ZONGULDAK BÜLENT ECEVİT UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

ANALYSIS OF A CRACKED LAMINATED GLASS PLATE UNDER LOW TEMPERATURE

DEPARTMENT OF MECHANICAL ENGINEERING

MASTER OF SCIENCE

TAYFUN İNİK

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ADVISOR : Prof. Dr. Mehmet YETMEZ

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“With this thesis it is declared that all the information in this thesis is obtained and presented according to academic rules and ethical principles. Also as required by academic rules and ethical principles all works that are not result of this study are cited properly.”

Tayfun İNİK

ABSTRACT

Master of Science

ANALYSIS OF A CRACKED LAMINATED GLASS PLATE UNDER LOW TEMPERATURE

Tayfun İNİK

Zonguldak Bülent Ecevit University
Graduate School of Natural and Applied Sciences
Department of Mechanical Engineering

Thesis Advisor: Prof. Dr. Mehmet YETMEZ
January 2022, 41 pages

Monolithic glass is generally known brittle material with its characteristic fracture strength. Due to the existence of surface cracks and their geometrical properties, laminated glass has been more preferable than monolithic glass since past four decades. On one hand, in the beginning, PVB (polyvinyl butyral) did not considered as a major effect of nonlinear behavior of laminated glass under mechanical conditions. On the other hand, later, it has been clearly seen that PVB is very important part of the laminated glass unit to compute failure stress analysis. In addition to the mechanical condition, variation of temperature influences stress behavior of laminated glass plate, especially post-crack response characteristics. Despite some advancements accomplished, more progress is still required to understand temperature effects on strain field behavior and fundamental vibration characteristics of cracked laminated plates. Today, the usage of laminated glass in structural designed process is quite common. Because of its nonlinear behavior, detailed studies gain importance to investigate the PVB effect on laminated glasses.

ABSTRACT (continued)

The influence of low temperature on the deflection behavior of cracked laminated glass circular plates is investigated both experimentally and numerically in this investigation.

For the circular plates with no-crack and with a surface crack, effect of PVB thickness is examined under different loading and thermal conditions. Also, free vibration behavior of a cracked laminated glass circular plates is also considered to understand the deflection behavior clearly.

Results show that (i) there are sharp rising values of major normal stress and deflection for both interlayer thicknesses of 0.38 and 0.76 mm in the range of -85 to -100°C, (ii) for cracked plate with 1.52 mm interlayer thickness, decreasing temperature gives approximately linear variations for the stress and deflection up till temperature of -85°C, (iii) in the same way as strain energy, decreasing interlayer thickness decreases shear stress, (iv) crack effect on free vibration characteristics are clearly observed for all three interlayer thicknesses.

Keywords: Laminated glass; Crack; Temperature; Deflection; Strain energy

Science Code: 625.03.00

ÖZET

Yüksek Lisans

DÜŞÜK SICAKLIK ALTINDA Kİ DAİRESEL LAMİNA CAMLARIN ANALİZİ

Tayfun İNİK

Zonguldak Bülent Ecevit Üniversitesi
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Tez Danışmanı: Prof. Dr. Mehmet YETMEZ
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Monolitik cam, kırılma mekaniği kapsamında iyi bilinen kırılgan bir malzemedir. Mikroskobik yüzey kusurlarının varlığı ve geometrik özellikleri nedeniyle, son kırk yıldan beri lamine cam, monolitik cama göre tercih edilmektedir. Bir yandan, başlangıçta, PVB (polivinil bütiral), mekanik koşullar altında lamine camın doğrusal olmayan davranışının önemli bir etkisi olarak kabul edilmedi. Sonrasında, PVB'nin lamine cam için yapılan gerilme analizleri için çok önemli bir parçası olduğu açıkça ancak görülmüştür. Mekanik koşula ek olarak, sıcaklık değişimi lamine cam levhanın gerilme davranışını, özellikle çatlak sonrası tepki özelliklerini etkileyeceği belirtilmelidir.

Bu çalışmada, çatlaklı lamine cam dairesel plakaların eğilme davranışı üzerindeki düşük sıcaklık etkisinin incelenmesi hem deneysel hem de sayısal olarak yapılmıştır. Çatlaksız ve yüzey çatlağı olan dairesel plakalarda PVB kalınlığının etkisi farklı yükleme ve ısıl koşullar altında incelenmektedir. Ayrıca, çatlak lamine cam dairesel plakaların serbest titreşim performansı da plaka davranışını anlamak için ele alınmıştır.

ÖZET (devam ediyor)

Sonuçlar göstermektedir ki : (i) -85 ile -100°C aralığında olan ara katman kalınlıkları 0.38 ve 0.76 mm olan plakların normal gerilme ve sehim değerleri ani yükselmektedir. (ii) Ara katman kalınlığı 1.52 mm olan çatlak plakanın, sıcaklığın düşmesi etkisiyle -85 °C sıcaklığa kadar doğrusal olarak değişmektedir. (iii) Gerinim enerjisi ile ara katman kalınlıkları arasında doğrusal oran vardır. Bununla birlikte ikisi azaldıkça kayma gerilmesi de azalmaktadır. (iv) Üç farklı katmana sahip plakanın, serbest titreşim karakteristiği ile arasında etki açıkça gözlenmektedir.

Anahtar Kelimeler: Lamine cam; Çatlak; Sıcaklık; Sehim; Gerinim Enerjisi

Bilim Kodu: 625.03.00

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Last but not least, I want to thank my father, Mehmet Zeki İNİK, my mother, Rübeye İNİK, and my beloved brothers, Oğuzhan and Yusuf İNİK, for their constant support, joy, and peace throughout my life. They are living proof that a family is the most valuable possession a person can have.

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LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOLS

°C	: Celsius
®	: Copyright
ζ	: Damping ratio
Δ	: Displacement
ω	: Natural frequency
E	: Modulus of elasticity
ν	: Poisson ratio
τ	: Shear stress
γ	: Shear strain
G	: Shear modulus
σ	: Stress

ABBREVIATIONS

JINT	**:** J-Integrated
k	**:** Stress intensity
LG	**:** Laminated glass
LVDT	**:** Linear variable differential transformer
MG	**:** Monolithic glass
mJ	**:** mill joule
mm	**:** millimeter
MPa	**:** Mega pascal
PVB	**:** Polyvinyl butyral
RO	**:** At Room Temperature
SRV	**:** Safety relief valve
T	**:** Temperature

LIST OF SYMBOLS AND ABBREVIATIONS (continued)

ZBEU **:** Zonguldak Bülent Ecevit University

3D **:** Three-dimensional

CHAPTER 1

INTRODUCTION

Laminated glass is made up of two or more plies that are bonded together with the help of an autoclave. The used in conventional commercial plies are used by the following steps: (i) Monolithic Glass, (ii) Polyvinyl Butyral (PVB). Laminated glass is the subject of current research. Consequently, the mechanical and thermal experimental of laminated glass with different thicknesses used in different temperatures and pressure has been investigated experimentally. If we investigated plies respectively in specimens. One of them, monolithic glass, the interaction of a glass ribbon with molten tin is used to make the majority of formerly monolithic glass. Glass members are typically thin, with a low elasticity modulus. About 50 years ago, the Pilkington float [1] process was introduced, leading to a shift in manufacturing methods. If laminated glass members had the same maximum allowable deflection as steel or reinforced concrete members, their potential use in engineering and architecture would be severely constrained. The primary fault with the cylinder process was that it was discontinuous, which meant that cylinders of any diameter had to be separated and compressed, which was difficult and damaging to the surface. Furthermore, all of the glass produced by these window processes was distorted. All of the production processes entailed extending the molten glass, whether by spinning, blowing, or dragging it, and this stretching caused homogeneities to become distorted. The new approaches products are suitable for most applications that formerly required plate glass, sheet glass, or window glass, and in some respects improve the previous products. Historically, glasses were formed by the solidification of oxide melts at high temperatures [1-4].

Otherwise, PVB is a polymer material with strong mechanical qualities and optical clarity that has been frequently applied in the construction and vehicle industries as an interlayer material for laminated glass. Two glass panes are generally connected by a transparent polymer interlayer in the fabrication of laminated glass.

Because of its high ductility and adhesive property with a glass pane, PVB has been frequently utilized as an interlayer material for laminated glass to reduce the hazard of crack glass fragmentation. When subjected to extreme dynamic blast pressures or ballistic contact, ordinary glass plates fracture into dangerous shards. The laminated-glass unit parts, on the other hand, bond to the PVB interlayer, making the material safer and more secure [5]. The application of PVB laminated safety glass has grown from quasi-static loading zones to impact and blast loading regimes, necessitating a more in-depth understanding of PVB material properties at high strain rates. Impact-resistant qualities, post-glass fracture load-bearing capabilities, and glass shard retention characteristics of polymer/glass laminates lower the risk of personal injury and property damage during severe weather events. Two glass plies are typically bonded together with a plasticized PVB interlayer in such safety glazing systems [6-8]. These findings are presented as engineering parameters for the shear force characteristics of thin PVB interlayers sheared through glass plates. The situation necessitates major technological requirements in order to withstand the crash of massive masses at low velocity [5,9].

In the last four decades, the use of glass in buildings has been growing significantly. It is obvious that, at first, monolithic glass is used as a window component. Later, as a modern design, it is constantly being used for a load-carrying element of roofs, beams, columns, and floors [10] Now, the ongoing demand for such technology has required the use of further complicate the design process. Consequently, it is seen that the development of the glass industry needs a better structural design process and a better understanding of the load-carrying capacity for improving the durability and service life of the glass.

Several experimental and numerical research on the behavior of laminated glass under dynamic loading circumstances have been conducted in the past, that’s why this topic is more important for the glass community [11]. Briefly introduce the laminated glass includes two or more glass ply bonded together with an interlayer [12]. Monolithic glass is a well-known brittle material with large scatters in its fracture strength. Due to the existence of microscopic surface flaws and their geometrical properties, laminated glass has been more preferable to monolithic glass for the past four decades [13]. On one hand, in the beginning, PVB (polyvinyl butyral) did not consider a major effect of the nonlinear behavior of laminated glass under mechanical conditions. PVB is often described as linear-viscoelastic, which means that its mechanical characteristics are affected by the time of loan application and the temperature of working circumstances. Because the plates are generally thin and prone to considerable deflection, a lot

of research and development has gone into them [14]. Furthermore, the mechanical characteristics of PVB are claimed to vary following the autoclave procedure in the glass community. This indicates that the PVB behaves differently when tested freely (not limited in a laminate) vs when tested bound in laminated glass components [15]. Particularly, the effect of PVB thickness as a major or number of layers plays an important role in critical deflection and buckling force capacity [16]. On the other hand, later on, it has been seen that PVB is a very important part of the laminated glass unit to compute failure stress analysis [17]. In addition to the mechanical condition, variation of temperature influences stress behavior of laminated glass plate, especially post-crack response characteristics [18]. Despite some advancements accomplished, more progress is still required to understand temperature effects on strain field behavior and fundamental vibration characteristics of cracked laminated plates [19-20]. Today, at first, the usage of laminated glass in the structural design process is quite common. Because of its nonlinear behavior depending on geometry and material, numerical and experimental studies become important to investigate the PVB effect for laminated glasses [16]. The temperature and interlayer thickness of the layered glass components possess a key role in the nonlinear approaches [22]. Second, the crack behavior of laminated glass is commonly considered by the finite element method (FEM) to find fracture toughness (K_1, K_2, and J-integral (JINT)) [23]. Third, natural frequency and damping characteristics of the laminated glass are also taken to analyze the accuracy of the response of effective thickness and other simplified approaches [24-25].

