for one and two layers of EVA interlayer

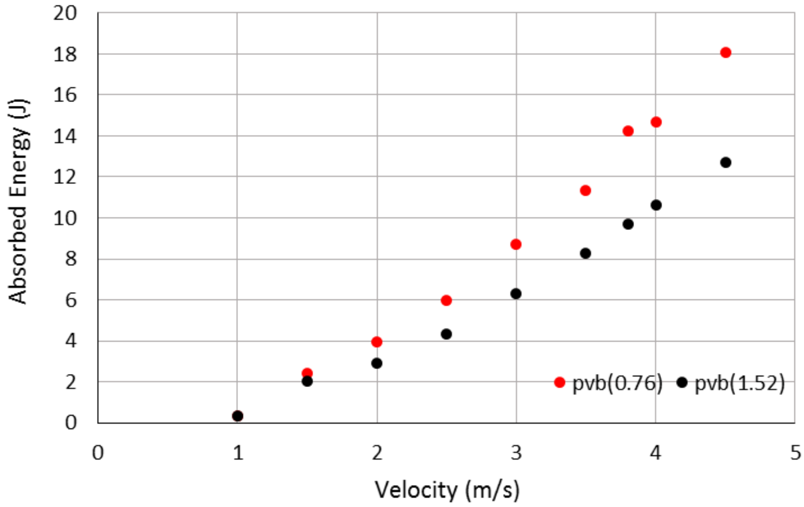


Fig. 12. Comparison of energies for one and two layers of PVB interlayer

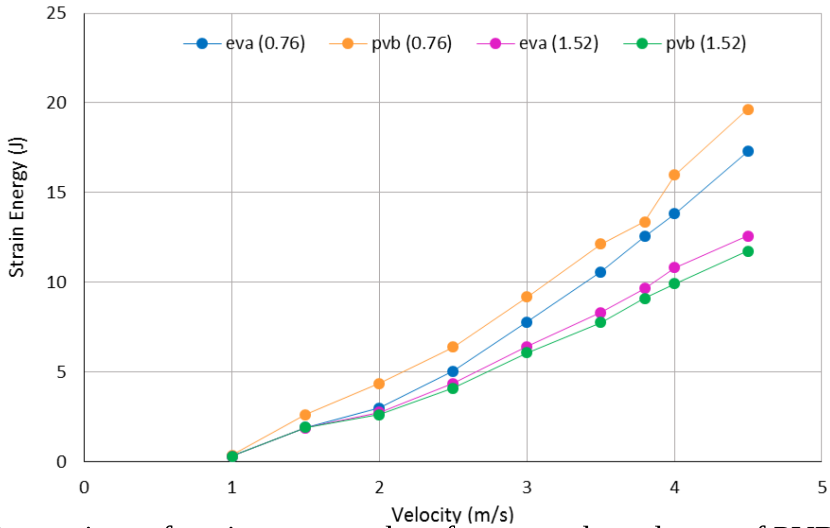


Fig. 13. Comparison of strain energy values for one and two layers of PVB and EVA

The contact force-displacement curves for different temperature values at the center of the laminated glass element are given in Fig. 14. It can be observed from Fig. 14 that bundles of curves with variable temperature values are within a narrow band between 20 and 60°C.

