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The Effect of Glass Plate Thickness and Type and Thickness of the Bonding Interlayer on the Mechanical Behavior of Laminated Glass

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ABSTRACT

In this work the effect of the type of the bonding interlayer (polyvinyl butyral (PVB) or Ethyl Vinyl Acetate (EVA)), number of bonding layers, and the position and the thickness of the Glass plates on the maximum load capacity and absorbed energy by laminated glass. Furthermore, this investigation presents a mathematical model that relates the maximum force capacity of the glass laminated structure to the glass plate thickness, type and thickness of the interlayer regardless the position of the fixed glass plate. Both practical work results and the theoretical model indicate that the maximum load capacity of laminated glass bonded with either PVB or EVA decreases as the interlayer thickness increases. Moreover, the maximum load capacity for the glasses bonded with EVA is greater than those for the PVB bonded ones under the same conditions. On the other hand, it was observed that that laminated glass absorbed energy increases with the increase of the interlayer thickness and the increase of glass plate thickness.

***Keywords**: Laminated Glass, Polyvinyl Butyral (PVB), Ethyl Vinyl Acetate (EVA), Layer, Load Capacity*

1. Introduction

Ceramics and glasses, which have strong ionic-covalent chemical bonds, are very strong and stiff. They are also resistant to high temperatures and corrosion, but are brittle and prone to failure at ambient temperatures. In contrast, thermoplastic polymers such as polyvinyl butyral, which have weak secondary bonds between long chain molecules, exhibit low strength, low stiffness, and a susceptibility to creep at ambient temperatures. These polymers, however, tend to be extremely ductile at ambient temperatures. When combine glass and polymer to form a laminated glass, some change in the maximum load capacity will occur, which depends on both the glass and polymer type. This led to investigate how the glass thickness and the type and number of laminated interlayer affect the maximum load capacity of laminated glass as well as their effect on the absorbed energy.

2. Literature Review

Laminated glass consists of two or more glass plies bonded together with an elastomeric interlayer, usually polyvinyl butyral (PVB) or Ethyl Vinyl Acetate (EVA). After breakage, the interlayer holds the resultant glass shards in place and, in most cases, the glass remains in the frame when laminated glass fractures. This post-breakage characteristic of laminated glass has made it desirable for use in vehicle windshields for decades because it makes the occupant safer from glass shards than other glazing materials.

The shear modulus studies were carried out by Quenett [1] and Hooper [2]. Quenett [1] noticed that when the interlayer thickness decreases, shear modulus increases and reported that the condition of the interlayer is a controlling factor in static bending and dynamic impact resistance. Hooper [2] confirmed the results of Quenett [1]. He stated that after testing glass beams in four points loading with varying temperatures and interlayer hardness, he found that the shear modulus of the interlayer is inversely proportional to the interlayer thickness and also mentioned that plasticizer contents, ambient temperatures, and load durations are the primary factors controlling bending resistance of laminated glass. He attributed this behavior to the "thermoplastic" nature of the interlayer, stating the decreased bending stiffness was the primary disadvantage to architectural laminated glass.

Strength of the monolithic and laminated glasses taking into account the geometry and thickness of the tested plates was studied by several researchers. For example, Pilkington Ltd. [3] compared monolithic glass strength to the strength of laminated glass specimens made of sheet and float glass. They found that, at normal temperature, laminated glass specimens exhibit the same strength as monolithic glass specimens having the same rectangular dimensions and glass thicknesses. On the other hand, Linden *et al.* [4] conducted a non-destructive test on monolithic, layered, and laminated glass specimens instrumented with strain gages. They concluded that laminated glass strength and monolithic glass strength appeared to be equivalent at normal temperatures; and the strength of laminated glass specimens approached that of layered glass specimens at elevated temperatures. In addition, Norville [5] tested two laminated glass specimen of sizes 38 x 76 and 66 x 66 in. destructively. His destructive experimentation also showed that the strength of laminated glass specimens is the same or greater than that of monolithic specimens having the same rectangular dimensions and nominal thicknesses under similar load conditions.