The damage and failure in research on laminated glasses are as follows; Researchers such as Grant et al. (1998) The Damage Threshold of Laminated Glass Structures [26]. Zhao et al. (2006) Analysis of damage in laminated automotive glazing subjected to simulated head impact [27]. Biolzi et al. (2010) Progressive damage and fracture of laminated glass beams [28]. Pyttel et al. (2011) Failure criterion for laminated glass under impact loading and its application in finite element simulation [29]. Examining closely at these researchers. Firstly, according to Grant et al. (1998), as specimens, 200mmx200mm*thickness lamina glass was investigated. The specimen's thickness varies. The specimens were clamped in a square frame with a gasket on either side of glass protection. Eight bolts clamping using a torque ensured 5 N. Impact velocities range from 4 m/s to 20 m/s. One of the purposes of this study was to discover the critical velocity at which damage began, often known as the damage threshold velocity. As a result, a study of the affected laminates revealed a shift in failure mode from flexure-induced star cracking in thin outer layer systems to top surface cone cracking in thick outer layer

structures. Finally, impact tests performed at 45° to the plane of the glass plate revealed that the normal component of the impact velocity defines the damage threshold [26].

The finite element approach was used to investigate the damage, according to Zhao et al. (2006). LS-DYNA3D made use of finite element algorithms. The models employed a viscoelastic material law, and the constitutive parameters were determined by comparing drop test simulations at different impact velocities to test data. [27].

Then, according to Biolzi et.al. (2010), flexure tests were performed on laminated glass beams produced from various combinations of glass sheets and interlayers. Furthermore, these flexure loads have been applied the parallel to lamination plane and are conducted at room temperature. The experimental set-up in this research is as follows; The testing equipment was a closed-loop electromechanical Instron load frame with a maximum capacity of 100 kN. On specimens [29], displacement control experiments were carried out to measure the residual strength of the laminate in the post-failure range with the tempered glass plies entirely cracked Three specimens, one each for float and tempered glass layers, demonstrated a linear load-deflection response until brittle fracture occurred at average strengths of 45 and 130 MPa, respectively. Furthermore, the thickness of this interlayer (PVB) is 0.76 mm. The laminated beams were subjected to three-point bending tests under force operating parallel to the lamination plane. The interlayer is important in determining the flexural response of in-plane loaded, layered beams. The progressive failure seen for the laminated glass/SGP beams varies significantly from that observed for the laminated glass/PVB beams. As a result, the quality of the utilized interlayer affects the post-crack range. Furthermore, glass beams have high lateral-torsional buckling slenderness. Even when a laminated glass beam is loaded parallel to the lamination plane (in-plane loading), an interlayer with increased stiffness activates the presence of an annealed float glass phase even in a cracked stage, stiffening the structural system, increasing the collapse load, and providing a higher residual strength by adding positive effects in improving flexural–torsional stability [28]. In later years Pyttel et. al (2011), researchers are following as Pyttel et al (2011) we also utilized windshield trials, but we also created a test setup for flat pieces to reduce the impact of curvature and analyze the influence of boundary conditions. Its first failure of the glass is determined by the impactor's velocity and the curvature of the glass. The tests provided in this paper demonstrate this. Following the initial failure, the cracks grow at a velocity of about 2000 m/s [29]. These two effects must be described by a failure criterion. The team specimens, two outer layers of glass and one interlayer. Meanwhile, the thickness of the Outer layers is different. These outer layers thickness respectively; 2.10

mm and 1.60 mm. Interlayers materials are PVB and thickness is 0.76 mm. The glass used for the test in this study was annealed. Furthermore, experimental set-up following as Two pairs of testing were carried out. The first test used curved safety glass specimens, whereas the second used flat specimens. The aircraft component tests were designed to provide information on the primary failure mechanism and its effects following a collision with the laminated glass. This impactor comes with three different weights (3.5 kg, 4.8 kg, and 6.3 kg). Inside the head, the impactor was a three-axis accelerometer. This accelerometer is utilized for all of the study's acceleration measurements. Consequently, the experiments span from no failure to major damage, as well as from convex to concave. In all of these circumstances, the simulation model can accurately determine impactor accelerations and deformations. The glasses input parameters consist of simply five values: i. Young's modulus, ii. Poisson's ratio, iii. critical stress for the failure, iv. critical energy for the failure and v. critical radius for the failure.

In addition, the viscoelastic properties of PVB are essential. The characteristic length we used is exceptionally lengthy in compared to known values for monolithic glass. This might be because a complicated structure with a strong strain rate-dependent layer (PVB) was used [11]. Many researchers investigated lamina-glass thermo-mechanics. Consequently, the thermal stresses of laminated-glass were investigated. The thermal effect of strains is more significant in fractured laminated-glass. Glass thermal breaking during freezing exposure has been explored experimentally at the component and assembly levels. Glass thermal fracture is known to be parameter related, like frame properties, glass type, coating, etc. For clear glazing, it was discovered that the heat load, panel size, smoke circulation, and installation method all had a significant impact on the collapse mechanism and loadbearing capability during the freeze [30]. The experimental and numerical analysis of local effects in the glass and interlayer components. Thermo-mechanical characteristics of glass improve with lamination without impacting the glass's transferability [31]. Because the overall thickness of the glass layers is constant, variations in the glass thickness ratio have no discernible effect on the pre-crack behavior [32]. Because glass is brittle, temperature displacement has a significant influence. In compared to a laminated glass, monolithic glass has extremely little deformation [31].

This chapter aims to investigate the low-temperature effect on the deflection behavior of a cracked laminated circular glass plate both experimentally and numerically. The circular laminated plates are handled with two groups: no-crack and a surface crack. The effect of PVB thickness is also examined under different loading and thermal conditions. Additionally, the

free vibration characteristics of the laminated glass circular plates are considered to understand the deflection behavior clearly.

To deflect what is dependent on displacement, plate a crack or no crack. We have performed on laminated glass under pressure and low-temperature conditions. Therefore, in the content of our study; In addition to the aviation industry, the temperature and dynamic conditions of the layered glass used in buildings with high steel construction are seen as an important issue in the approaching period [33] However, few studies are investigating the dynamic fracture of laminated glass. It is focused on experimental work on dynamic/static fracture of laminated glass [22]. The reference specimen of laminated glass was investigated in this study in a laminated glass plate (Ø160mm). Monolithic Glass thicknesses are equal and 3 mm. They carried out the experiments on a circular plate with interlayer thicknesses of 0.38, 0.76, and 1.52 mm. They determined that the effect of interlayer thickness on laminated glass behavior was modest. However, relatively thin interlayer thicknesses such as 0.38 mm, glass and interlayer modulus ratios, and temperature all play critical roles in the behavior of laminated glasses [34]. Consequently, depending upon PVB thickness, room-temperature T and characteristic load-duration t0, the deflection of the interlayer may vary from 0.1 MPa (PVB at T = -100 °C under permanent load) up to 1 MPa (Laminated glass at T = 0 °C and t0 = 1 s) [32]. Deflection on laminated glass using displacement from approximately 0 mm to 0.4 mm. As the thickness of the PVB decreases, the deflection decreases, but the deflection/thickness rate is greater. After the experimental results were obtained, a comparison with the numerical results was made. As for the impact fracture and fragmentation of laminated glass, the finite element method (FEM) is commonly used [23]. The finite element method was used to obtain numerical solutions. In the numerical simulation with the statics and dynamics solver ANSYS [34]. The of the layers are given as they are exposed to temperature and pressure. According to these properties, the specimens are modeled. It was investigated statically with and without cracks depending on the displacement conditions. Consequently, the found values are considered by the following steps: (i) deflection to see in Fig.4.1-4.3., (ii) strain energy see in Fig. 4.4-4.6, (iii) Shear Stress see in Fig4.7-4.9 and (iv) stress intensity factors and JINT values of a cracked LG plate see in Table 4.1. The mesh model is given in see Fig 3.18. Dynamically, the modal analysis of the laminated glasses before and after the low-temperature test was investigated. The found values are given in see Fig 4.7-4.9. The mesh model is given in see Fig. 3.18. Finally, static and dynamic experiments on a laminated glass were performed under pressure and low at temperatures. The experimental results were compared.

CHAPTER 2

2.1 MATERIAL

The laminated glass specimens developed in this work are made up of monolithic glass and PVB layers [35]. The plies are mechanically and chemically fused together in an autoclave using heat and pressure [13,36-37]. Laminated glass specimens given by Sisecam (Sisecam A.S., Turkey) for this investigation are three-ply circular plates with a diameter of 160 mm and a monolithic thickness of 3 mm. A PVB interlayer has three thicknesses: 0.38-, 0.76-, and 1.52-mm. Details for the laminated glass specimens are given in Fig.2.1.

Table 2.1 Properties of materials used in laminated glass

Layer	**ρ (g/cm^3)**	**E (GPa)**	**ν (mm/mm)**	**α ($\times 10^{-6}$, 1/°C)**	**Reference**
Glass	2.35	20	0.22	9	[38]
PVB	1	0.7	0.44	15.1	[36]

Glass plates crack primarily under tension, and the fracture strength is determined by the applied stresses and the characteristics of the surface flaws [39-41]. Consequently, in addition to PVB thickness, second testing parameter of this study is central surface crack with 10 mm in length and 0.1 mm in depth. Furthermore, low temperature and pressure applied to the bottom-layer surface of a laminated circular glass plate are the last parameters. On one hand, depending on these conditions, the effects of temperature, large deflection and surface crack on behavior of a laminated circular glass plate are investigated. On the other hand, due to the toughness and flexibility properties of PVB [1,42], free vibration behavior of a cracked laminated glass circular plates are also considered to understand the deflection behavior clearly.