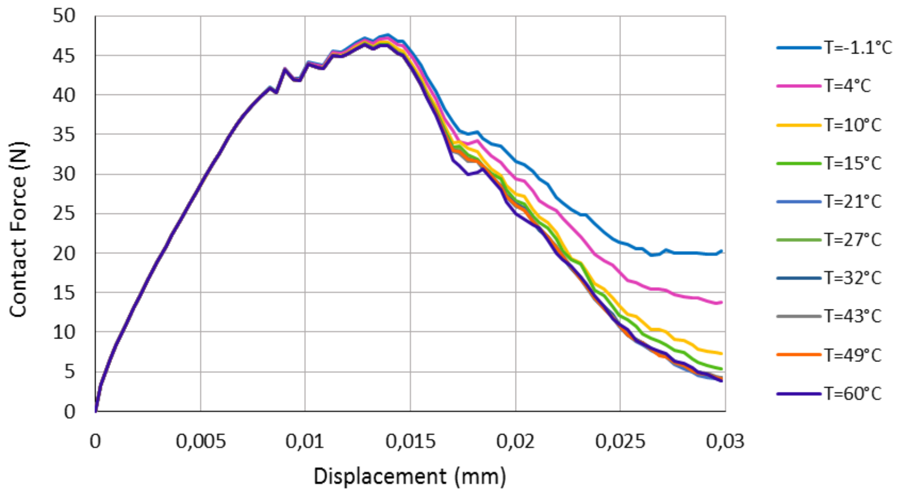


Fig. 14. Force-deflection curves

In order to investigate the effect of interlayer material on the von Mises stress, laminated glass units with PVB and EVA interlayers are analyzed at 20°C. The time history of Von Mises stresses at the center of the unit is illustrated in Fig. 15. As is seen in this figure, the Von Mises stresses of LG-EVA are higher than those of LG-PVB. The comparison of time histories of contact forces for different interlayers at the center of the laminated unit at 20°C is depicted in Fig. 16. We can see from this figure that laminated glass with EVA showed a higher contact force than laminated glass with PVB. As illustrated in Fig. 17, while under the room temperature the stress values show great amount of change, they are nearly the same at the room temperature.