Keller [6] used novel method to measure the delaminating energy in laminated glass in the relevant dynamic range. He found that increasing the interlayer thickness improves the penetration resistance of laminated glass because more energy can be absorbed in the high speed delimitation process since the interlayer is simply less like to tear.

In contrast to the results of the above mentioned researches contradiction was reported in Nagalla *et al.* [7]; Minor and Reznik [8]. Nagalla *et al.* [7] in their advanced theoretical work compared layered glass to monolithic. They discovered that some aspect ratios of the layered glass experienced lower principal stresses than monolithic glass subjected to uniform, transverse loading in some ranges of the loading. They concluded that the strength factor of 0.6 used by some building codes for laminated glass may be too low for many window geometries and design pressures.

Minor and Reznik [8] destructively tested three sizes of laminated glass specimens (33 x 66, 38 x 76, and 66 x 66 in.) with an 0.030 in. interlayer, and compared the resulting failure pressures to those from tests on monolithic glass specimens having the same rectangular dimensions and nominal glass thicknesses. They introduced four variables, which are: glass thickness, glass type, temperature, and damage to one plate of glass (*i.e.*, damage to tension or compression side). Their testing led to the following geral conclusions:

1) Laminated glass specimens tested at room temperature have approximately the same failure pressure as monolithic glass specimens having the same rectangular dimensions and nominal glass thicknesses;

2) As temperature increases laminated glass behavior migrates towards the layered glass model;

3) Laminated glass specimens having twice the nominal glass thickness of monolithic specimens display strength greater than or equal to twice the strength of the monolithic specimens.

Some researchers investigated the effect of temperature on the properties of glass. Linden *et al.* [9] conducted non-destructive testing on two different plate geometries. First, they tested the same plate geometry (60 x 96 x 1/4 in.) as used in the parent report to study load duration and temperature effects. Second, they tested a different geometry (55-1/8 x 57-1/8 x 3/8 in.) with two interlayer thicknesses (0.030 and 0.060 in.) to study the effects of interlayer thickness on strength and deflection. They conducted destructive tests on one plate geometry (60 x 96 x 1/4 in.) at room temperature and at 170°F. Perusal of their data indicates that while load duration and elevated temperatures acting individually reduce the structural rigidity of the laminated glass, the two factors do not interact, producing a greater combined reduction in laminated glass strength. Weller [10], Used experimental study to compare different interlayer materials in laminated glass in respect to their structural behaviour. The material properties above the verification temperature clearly showed the temperature dependency. The relaxation times fall with increasing temperature and the shear stress gets smaller.

Theoretical modeling of the glass behavior was also carried out by many researchers. Linden *et al.* [4] derived theoretical results through the finite difference solution and compared experimental and theoretical results. They concluded that the theoretical finite difference model for monolithic and layered glass appeared to be acceptable for the one glass plate geometry tested. Moreover, Behr and Kremr [11] used experimental validation of a mechanics-based finite element model for architectural laminated glass units subjected to low velocity and two gram projectile impacts. The impact situation models a scenario commonly observed during severe windstorms. This study confirmed the ability of an analytical finite element model to predict accurately the peak strains in representative architectural laminated glass units as a function of impact velocity. Correlations between peak radial strains computed using finite element analysis and those measured experimentally were close, with the average difference between analytical predictions and experimental data being 7.7%.

Zang *et al.* [12] investigation focused on the use of the 3D discrete element method to study the impact fracture problem of laminated glass. The glass and the (PVB) of laminated glass plane are discretized to uniform rigid spherical elements. This investigation showed that the accuracy of the 3D model and numerical analysis code are more validated in the elastic range by comparing with FEM.

Recently, Belies [13] compared (PVB) with stiffer and stronger interlayer Sentry Glass Plus (SGP). After breakage of both glass sheets the load decreased to a relatively low level (typically between 2 kN and 3 kN) before the broken glass pieces and interlayer started again to build up compressive and tensile stresses, respectively. Subsequently, the load slightly increased again and after reaching the maximum, it decreased significantly (to less then 0.3 kN). When subjected to in-plane bending (buckling prevented), the post breakage residual resistance is relatively poor for both interlayers, as illustrated above. The residual load-bearing capacity was very limited and far below the initial glass strength.