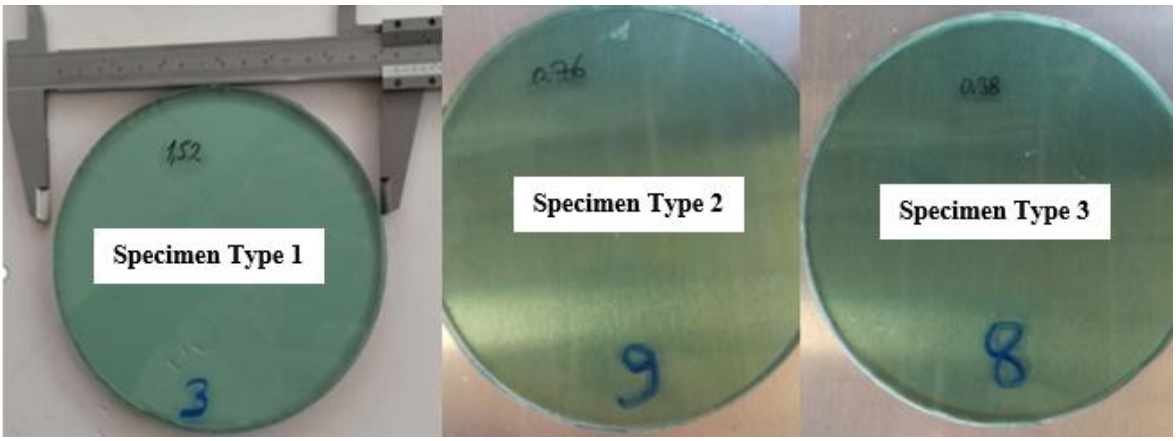
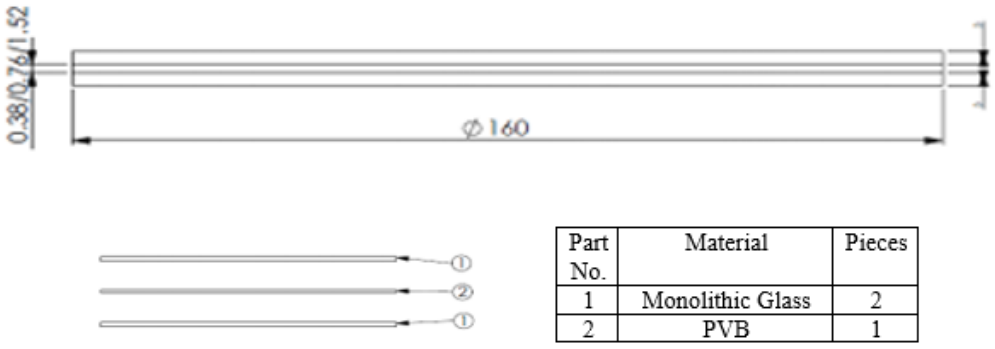


Figure 2.1. General view of specimens with 0.38, 0.76 and 1.52 mm in PVB thickness

2.1.1 Monolithic Glass (MG)

The author of the study laminated glass specimens are composed of monolithic glass. Monolithic glass a typical linear elastic brittle material. As a result, glass plates crack mainly under tension, and fracture strength is determined by the applied pressures as well as the characteristics of the surface flaws [39]. As known glass has been commonly used in buildings. Furthermore, annealed glass, heat-strengthened glass, toughened glass, and laminated glass are all commonly used varieties of glass. Monolithic glass production process is applied in the construction of the glass structure of monolithic glass consisting of a single glass plate. Monolithic glass is frequently improvement in order to increase its durability, improve insulating property and meet safe glazing requirements. Glass windows, on the other hand, are particularly vulnerable to vibration and impact loads due to their low strength in comparison to other structural parts with lower strength. In this investigation, we employed monolithic glass specimens in two distinct top-layer glass conditions. This condition are the circular plates with no-crack and with a surface crack. The influence of fractures on the behavior of laminated glass was explored depending on this circumstance. Furthermore, low temperature and pressure affected the bottom-layer glass. Monolithic glasses experience laterals large deflection which

are in the importance of thickness increases when exposed to displacement [41]. The middle surface of the circular plate extends when laminated glasses are subjected to high deflections. Finally, this causes tensions to be introduced in surface faults [40]. Some recent studies looked at the shortcomings of monolithic glasses. As a result, these faults are the product of the manufacturing process and subsequent exposure [41].



Part No.	Material	Pieces
1	Monolithic Glass	2
2	PVB	1

Figure 2.2. Detail view of specimens with 0.38, 0.76 and 1.52 mm in PVB thickness.

2.1.2 Polyvinyl Butyral (PVB)

The PVB interlayer was employed in the laminated glass specimens used in this investigation. PVB (polyvinyl butyral) is a unique binder used in the temperature and pressure bonding of two or more glass plates. It is a polyvinyl butyral based, two components, adhesion primer. It has been specially developed to meet the needs of the metal industry as a primer that provides excellent adhesion to all kinds of surfaces such as aluminum, steel, phosphate steel and galvanized. PVB used as interlayer are generally used in laminated glasses and especially in windshields of cars. Polyvinyl butyral (PVB) is a plastic from the group of polyvinyl acetyls. Polyvinyl butyral (PVB) is utilized for applications requiring high adhesion, optical clarity, toughness, and flexibility. Deformation of the interlayer can absorb energy, reducing the stress transferred to the remainder of the structure [13]. PVB is a flexible and nonlinear material with highly sensitive behavior on loading speed and temperature [43]. PVB is likewise thought to be nearly incompressible, with little to no persistent deformation following loading [42]. When

the numerical simulations and experimental findings were compared, they were found to be quite accurate.

CHAPTER 3

METHODS

3.1 Experimental Methods

Experimental setup with liquid nitrogen tank, LVDT and data collection system are presented in Fig.3.1.

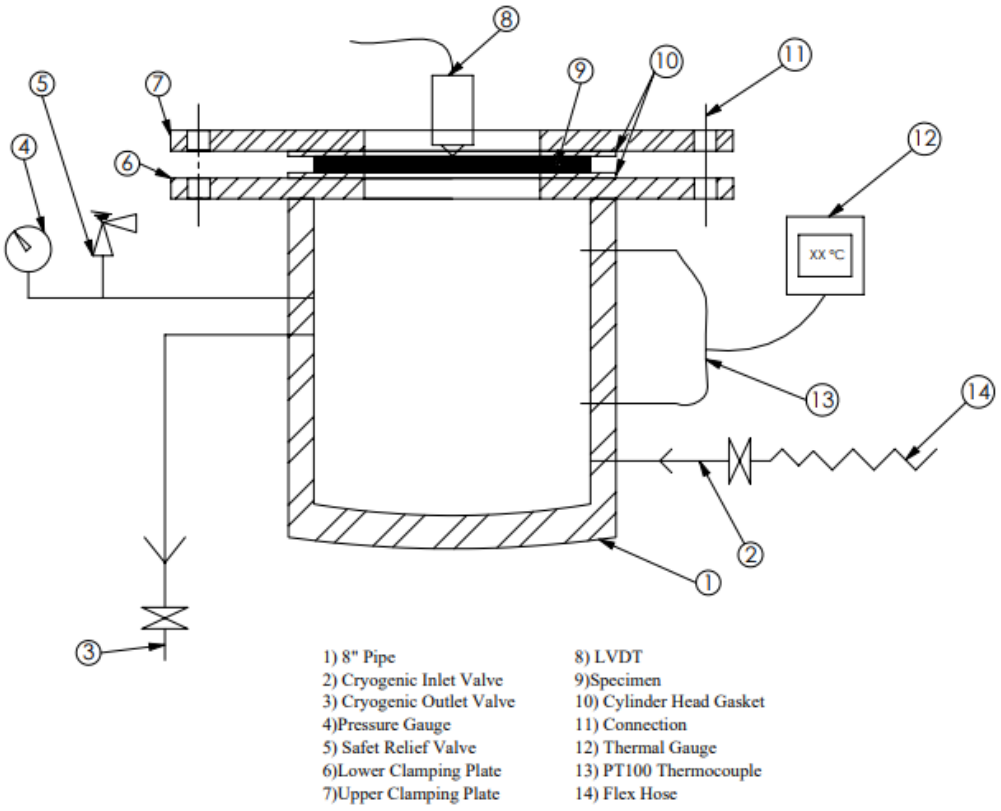


Figure 3.1. Details: Representation of the experimental setup

Figure 3.2. General View: Representation of the experimental setup

3.1.1 Quasi-static Testing

Each specimen is insulated with a 2 mm thick head cylinder gasket. The specimen is properly connection to the experimental setup and positioned. After centering, to connecting the lower clamping plate with upper clamping plate, eight equidistant M16 bolts are taken into consideration to connect the clamping plates together with a torque of 120 Nm. The bolt length is 85 mm. In order to get low temperature, liquid nitrogen tank is connected with inlet cryogenic valve flex hose. Temperature range considered in this study is between 0 to -100°C. Moreover, applied pressure range varies from 0 to 1 MPa.

3.1.2 Experimental Set-up Elements

Laminated glasses were also used in many places. In addition, it is used in the manufacturing of aerospace and aircraft components, therefore it should be tested. Consequently, the experimental setup was adjusted for the air conditions. This conditions are low temperature and pressure. Additionally, experimental setup assemblies considered by the following steps: (i) 8” Pipe, (ii) Cryogenic Inlet Valve, (iii) Cryogenic Outlet Valve, (iv) Pressure Gauge, (v) Safety Relief Valve, (vi) Lower Clamping Plate, (vii) Upper Clamping Plate, (viii) LVDT, (ix) Specimens, (x) Cylinder Head Gasket, (xi) Connection, (xii) Thermal Gauge, (xii) PT100 Thermocouple, (xiv) Flex Hose.

Figure 3.3. 8" Pipe

Since there is low temperature and pressure in the test setup, 8 "pipe made of austenitic stainless steel AISI316-L purchased from Borsen was preferred.

Table 3.1. Details for Austenitic Stainless Steel AISI316L

C	Si	Mn	P	S	Cr	Mo	N	Ni
≤0.03	≤1.00	≤2.00	≤0.045	≤0.015	16.50-18.50	2.00-2.50	≤0.110	10.00-13.00

Figure 3.4. Cryogenic Inlet Valve

The REGO [45] branded inlet valve used as the go into of the refrigerant gas to the experimental setup. Working temperature is -196°C to 74°C and working pressure is to 42 Bar. Inlet connection is G3/8” NPT, Outlet connection is G1/2” with tapered record.

Figure 3.5. Cryogenic Outlet Valve

The BESTOBEL [46] branded outlet valve used as the out of the refrigerant gas to the experimental setup. Working temperature is -196°C to 74°C and working pressure is to 32 Bar. Inlet and outlet connection.

Figure 3.6. Safety Relief Valve

The REGO branded SRV working principle is as follows: if the pressure exceeds 16 bar in the experimental setup, it will discharge. Working range is 0 to 16 Bar. Connection measure is G 3/8". branded SRV used.