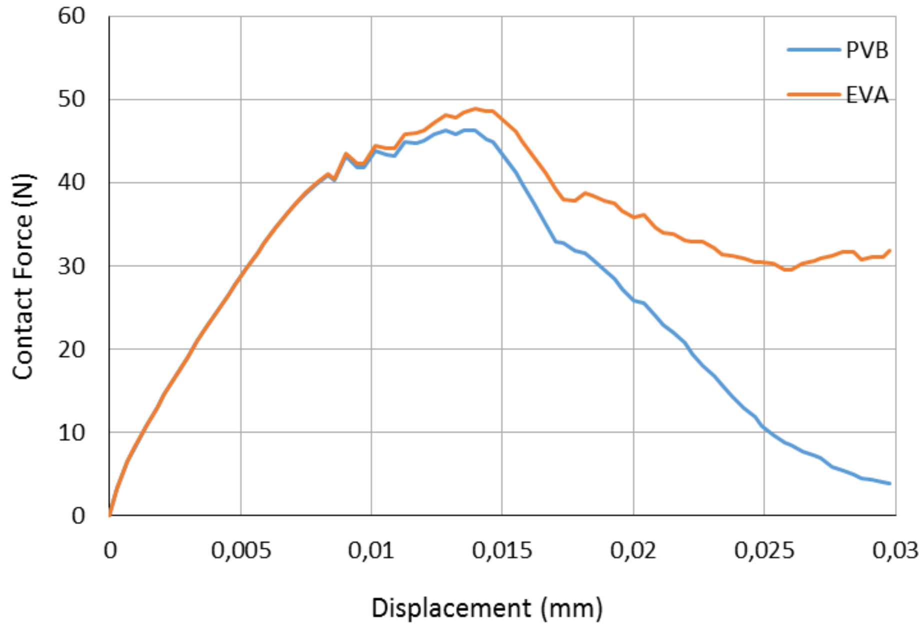


Fig. 15. Force-deflection curves of LG-EVA and LG-PVB

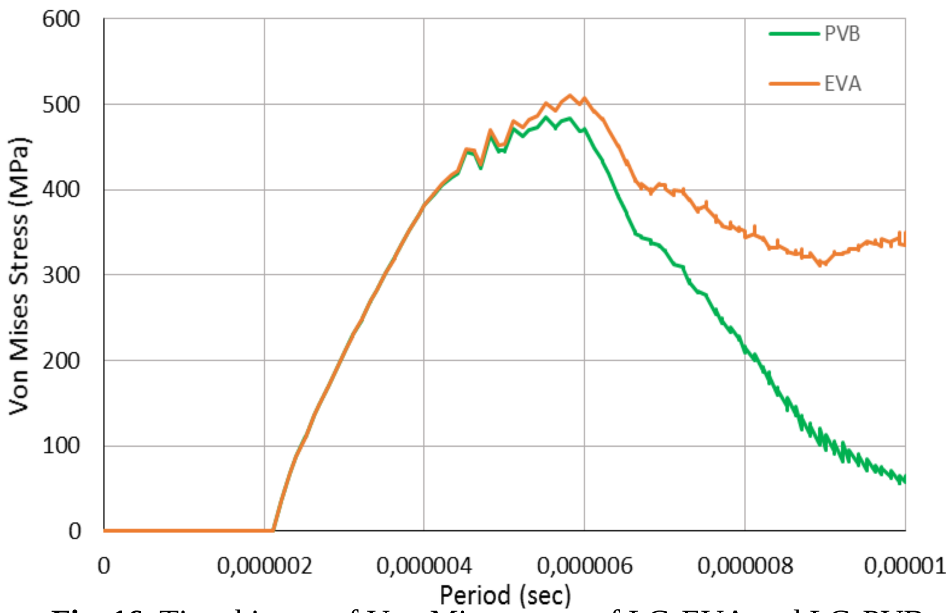


Fig. 16. Time history of Von Mises stress of LG-EVA and LG-PVB

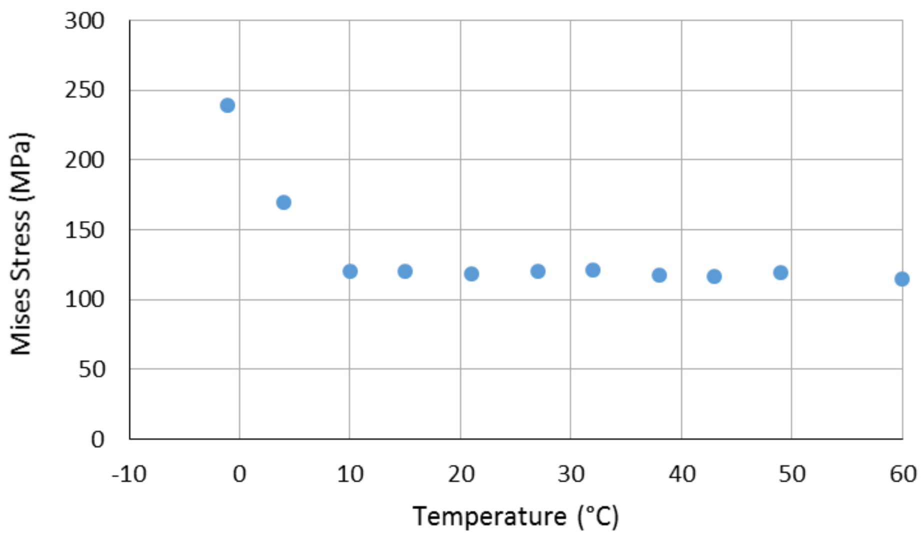


Fig. 17. Change of the Von Mises stress with different temperature values

Figures 18 and 19 demonstrate displacement in y- and z-direction, respectively. These figures demonstrate the behavior of the laminated glass units at 20 degrees centigrade. The layers are connected to each other by PVB interlayer.

The velocity of the impactor is 3.8 m/s. As can be seen from the figures the breakage occurs in the outer layer of the unit. Because of the adhesion property of the interlayer, the bottom unit stays unbroken. The vertical displacement takes their maximum value at the top surface of PVB interlayer. Figure 19 shows the front and back views of the unit. It is understood from the figure that the displacement in z-direction, takes its maximum value on the front surface of PVB interlayer and it takes its minimum value on the back surface of PVB interlayer. The effect of shear transferred by PVB interlayer is observable from Fig. 19.

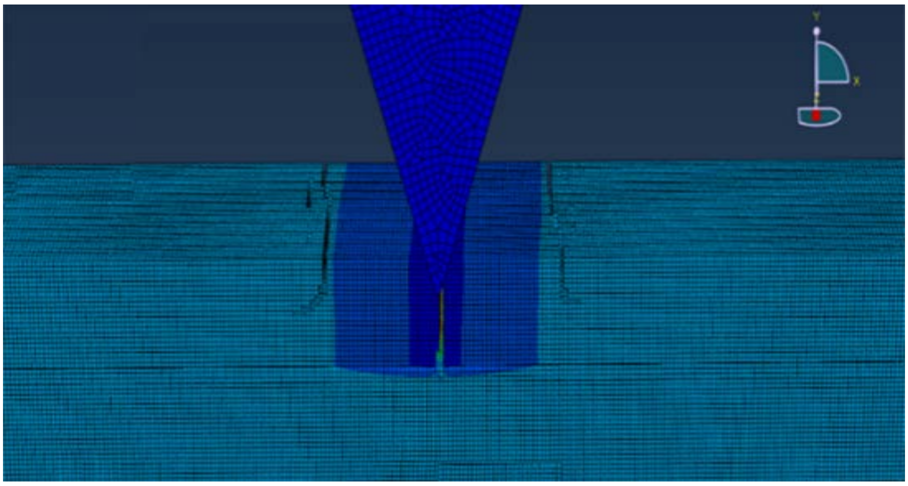
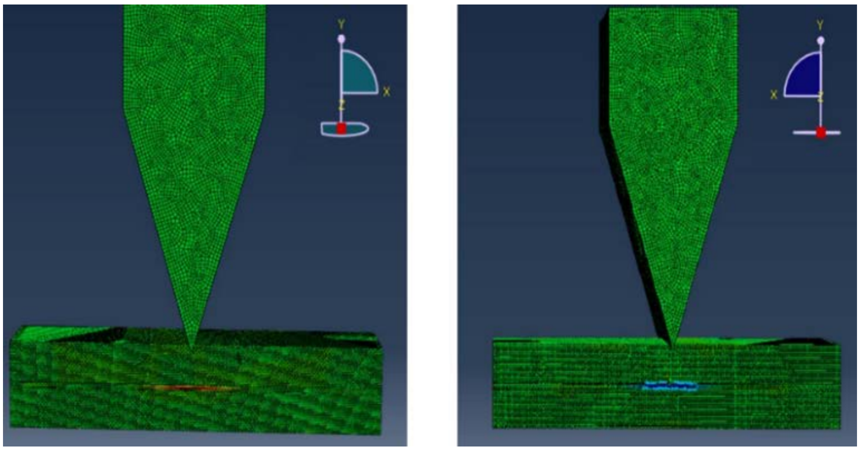