It is clear from the above review that the research work focused on the comparison between the strength of monolithic and laminated glases and did not take into consideration the bonding interlayer thickness, and the position and thickness of the glass plates. 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 glass thickness and the type and number of laminated interlayer affect the maximum load capacity of laminated glass as well as their effect on the absorbed energy.

Details for the preparation of the mullite ceramic tile (900 mm × 1800 mm × 5.5 mm) were reported in [4]. The raw materials were as follows: 50 wt% - 55 wt% fly ash, 30 wt% - 35 wt% pyrophyllite, 10 wt% - 15 wt% bauxite and 4 wt% AlF_3.

Microcrystal glass was a sort of borosilicate glass and the composition is shown in **Table 1**.

High purity silica, reagent grade boric acid, zinc oxide, sodium carbonate and yttrium oxide were used as source materials and mixed in the above ratios, ball milled and dried. Then, the mixture was ground in a platinum crucible and kept it at 1500˚C for 3 h. The molten glass transformed from the mixture at high temperature and underwent water quenching and a course of drying and ball milling to produce a glass power with an average size about 1 - 3 μm. These glass powder was distributed uniformly by distributor on the surface of mullite ceramic tile and its thickness was kept at 1.2 mm. Next, the covered tile was placed in a furnace for a second sintering at 1000˚C - 1200˚C, causing the glass powder to remelt, nucleate, crystallize and combinesolidly with the ceramic base. After cooling down to the room temperature, the large-size ultra-thin mullite glass ceramic tile was prepared finally.

3. Materials, Equipment, and Experimental Procedure

3.1. Material

The materials used in this investigation are float glass plates, and Polyvinyl Butyral (PVB) and Ethylene Vinyl Acetate (EVA) as interlayer materials. The maximum force capacity and the amount of the absorbed energy of the laminated glass were determined for the input variables that are summarized in **Tables 1-4** below. **Figure 1** shows the schematic diagram for the assembly of the glass plates and interlayer.

3.2. Equipment

Equipment used in this investigation are Glass cutting machine of BSJ-NL3725 type, Bend testing machine of OUTOGRAPH AG—1S type, and Charpy testing machine.

3.3. Experimental Procedure

Testing procedure can be summarized as follows:

1) Cutting plates of 40 cm x 30 cm from glass panels of 4 mm, 6 mm , 8 mm, 10 mm, 12 mm thicknesses. The sharp cut edges have been broken off or beveled with a grinding tool;

2) Manufacturing of PVB-laminated glass. It comprises the washing and drying of individual glass sheets, laying the PVB film between the two glass sheets by using roller process, and heating and pressing the assembly.

An assembly full-surface bond is created in an autoclave using temperatures of about 140°C and pressure of about 150 psi. The interlayer becomes a viscous at this temperature and pressure, and any remaining air dissolves into the laminate layer;

3) Manufacturing of EVA laminated glass. It comprises the washing and drying of individual glass sheets, laying the EVA film between the two glass sheets by using roller process, and the assembly is headed in single stage lamination process (vacuum with integrated heating and cooling in the same apparatus);

4) Cutting of the manufactured laminated glass to the required size by using the cutting machine. For point bend test, the rectangular sheets dimension is 80 mm x 300 mm while for Charpy test, the rectangular sheets di-

Table 1. PVB samples for bending and Charpy impact tests (the outer plates and interlayer thickness changeable).

One interlayer		Four interlayers		Six interlayers	
Inner plate (mm)	Outer plate (mm)	Inner plate (mm)	Outer plate (mm)	Inner plate (mm)	Outer plate (mm)
4	4	4	4	4	4
4	6	4	6	4	6
4	8	4	8	4	8
4	10	4	10	4	10
4	12	4	12	4	12

Table 2. PVB samples for bending and Charpy impact tests (the inner plates and interlayer thickness changeable).