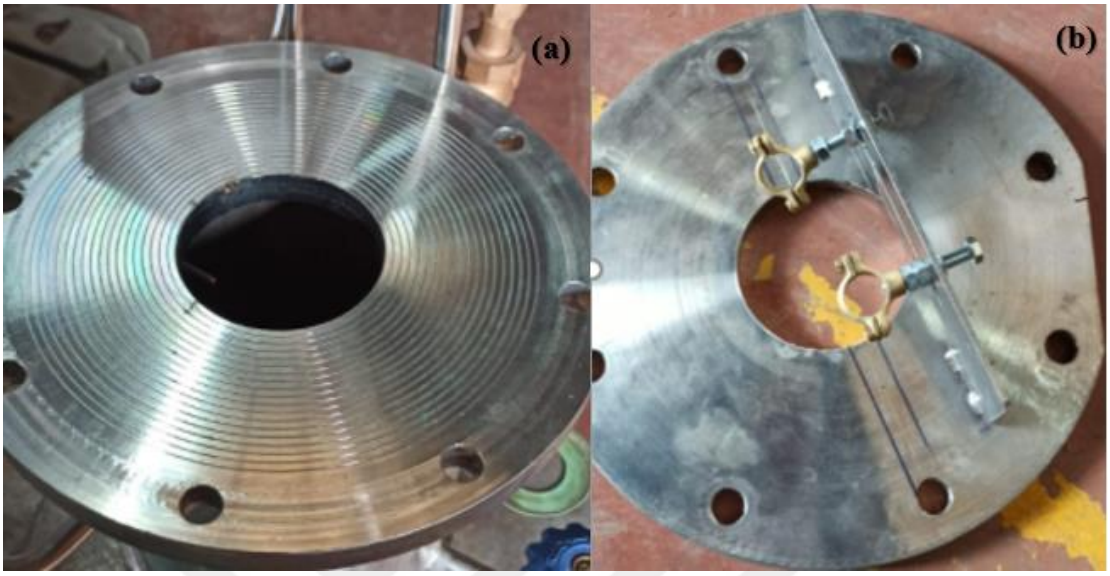


Figure 3.7. Clamping Plate: (a) Lower, (b) Upper

Since there are more than one specimen, a plate was used for clamping the specimens. These plates related to fittings. The geometry measure is considered by following steps: (i) Out diameter: 244 mm (ii) inner diameter: 100 mm, (iii) thickness: 20 mm, (iv) connection hole: Ø18mmx8 piece. Borsen Boru branded plate used.

Table 3.2. Dimensional representation of LVDT (mm)

Models (DTH-A-*)	A		B	C	ØD	ØE	F	(G)
	MAX	MIN						
*5	84.4	78.4	68	60	4	20	21	57
*10	96.4	85.4	75	67				
*20	122.4	101.4	91	83				
*30	149.4	118.4	108	100				
*50	209.5	158.5	148	140	4	25	25	62
*100	359.5	258.5	248	240	5	35	28.5	72

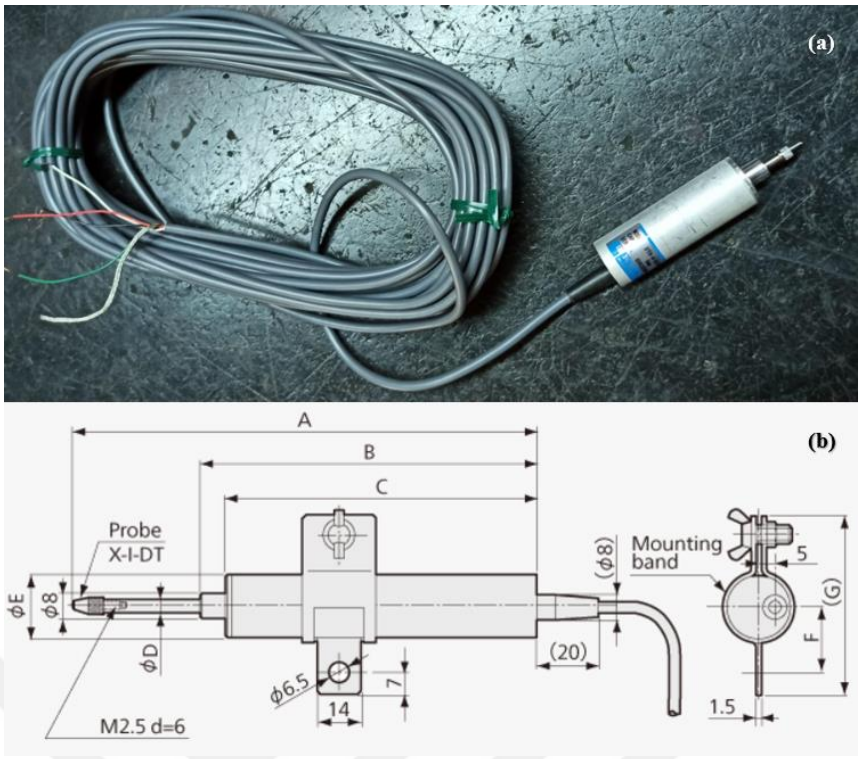


Figure 3.8. Representation of the LVDT : (a) General View, (b) Details

The KYOWA branded LVDT is measuring deflection. Unit of measurement is mV. Therefore, LVDT calibration curve can be easily obtained by using unit change from mV to mm (see Fig.3.8).

Mounting band in should be two conditions: (i) One mounting band is provided standard to DTH-A-5 to 30, (ii) Standard to DTH-A-50 to 100 are two mounting bands. The following procedures are taken into account while evaluating the LVDT DTH-A-5 Z10K specs: (i) Performance, (ii) Environmental Characteristics, (iii) Electrical Characteristics, (iv) Mechanical Properties.

Firstly, performance values depend on room temperature and this values are following steps: (i) Rated Capacity: 5 mm, (ii) Nonlinearity: 0.1 percent, (iii) Hysteresis: 0.1 percent, (iv) Repeatability: 0.1 percent, and (v) Rated Output: 5 mV/V 0.15 percent.

And then, environmental characteristics values following are steps: (i) Safe Temperature (°C): -10/70, (ii) Compensated Temperature (°C): 0/60, (iii) Temperature Effect on Zero: Within 0.01percent RO/°C, (iv) Temperature Effect on Output: Within 0.01percent /°C.

It is necessary to examine two separate issues as an electrical characteristic. These are excitation and resistance. Excitation works both AC and DC. Furthermore, there are also two different

types. (i): Safe Excitation: 6 V (ii) Recommended Excitation: 1 to 4 V. Resistance unit is Ω. In addition to there are two different type. (i) Input Resistance: 350 Ω within 1 percent, (iv) Output Resistance: 350 Ω within 1 percent. Four-conductor vinyl insulated cable, ØD:4 mm and L: 2m with a connector plug PRC03-12A10-7M.

Finally, electrical characteristics values are the following steps: (i) Frequency Response: ~2Hz (DC), (ii) Measuring Force: 1.5 N, (iii) Mass: 30 g , (iv) Mounting band model is FXB-5Ax1.

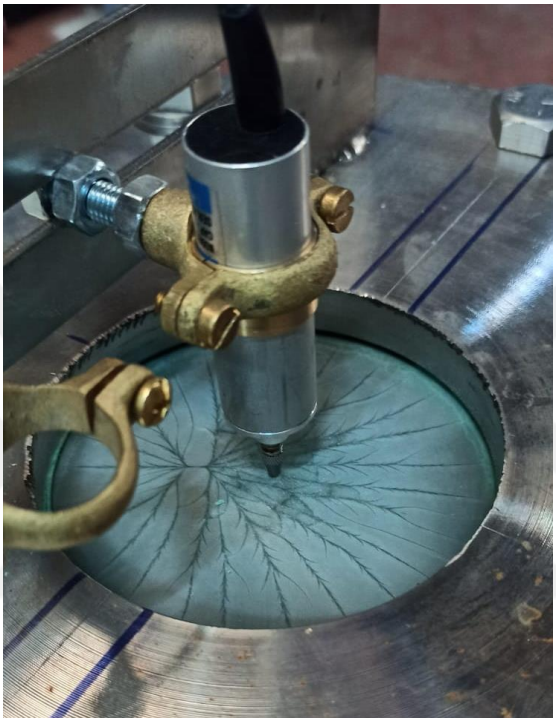


Figure 3.9. LVDT on Experimental Set-up

Using clips, secure the transducer to the steady point.

Transducers with linear variable differential transformers (LVDTs) are commonly used for measuring displacement, pressure, force, level, flow, and other physical parameters. These provide strong sensitivity and linearity throughout a wide range, consistent readings, high dependability, and adequate durability. The shape of the transducer, the configuration of the main and secondary windings, the quality of the core material, fluctuations in excitation current and frequency, and changes in ambient and winding temperatures all have an effect on LVDT performance [45,46].