Fig. 18. A view of contours of lateral displacement obtained from ABAQUS for laminated glass units



(a) **(b)**

Fig. 19. A view of contours of displacement in z-direction obtained from ABAQUS for laminated glass units. a) Front view, b) Back view

Figure 20 shows the maximum stress distribution of the laminated glass unit. The deformation process of Von Mises stress is illustrated in Fig. 21. As can be seen from the figures the breakage starts from the bottom surface of the top glass layer and crack spreads in an upward direction. Then two other crack develops on the top surface of the unit and they spread towards the interlayer. It is clear from the figure that Von Mises stress takes its maximum value on the top surface of the outer glass layer. The maximum stress develops at the center of the unit where the impactor is hitting.

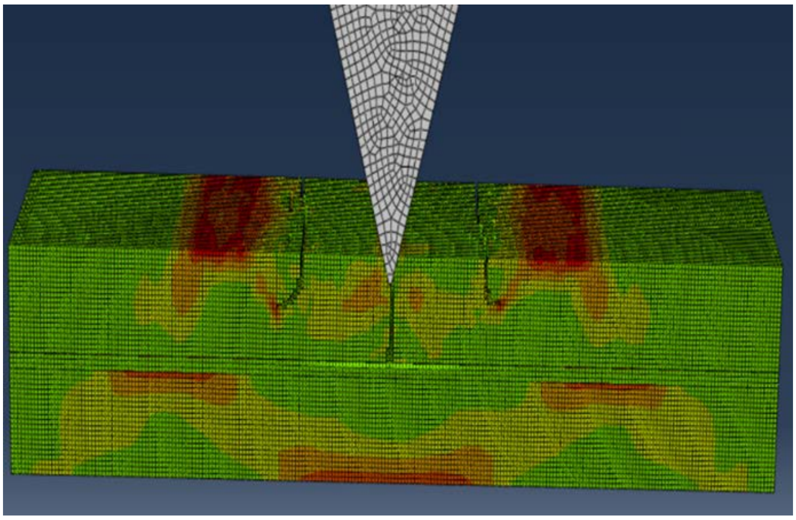


Fig. 20. A view of contours of maximum stress obtained from ABAQUS for laminated glass units