One interlayer		Four interlayers		Six interlayers	
Inner plate (mm)	Outer plate (mm)	Inner plate (mm)	Inner plate (mm)	Outer plate (mm)	Inner plate (mm)
4	4	4	4	4	4
6	4	6	4	6	4
8	4	8	4	8	4
10	4	10	4	10	4
12	4	12	4	12	4

Table 3. EVA samples for bending and Charpy impact tests (the outer plates and interlayer thickness changeable).

One interlayer		One interlayer		One interlayer	
Inner plate (mm)	Inner plate (mm)	Inner plate (mm)	Inner plate (mm)	Inner plate (mm)	Inner plate (mm)
4	4	4	4	4	4
4	6	4	6	4	6
4	8	4	8	4	8
4	10	4	10	4	10
4	12	4	12	4	12

Table 4. EVA samples for bending and Charpy impact tests (the inner plates and interlayer thickness changeable).

One interlayer		One interlayer		One interlayer	
Inner plate (mm)	Inner plate (mm)	Inner plate (mm)	Inner plate (mm)	Inner plate (mm)	Inner plate (mm)
4	4	4	4	4	4
6	4	6	4	6	4
8	4	8	4	8	4
10	4	10	4	10	4
12	4	12	4	12	4

mension is 80 mm x 300 mm.

4. Results and Discussion

As stated before, the maximum force capacity and the amount of the absorbed energy of the laminated glass were determined for the input variables that are summarized in **Tables 1-4** for the assembly shown in **Figure1**. The outer surface is the one in contact with the force while the inner surface is that locates on the other side from the force. Results and discussions of the investigation will be briefed in the following sections.

4.1. Load Capacity (Force) and Absorbed Energy

It is clear from **Figure 2** that the higher the thickness (number) of interlayer, the less the maximum load capac-

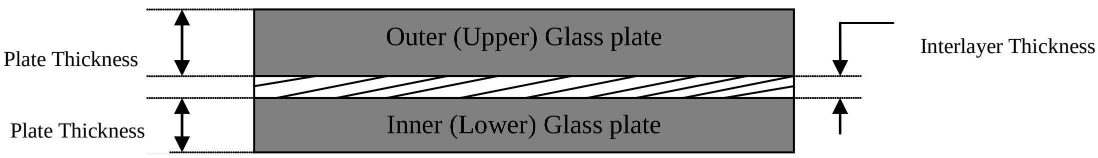


Figure 1. Schematic diagram for the assembly of the glass plates and interlayer. Outer glass is the one in contact with the applied force.

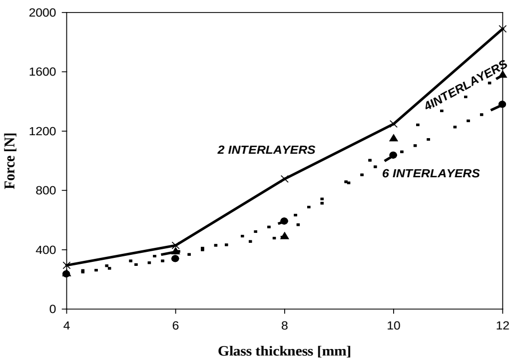


Figure 2. Testing the maximum force on (PVB) laminated glass where the thickness of inner plate was fixed and the outer plate was fixed and the outer plate and interlayer were changeable.

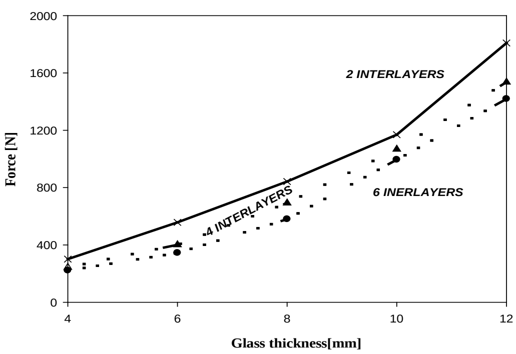


Figure 3. Testing the maximum force on (PVB) laminated glass where the thickness of outer plate was fixed and the inner plate was fixed and the inner plate and interlayer were changeable.