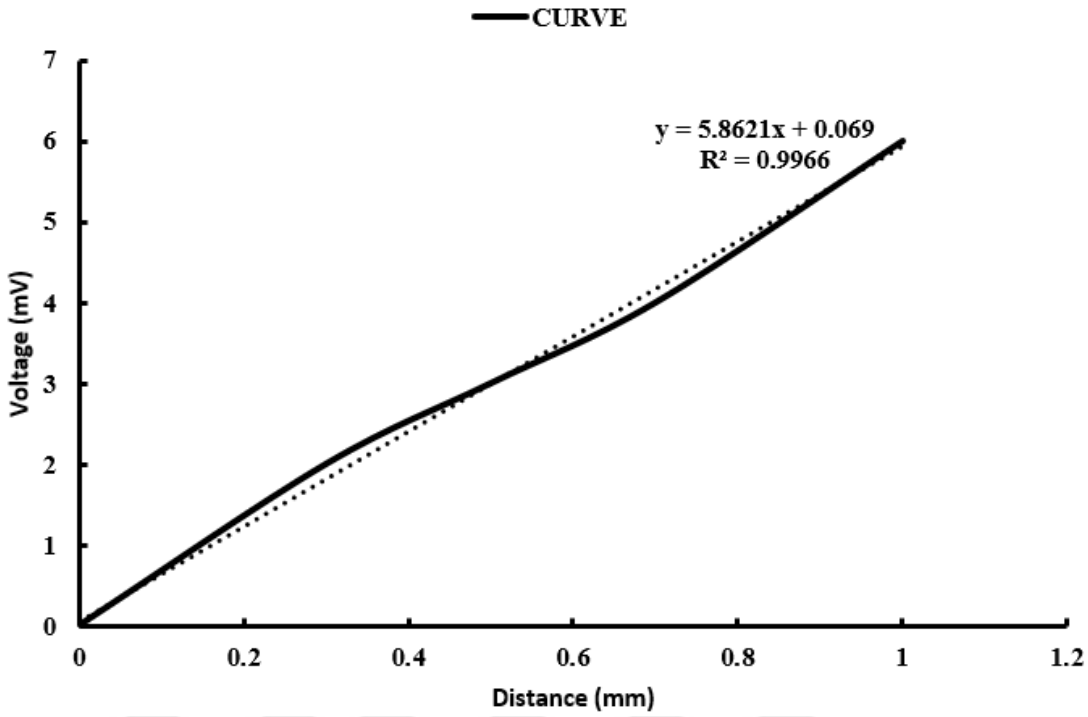


Figure 3.10. Calculated LVDT Calibration Curve

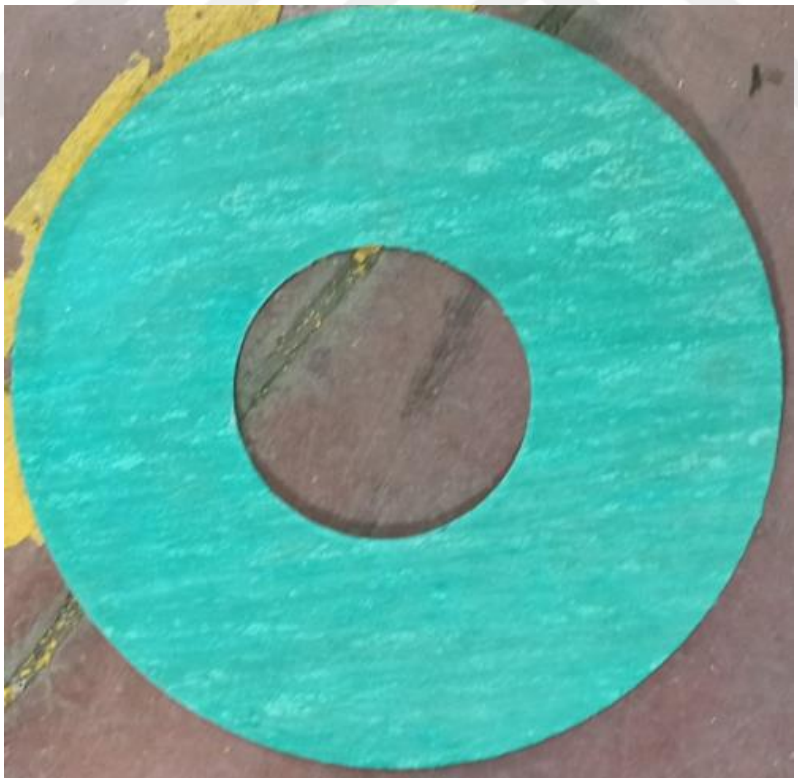


Figure 3.11. Cylinder Head Gasket

To avoid escaping gas from the experimental setup from impacting the overall performance of the experimental setup during operation, both the right pre-stressing force of the bolts and the

gasket design are key variables in boosting the effectiveness of the gasket sealing (8). The geometry measure is considered by following steps: (i) Outer Diameter Ø160 mm, (ii) Inner hole Ø100. (iii) Thickness: 2 mm.

Figure 3.12. Control unit of the thermal gage

It was used to show the temperature felt by the thermocouple of the experimental setup during operation. It was designed by May Otomasyon.

Figure 3.13. General view of a PT100 Thermocouple

In industry, there are several ways for detecting temperature. The PT100 is the most often utilized approach. The PT100 is used in a wide range of temperature measuring systems. When the temperature is between -200°C and +850°C, the thermocouple becomes more accurate and linear. The PT100's voltage drop is substantially more than the thermocouple's output. Furthermore, no cold junction adjustment is required [47-48].

Figure 3.14.Liquid Nitrogen Tank

3.1.3 Modal Analysis

The following steps are taken into account in experimental free vibration analysis: (i) To stimulate each of the uncracked/cracked circular laminated plates via the designated spot, an impulse hammer with a force transducer is employed ; (ii) an accelerometer is used to get the responses; and (iii) the measurements are completed using a microprocessor-based data acquisition system, specifically SoMat^{TM} eDAQ-lite and nCode GlyphWorks software.

Figure 3.15. Accelerometer used in this study

Frequency values obtained from specimens subjected to low-speed impact Dytran Measured with model 3093B accelerometer.

3.2 Numerical Method

Basically saying code of finite elements In order to do computational analysis, Ansys is used.

The next steps take into account numerical analysis:

(i) Static structure is used to find directional deformation strain energy, K_1, K_2 and J-integral (JINT) for uncracked/cracked circular laminated plates. Both SOLID186 and SOLID187 are preferred in this part of the analysis (#nodes: 71288 and #elements: 54362) (see 3.16).

(ii) [Modal Analysis is conducted to find the natural frequencies and damping ratios with element type SOLID187 (#nodes: 62525 and #elements 30482) (see 3.17).

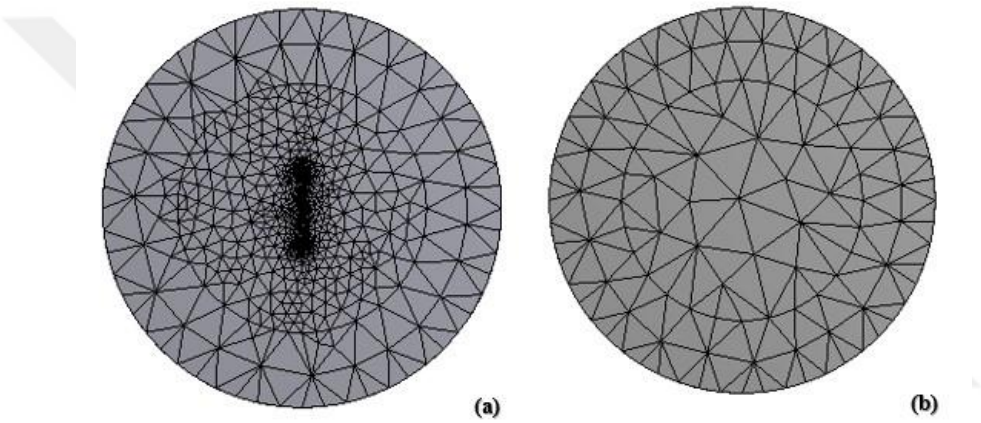


Figure 3.16. Static structural mesh model: (a) with a surface crack, (b) with no-crack

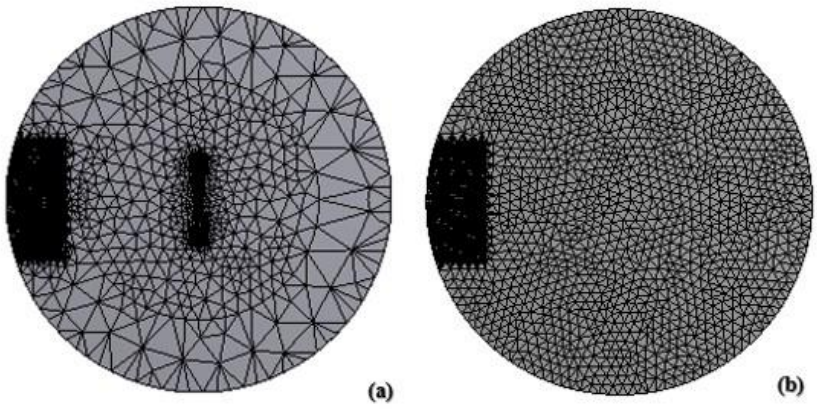


Figure 3.17. Modal analysis mesh model: (a) with a crack, (b) with no-crack

3.2.1 Ansys

In this study, numerical analysis is considered by the following steps: (i) Static structural and (ii) modal analysis [51]. Figures 3.16 and 3.17 show the geometry, node locations, and three-dimensional for this element. The two analysis have got two different element types. Element type 1 as Solid187 (see Fig. 3.18). Element type2 as Solid186 (see Fig. 3.19). [49-50]

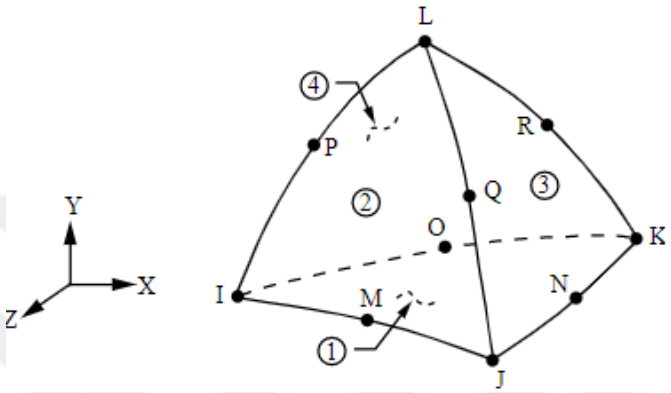


Figure 3.18. Geometrical view of SOLID187

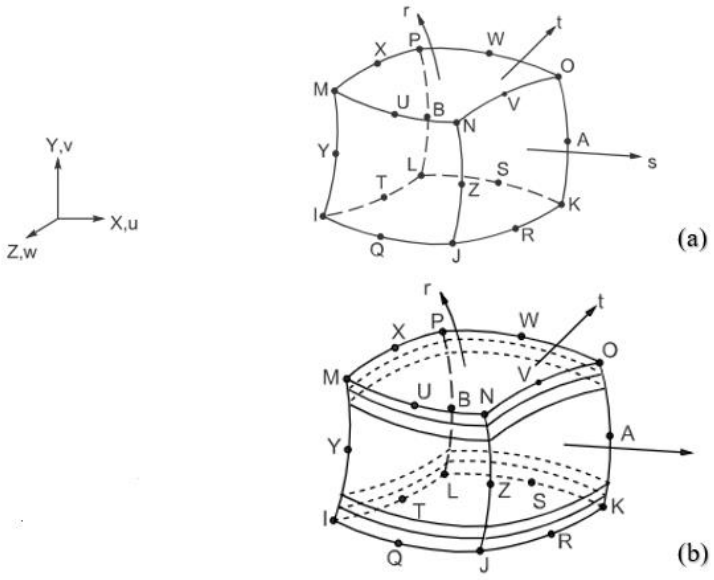


Figure 3.19. SOLID186 Geometry: (a) Homogeneous Structural, (b) Layered Structural

CHAPTER 4

RESULT&CONCULUSION

4.1 Results

Experimental and numerical results of variations of major normal stress (σ_z) and deflection (Δ_z) for a laminated glass with no-crack and with a central surface crack are presented in Figures 4.1-4.3. It can be noted that numerical results are compatible with the experimental evaluations. Figure 4.1. indicate that, decreasing temperature effect for 1.52 mm may be observed clearly at -20°C, Figure 4.2. and 4.3. indicate that, characteristic stress and deflection responses for 0.38 mm starts slightly while that responses for 0.76 mm begins moderately at -20°C. (iii) In the range of -85 to -100°C, there are sharp rising values of major normal stress (σ_z) and deflection (Δ_z) for both interlayer thicknesses of 0.38 and 0.76 mm, (iv) for cracked plate with 1.52 mm interlayer thickness, decreasing temperature gives approximately linear variations for the stress and deflection up till temperature of -85°C as fracture point.

Numerical results of variation of strain energy through diameter of cracked laminated glass plates at room temperature are given in Figures 4.4-4.6 It is seen that (i) decreasing interlayer thickness decreases strain energy, (ii) sharp increase of fluctuations appears when decreasing interlayer thickness.