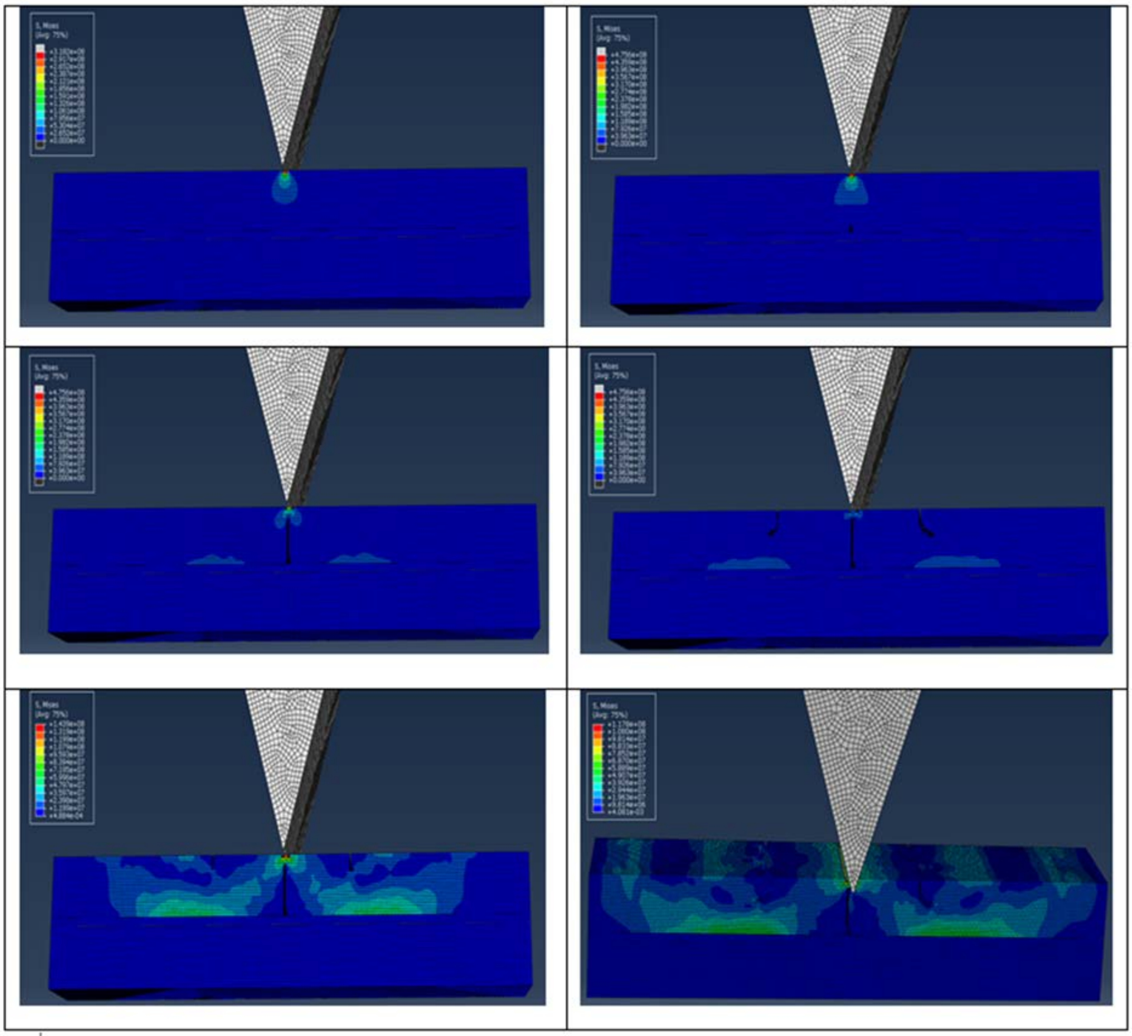


Fig.21. Crack propagation of Von Mises stress

5. Conclusion

The goal of this study is, to experimentally determine the influence of several factors like the interlayer thickness, the interlayer material, and the temperature effect on the dynamic behavior of laminated glass by means of Charpy impact test. Two types of test samples, which contain glass layers combined with one or two layers of PVB were used in the experiments. Parameters like the temperature and the interlayer thickness were investigated. The experimental results were compared by the developed finite element model results. The results are quite close to each other as can be seen in Figs. 7 and 8. It is observed that as the temperature is increasing, the amount of absorbed energy is decreasing.

Polyvinyl butyral films are the most preferred interlayers in the laminated glass industry. Studies are underway on new intermediate layers that will be alternatives to PVB. EVA is one of these alternatives. Studies of the fracture analysis of laminated glass, connected by different interlayer films, are limited. For this reason, in the current study, the laminated glass which contains EVA as the interlayer material is modeled using a finite element package program and the results are compared by those combined by PVB.

The analysis shows that as the thickness of the interlayer is increasing the amount of absorbed energy decreases for both types of interlayers. There is no obvious difference between the amount of absorbed energy values for EVA and PVB interlayers. From the analysis and experiment, it is concluded that the interlayer in the laminated unit prevents the fracture of the inner glass layer. It is also observed that the developed finite element model and conducted experiments proved that PVB and EVA interlayers showed good performance against fracture. It is also observed that laminated glasses are exposed to large deformation. In the moment of breakage, the glass fragments remain attached to the interlayer and this makes laminated glass several times stronger than monolithic glass.

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