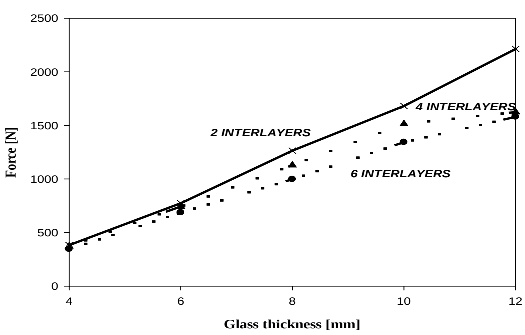


Figure 4. Testing the maximum force on (EVA) laminated glass where the thickness of inner plate was fixed and the outer plate and interlayer were changeable.

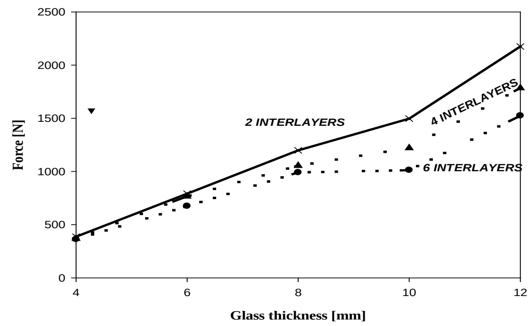


Figure 5. Testing the maximum force on (EVA) laminated glass where the thickness of outer plate was fixed and the outer plate and interlayer were changeable.

ity of the laminated glass bonded with PVB material for the fixed thickness of the inner glass plate. This load capacity is a characteristic strength from Weibull strength distribution. The same behavior can be observed for the laminated glass bonded with the same material although the fixed thickness is the thickness of the outer glass plate (**Figure 3**). The same trends also can be observed for the laminated glass bonded with EVA (**Figures 4** and **5**). The trend of these results is in agreement with the shear modulus results reported by Quentt [1], Hooper [2], and the predictions of Zang *et al.* [12]. On the other hand, they contradict with the results of Minor and Reznik [8].

Figure 6 shows that the position of the plate of the fixed thickness does not affect the maximum load capacity and the maximum load capacity for laminated glasses bonded with EVA is greater than that for the ones bonded with PVB provided that the same conditions are maintained.

The absorbed energy shows an opposite effect. For example, **Figure 7** shows that the higher the thickness (number) of bonding interlayer, the higher the amount of the absorbed energy. Moreover, the laminated glass which is bonded with PVB absorbs more energy than those bonded with EVA. The trends in these results are in agreement with the results of Keller [6].

An interesting behavior is shown in **Figure 2** when the outer thickness of the outer glass is 6 mm. In this case, the maximum load capacity for the 4 interlayer is less than that for the laminated glass bonded with 6 interlay-

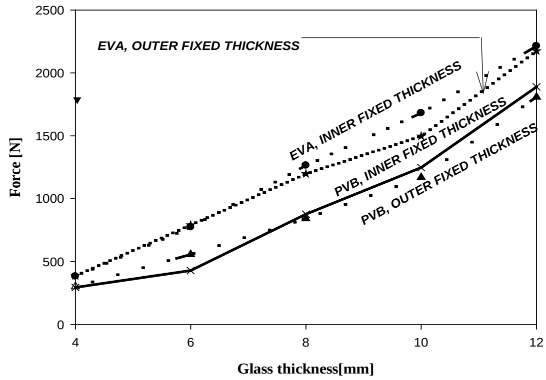


Figure 6. Comparison of the maximum load capacity for the 2 or fixed interlayer thickness, variable bonding material, and different positions of glass thicknesses.