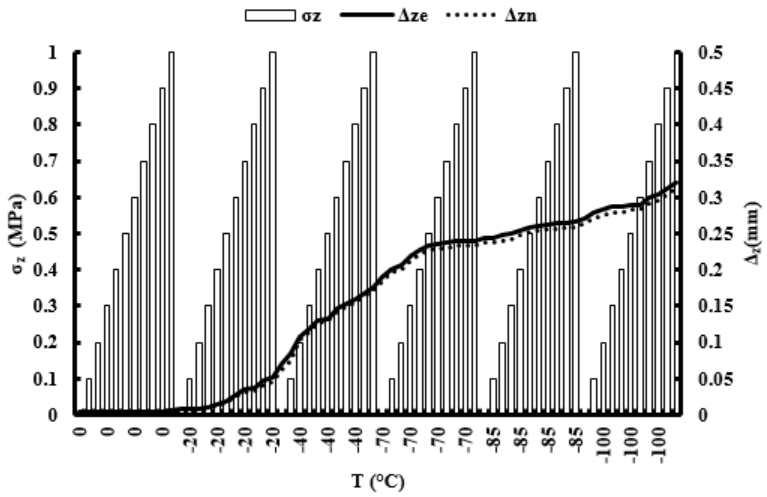


Figure 4.1. Variation of deflection for the laminated glass plates with 3 mm+1.52 mm+3 mm for the plate with no-crack (experimental results: Δze, numerical results: Δzn).

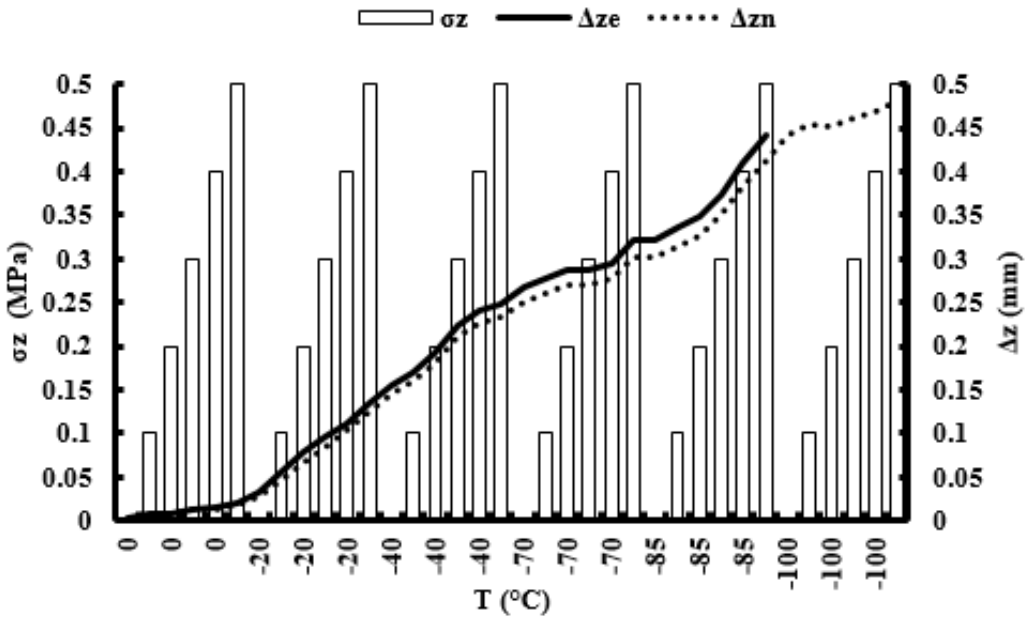


Figure 4.2. Variation of deflection for the laminated glass plates with 3 mm+ 1.52 mm+ 3 mm for the plate with a crack(experimental results: Δze, numerical results: Δzn).

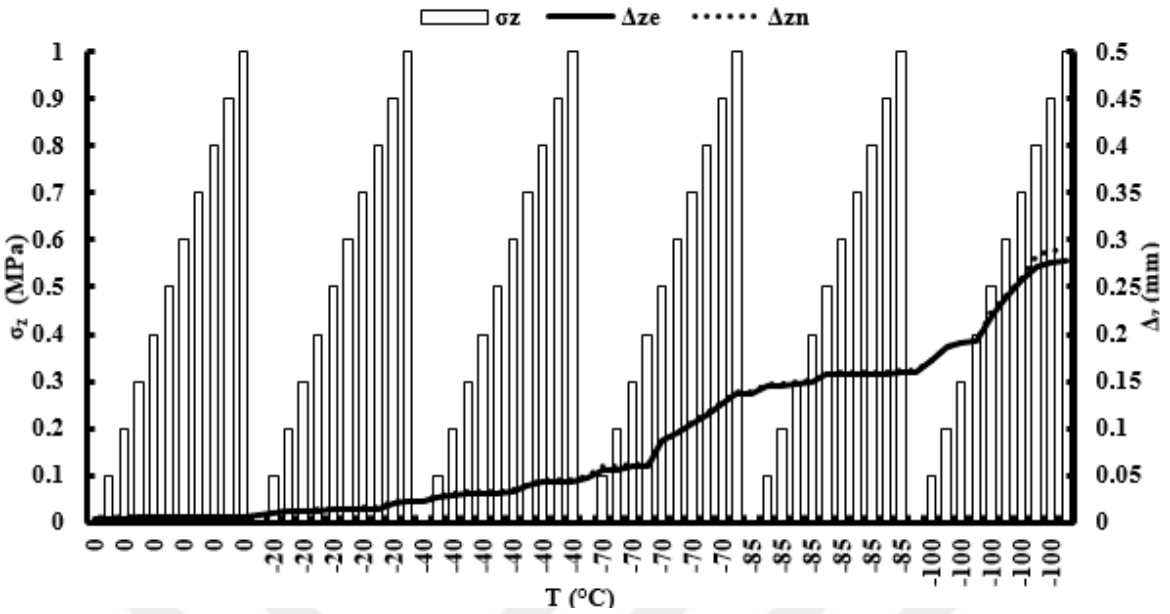


Figure 4.3. Variation of deflection for laminated glass with 3 mm+ 0.76 mm+ 3 mm) for the plate with no-crack (experimental results: Δze, numerical results: Δzn).

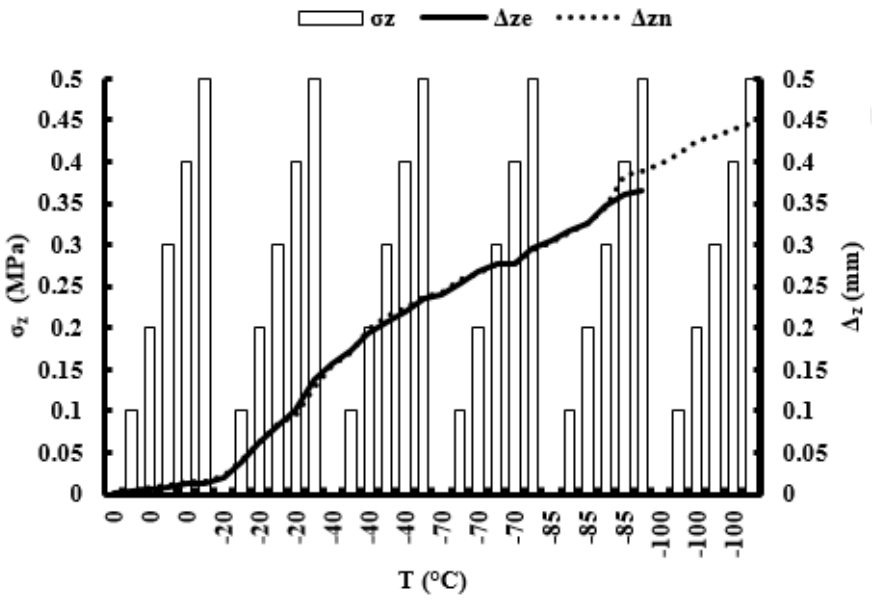


Figure 4.4. Variation of deflection for laminated glass with 3 mm+ 0.76 mm+ 3 mm) for the plate with a crack (experimental results: Δze, numerical results: Δzn).

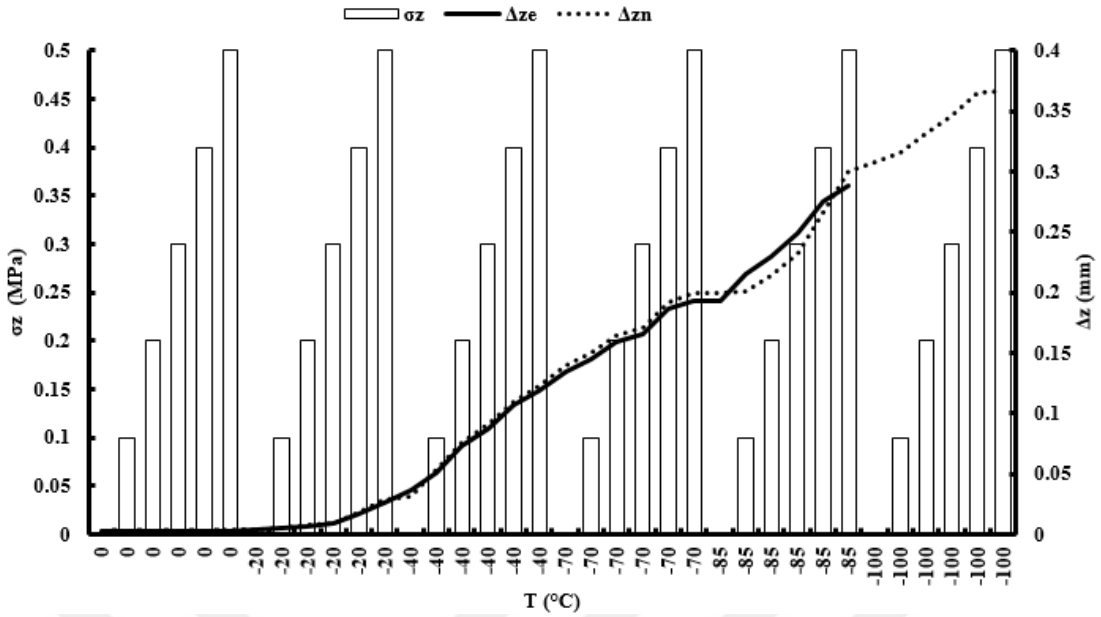


Figure 4.5. Variation of deflection for laminated glass with 3 mm+ 0.38 mm+ 3 mm for the plate with no-crack. (experimental results: Δze, numerical results: Δzn).

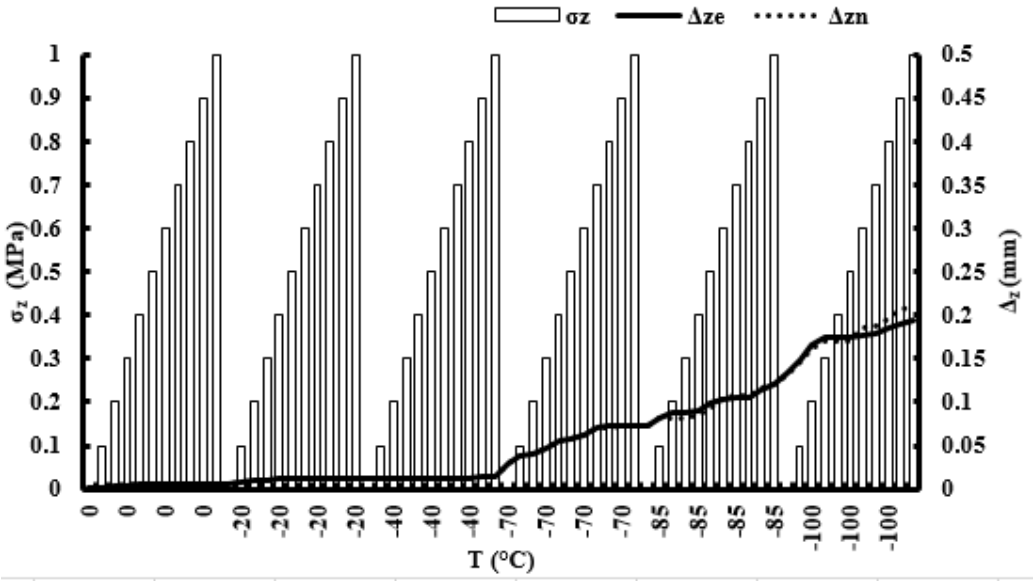


Figure 4.6. Variation of deflection for laminated glass with 3 mm+ 0.38 mm+ 3 mm for the plate with a crack (experimental results: Δze, numerical results: Δzn).

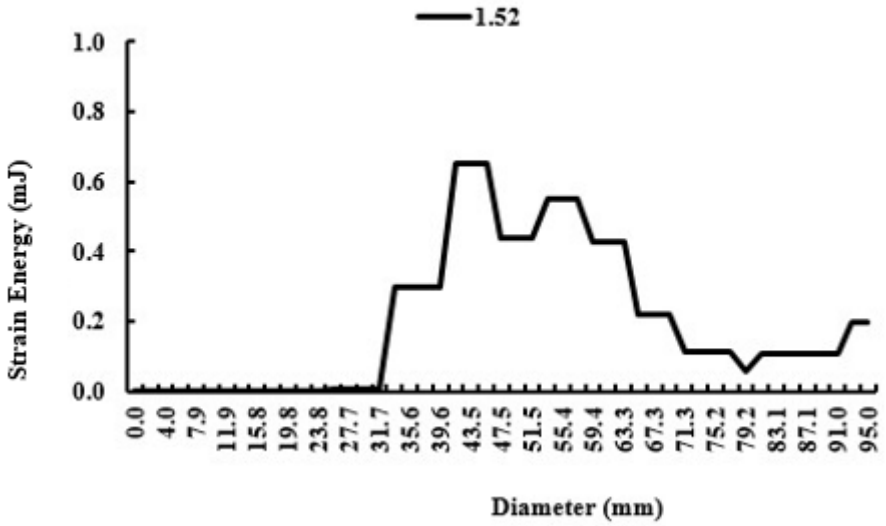


Figure 4.7. Variation of strain energy through diameter of cracked laminated glass plate with 3 mm+ 1.52 mm+ 3 mm.

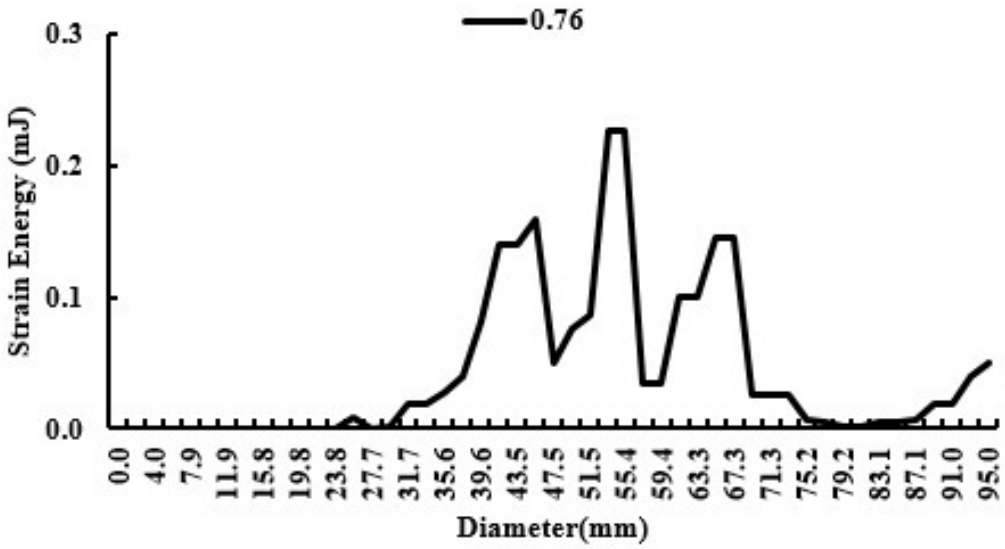


Figure 4.8. Variation of strain energy through diameter of cracked laminated glass plate with 3 mm+ 0.76 mm+ 3 mm

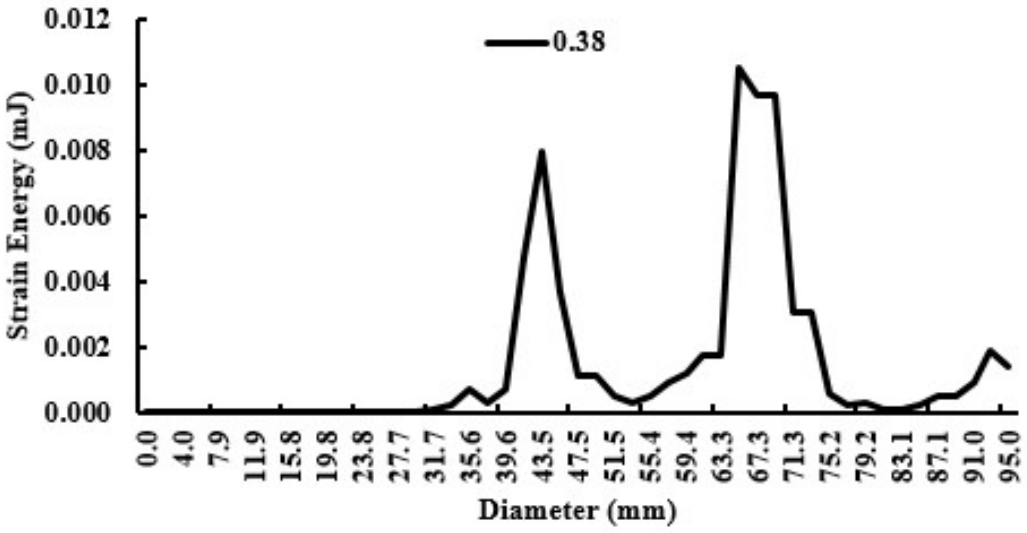


Figure 4.9. Variation of strain energy through diameter of cracked laminated glass plate with 3 mm+ 0.38 mm+ 3 mm

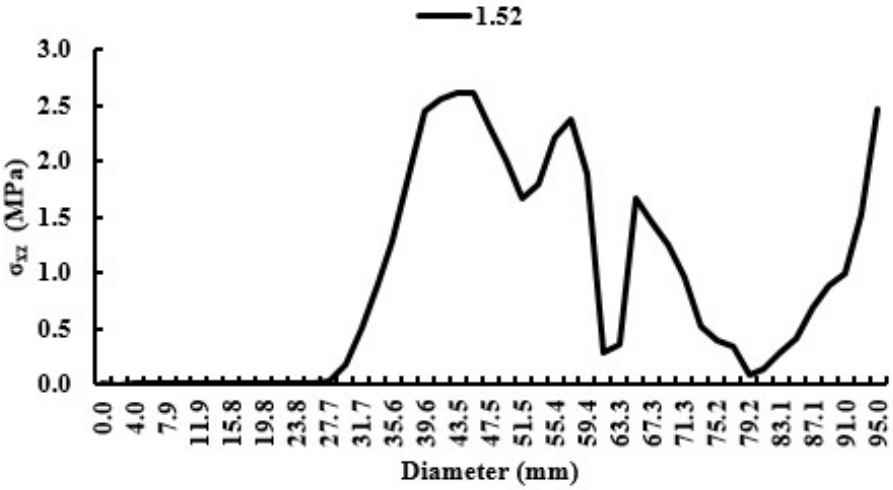


Figure 4.10. Variation of shear stress through diameter of cracked laminated glass plate with 3 mm+ 1.52 mm+ 3 mm

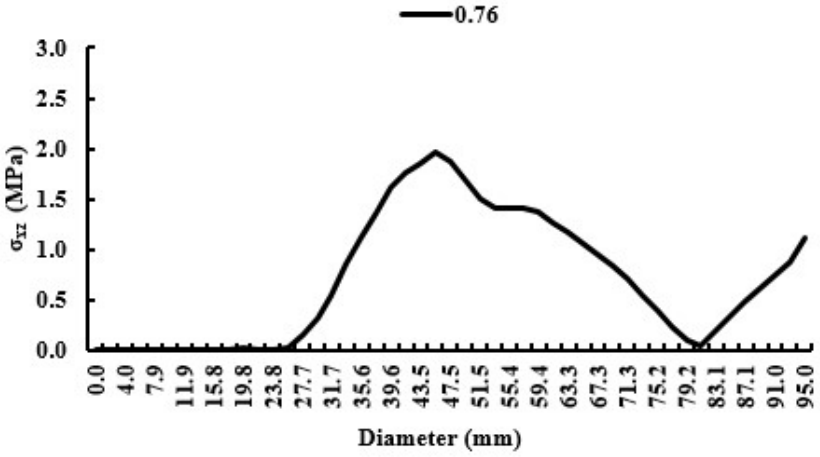


Figure 4.11. Variation of shear stress through diameter of cracked laminated glass plate with 3 mm+ 0.76 mm+ 3 mm

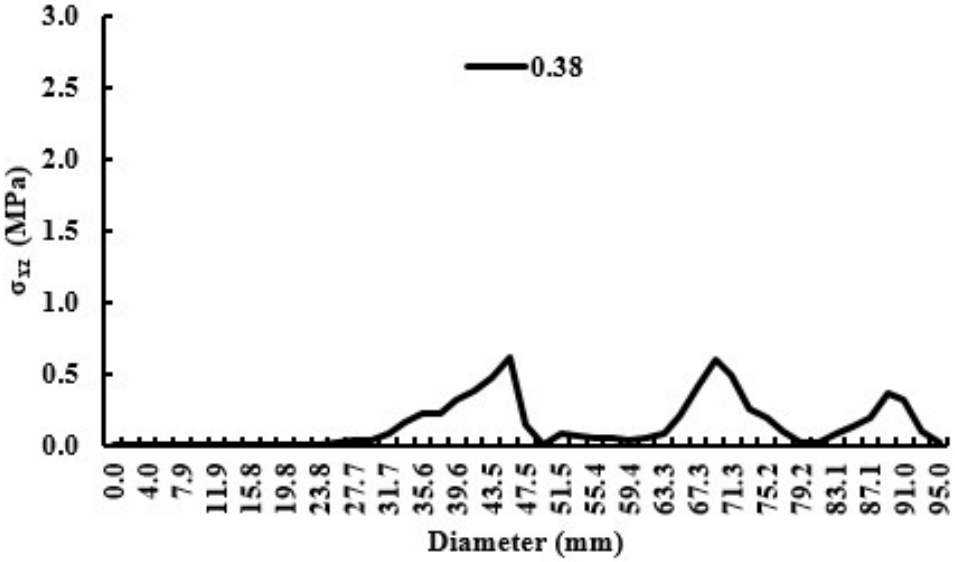


Figure 4.12. Variation of shear stress through diameter of cracked laminated glass plate with 3 mm+0.38 mm+3 mm

Table 4.1. Stress intensity factors and JINT values of a cracked laminated glass plate

PVB thickness	K_1	K_2	JINT
1.52	38.075	21.775	0.084
0.76	43.421	13.728	0.074
0.38	40.623	1.4671	0.078

By the way, the table's units of terms are as follows: (i) pvb thickness unit is mm, (ii) K1 and K2 unit are (MPa$\sqrt{mm}$) and (iii) J-INT unit is MPa mm.