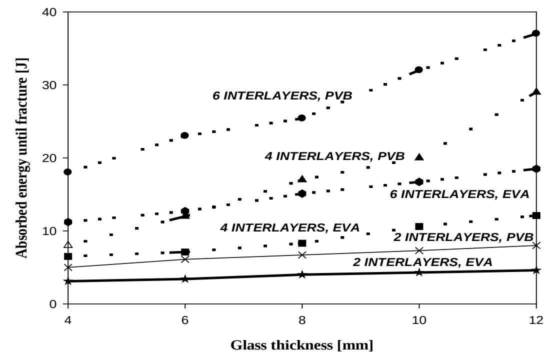


Figure 7. Absorbed energy until fracture by Charpy impact test when the inner thickness is variable and the bonding material is PVB and EVA.

ers. Furthermore, the amount of absorbed energy the laminated glass of 4 mm thickness and 6 bonding inter layer of EVA is greater than that for 4 interlayers boded with PVB for the same thickness. These interactions worth more investigations in the future.

4.2. Modeling of the Maximum Load Capacity (Force) and the Absorbed Energy

The maximum load capacity of glass and its absorbed energy are very important in real life applications. For example, high rise buildings or some open areas are exposed to a high impact wind forces. To be able to find the suitable glass to resist the forces and help in absorbing higher energy, it is of a great importance to select the suitable glass. As it was noticed before, there is a contradiction in the results when comparing the maximum load capacity and the amount of absorbed energy. To overcome this, the modeling took place for the maximum load capacity and the amount of absorbed energy separately depending on the thickness of glass and the thickness of the bonding interlayer regardless the position of glass plates. The modeling of the interaction of the maximum load capacity and the amount of absorbed energy will be considered in our future investigation.

The modeling tool used in this investigation was multiple regressions with the help of minitab software. Four relationships were determined because the measured results of failure strength and absorbed energy till failure upon impact is different due to the visco-elastic damping of interlayer. These are:

1) The maximum load capacity as a dependent variable and thickness of glass and the thickness of the PVB bonding interlayer as independent variables.

2) The amount of absorbed energy as a dependent variable and thickness of glass and the thickness of the PVB bonding interlayer as independent variables.

3) The maximum load capacity as a dependent variable and thickness of glass and the thickness of the EVA bonding interlayer as independent variables.

4) The amount of absorbed energy as a dependent variable and thickness of glass and the thickness of the EVA bonding interlayer as independent variables.

The multiple linear regression assumes that the variable response is a linear function of the model parameters and there are more than one independent variable in the model.

The general form of the developed model may be written:

$$y = \alpha + \beta x_1 + \gamma x_2 \tag{1}$$

where

y: is dependent variable (Max bending force or Max absorbed energy);

α, β, γ: are regression coefficients;

x_1, x_2: are the thickness of glass and the interlayer glass thicknesses respectively.

After running the minitab software, the results can be summarized as follows:

1) The equation that relates the maximum load capacity (y) as a dependent variable and thickness of glass (x_1) and the thickness of the PVB bonding interlayer (x_2) as independent variables is:

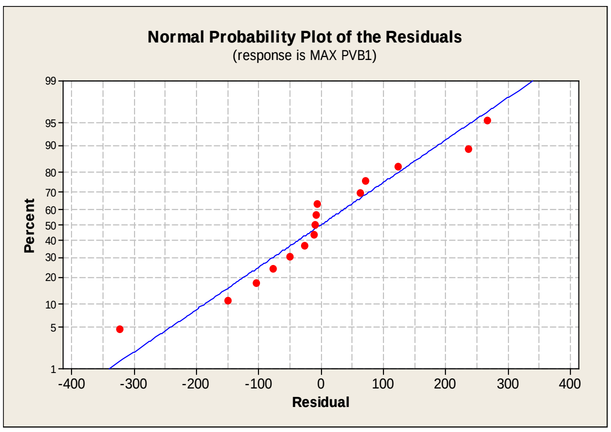
$$\text{Maximum load capacity (PVC)} = -348 + 174x_1 - 58.3x_2 \tag{2}$$

The observations, which were described by this relationship, are independent random variable as can be seen on **Figure 8(a)** as this figure presents the normal percent probability of the residuals and the plot points lie along a straight line. So, the hypothesized distribution adequately describe data and the model is appropriate. Furthermore, the model explains about 91.5% of the variability of the process because the adjusted R-sq = 91.5%. The analysis of variance of the process shows that the results are extremely significant as the P-value is about zero. The benefits of this equation can be seen clearly when applied to real life cases. To find the suitable laminated glass with dependent variables x_1(thickness of glass) and x_2 (the thickness of the PVB bonding interlayer) that can resist the external force (wind force as an example), the variable x_1 can be changed as it is the only variable that has a positive sign.

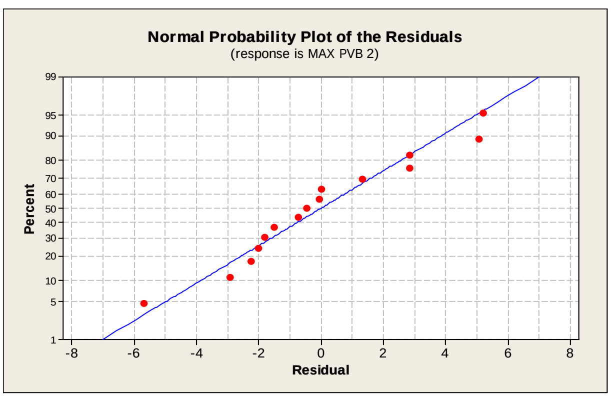
2) The equation that relates the amount of absorbed energy as a dependent variable and thickness of glass (x_1) and the thickness of the PVB bonding interlayer (x_2) as independent variables is:

$$\text{Amount of absorbed energy (PVB)} = -17.4 + 5.12x_1 + 1.74x_2 \quad (3)$$

Figure 8(b) presents the normal percent probability of the residuals and shows that the observations are independent random variable and follow the normal distribution. Moreover, the model explains about 90.3% of the

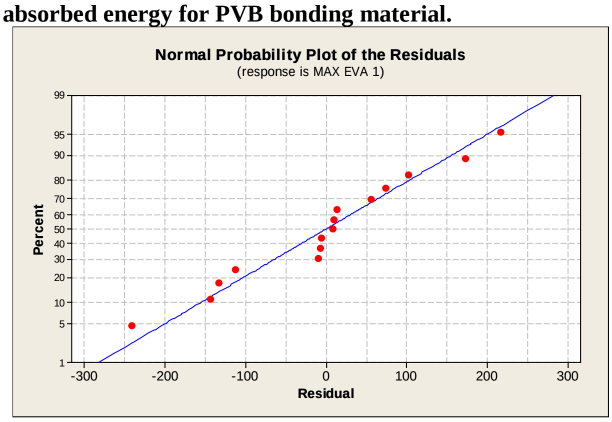


(a)

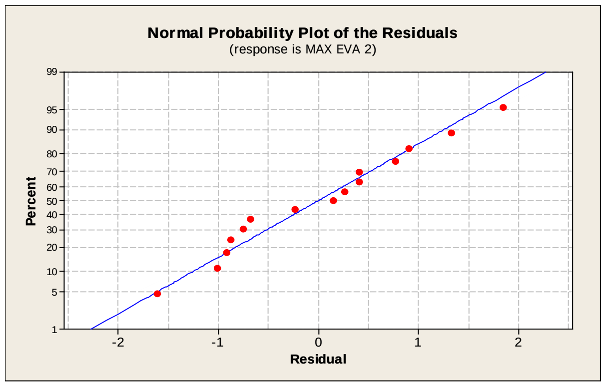


(b)

Figure 8. Normal probability plot of residuals of (a) the maximum load capacity relationship and (b) amount of absorbed energy for PVB bonding material.