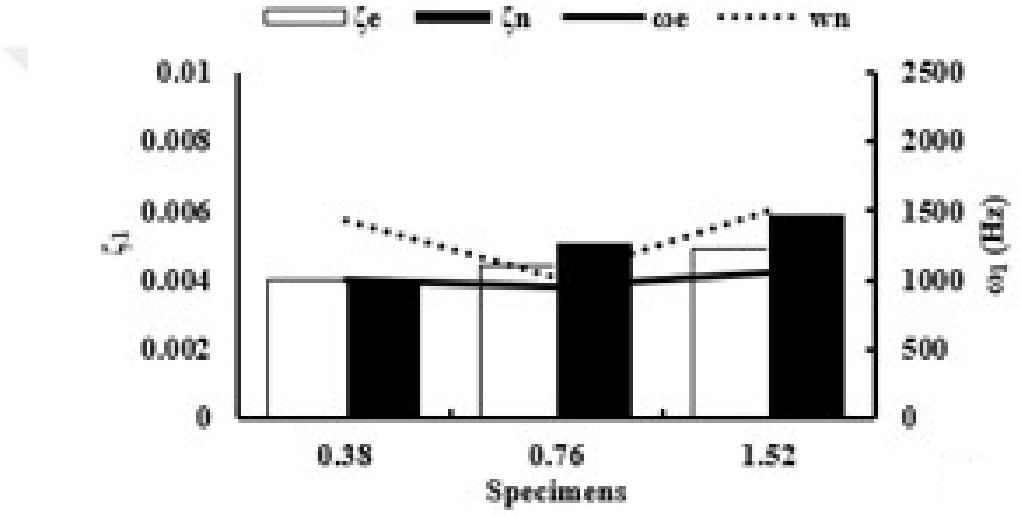


Figure 4.13. After low temperature testing, modal results of mode-1 of a laminated glass plate with no-crack crack(experimental: ωe, ζe, numerical: ωn, ζn).

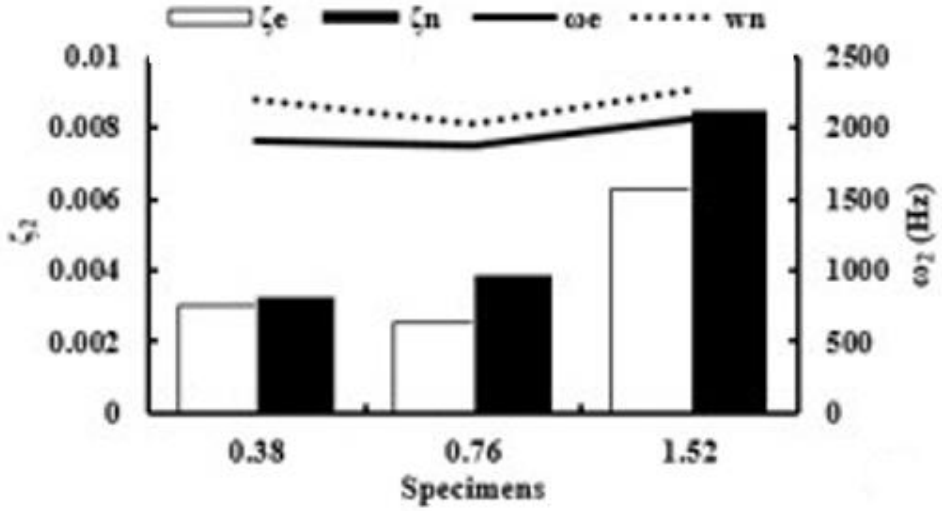


Figure 4.14. After low temperature testing, modal results of mode-2 of a laminated glass plate with no-crack crack (experimental : ωe, ζe, numerical: ωn, ζn).

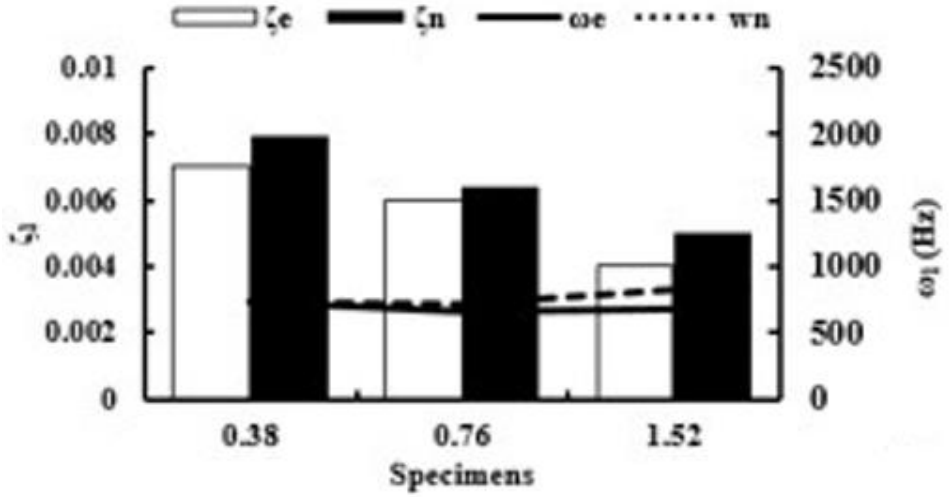


Figure 4.15. After low temperature testing, modal results of mode-1 of a laminated glass plate with a crack (experimental: ωe, ζe , numerical : ωn, ζn).

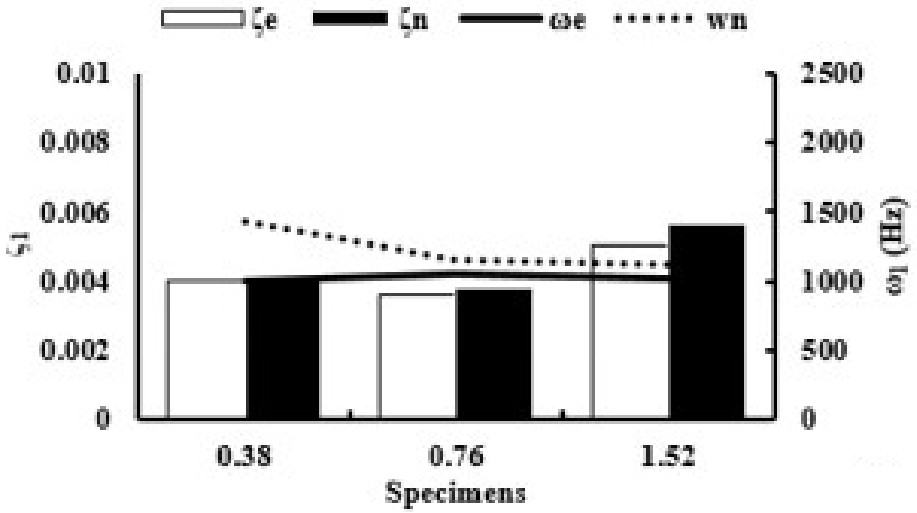


Figure 4.16. Modal analysis results of a laminated glass plate before low temperature testing mode-1 (experimental : ωe, ζe , numerical: ωn, ζn)

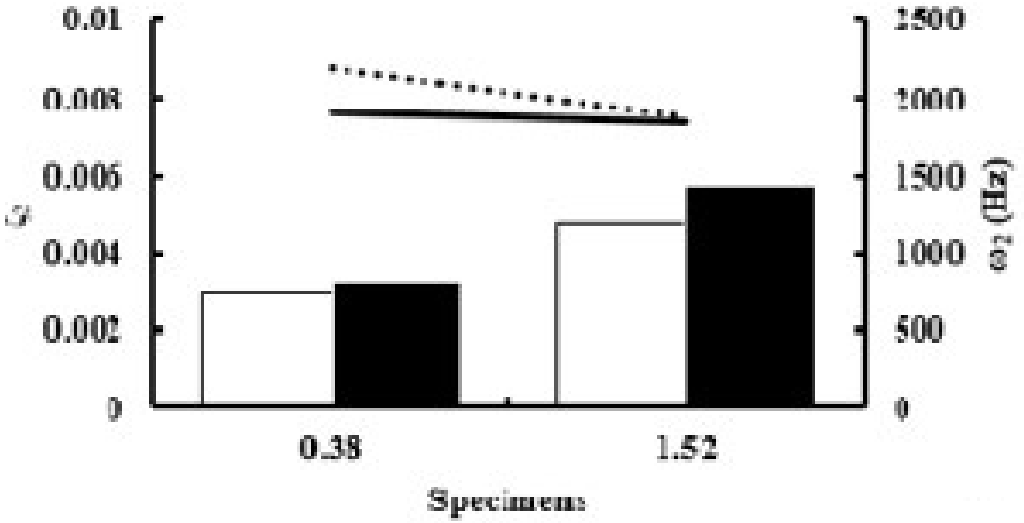


Figure 4.17. Modal analysis results of a laminated glass plate before low temperature testing mode-2 (experimental: ωe, ζe, numerical: ωn, ζn)

Numerical results of variation of shear stress through diameter of cracked laminated glass plates at room temperature are given in Figures 4.7-4.9 It is concluded that (i) in the same way as strain energy, decreasing interlayer thickness decreases shear stress, (ii) center through shear edge effect decreases when decreasing interlayer thickness (see K_2 values in Table 4.1).

Modal analysis results of a laminated glass plate before and after low temperature testing are given in Figure. 4. 10 and 4.11. One may conclude that (i) finite element model for the dynamic analysis is slightly acceptable, (ii) after low temperature testing, both natural frequency and damping ratio values increase slightly for interlayer thickness of 1.52 mm, (iii) Crack effect on free vibration characteristics are clearly observed for all three interlayer thicknesses.

4.2 Conclusion

Mechanical characteristics of a laminated glass plate at low temperatures are investigated by considering three main interlayer thicknesses. External stress and temperature are applied to the lower monolithic glass layer. Effect of the stress and temperature variations on central surface crack at upper monolithic glass layer is also taken into account. Experimental and numerical

results indicate that (i) there are nonlinear displacement and stress behaviors through the lower temperatures up to -100ºC, (ii) PVB thickness is the key for critical mechanical characteristics such as elastic strain energy and shear stress, (iii) temperature range between -50 and -85ºC is critical for the fracture mechanics point of view, (iv) fracture pattern in temperature range of -50 and -85ºC is to be focused for the interlayer studies.

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