(a)



(b)

Figure 9. Normal probability plot of residuals of (a) the maximum load capacity relationship and (b) amount of absorbed energy for EVA bonding material.

variability of the process because the adjusted R-sq = 90.3%. The analysis of variance of the process shows that the results are extremely significant as the P-value is about zero. To find the suitable laminated glass with dependent variables x_1 (thickness of glass) and x_2 (the thickness of the PVB bonding interlayer) that can absorb the highest amount of energy until fracture, the variables $x_1$and x_2 can be changed.

3) The equation that relates the maximum load capacity as a dependent variable and thickness of glass (x_1) and the thickness of the EVA bonding interlayer (x_2) as independent variables is:

$$\text{Maximum load capacity (EVA)} = -88 + 185x_1 - 68.3x_2 \quad (4)$$

Figure 9(a) presents the normal percent probability of the residuals and shoes that the observations are drawn from independent variables and the standard deviation and the variance of both populations are equal as the plot points shows that the data follows a normal distribution. Also the model explains about 94.7% of the variability of the process because the adjusted R-sq = 94.7%. The analysis of variance of the process shows that the results are extremely significant as the P-value is about zero.

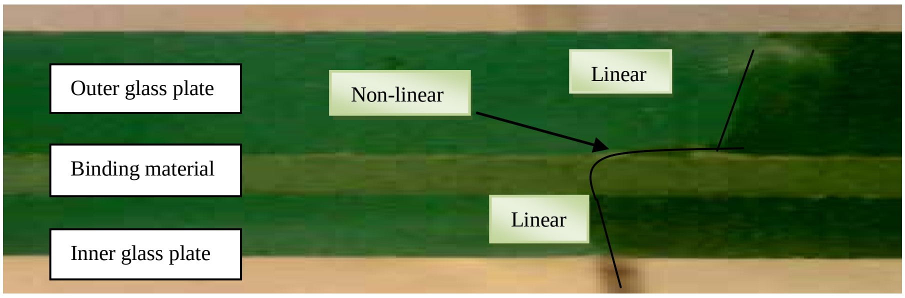


Figure 10. Failure observed after bending test (side view).

Figure 11. Failure observed after bending test (top view).

Figure 12. Failure after Charpy test.

4) The equation that relates the amount of absorbed energy as a dependent variable and thickness of glass (x_1) and the thickness of the EVA bonding interlayer (x_2) as independent variables is:

$$\text{Amount of absorbed energy (EVA)} = -6.71 + 2.74x_1 + 0.620x_2 \quad (5)$$

Figure 9(b) presents the normal percent probability of the residuals. The plot points show that the process data followed a normal distribution and the observations are independent random variable. Moreover, the model explains about 95.7% of the variability of the process because the adjusted R-sq = 95.7%. The analysis of variance of the process shows that the results are extremely significant as the P-value is about zero.

4.3. Failure Observation

Bending test took place until fracture. Then the fractured surface was analyzed. It was found that the propagation of fracture was linear within the glass plate and non linear within the bonding polymer as seen in the side view (**Figure 10**). This difference may be due to the thermoplastic nature of the bonding material which was described by Hooper [2]. The top view in **Figure 11** shows the linear nature of propagation within the brittle glass AND **Figure 12** shows the failure after Charpy test.

5. Conclusions

The conclusions that can be drawn from this investigation are:

1) The higher the thickness of interlayer, the less the maximum load capacity of the laminated glass bonded whether with PVB or EVA bonding material for the fixed thickness of the inner glass plate

2) The position of the plate of the fixed thickness does not affect the maximum load capacity and the maximum load capacity for laminated glasses bonded with EVA is greater than that for the ones bonded with PVB provided that the same conditions are maintained

3) The higher the thickness of bonding interlayer, the higher the amount of the absorbed energy whether the laminated glass bonded with PVB or EVA bonding material. Moreover, the laminated glass which is bonded with PVB absorbs more energy than those bonded with EVA

4) Regression models were developed to calculate the maximum load capacity and the amount of absorbed energy separately depending on the thickness of glass and the thickness of the bonding interlayer regardless the position of glass plates. Positive variables are taken into consideration during calculations.

5) The propagation of fracture was linear within the glass plate and non linear within the bonding polymer

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