BEHAVIOUR OF LAMINATED GLASS PANELS SUBJECTED TO IMPACT AND AIR BLAST LOADING

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Thesis submitted to Centre for Graduate Studies, **Universiti Pertahanan Nasional Malaysia**, in fulfillment of the requirements for the Degree of Master of Science (Civil Engineering)

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Specially dedicated to:

My beloved father, Lee Yoon Fut,

My beloved mother, Hoo Len Yin,

My lovely brother, Lee Wei Shiong,

My supervisors, Assoc. Prof. Ir. Dr. Mohammed Alias Bin Yusof and

Brig Jen Prof. Ir. Dr. Norazman bin Mohamad Nor

ABSTRACT

Attacks directed towards vulnerable structures have caused considerable damages to personnel, equipment and also loss of life. Due to this, laminated glass has been adopted as a safety glass for building as it offer higher protection to human and surroundings even after the glass is cracked. The objectives of this research is to investigate performance for impact and blast resistance of LG PVB, LG EVA, LG PU Resin and LG SGP. The methodology in this research is divided into three major parts. The first part is to determine the mechanical properties of the laminated glass with different interlayers. Second, experimental work for impact test was carried out using EN 356 and third is field blast testing carried out according to ASTM F 1642-04 to obtain the blast related data and also to investigate the behaviour of the laminated glass subjected to air blast loading. The impact test result shows that only LG SGP survived in the impact test using 5.5 kg of steel indenter at a distance of 1.15m and be able to absorbed a total of 65 Joule of impact energy. On the other hand, the blast test result shows that LG SGP, LG PU Resin and LG PVB able to withstand the peak overpressure of 337.84 kPa and reflected pressure of 4688.43 kPa with the SGP interlayer perform the best among all the other interlayers. While LG EVA failed during the test. It is recommended that the SGP to be used as blast resistant glass for building subjected to terrorist attacks. This research is expected to contribute new knowledge on safety to human as glass is widely used in all areas.

ABSTRAK

Serangan ke struktur terdedah telah menyebabkan kematian dan kerosakan kepada peralatan. Oleh itu, kaca berlapis telah digunakan sebagai kaca keselamatan untuk bangunan kerana menawarkan perlindungan yang lebih tinggi kepada manusia dan persekitaran walaupun selepas kaca itu retak. Objektif penyelidikan ini adalah untuk menyiasat prestasi kesan dan rintangan letupan LG PVB, LG EVA, LG PU Resin dan LG SGP. Metodologi dalam kajian ini dibahagikan kepada tiga bahagian utama. Bahagian pertama adalah untuk menentukan sifat mekanik kaca berlapis dengan interlayer yang berbeza. Kedua, kerja eksperimen untuk ujian impak dijalankan berdasarkan EN 356 dan ketiga adalah ujian letupan lapangan yang dijalankan mengikut ASTM F 1642-04 untuk mendapatkan data yang berkaitan dengan letupan dan juga untuk mengkaji kelakuan kaca berlapis dengan pemuatan letupan udara. Hasil ujian menunjukkan bahawa hanya LG SGP terselamat dalam ujian impak menggunakan 5.5 kg indenter keluli pada jarak 1.15m dapat menyerap sejumlah 65 Joule tenaga impak. Seterusnya, keputusan ujian letupan menunjukkan bahawa LG SGP, LG PU Resin dan LG PVB mampu menahan tekanan tinggi tekanan 337.84 kPa dan tekanan yang dicerminkan 4688.43 kPa. LG SGP adalah terbaik di kalangan kaca berlapis yang lain. Adalah dicadangkan bahawa SGP akan digunakan sebagai kaca tahan ledakan untuk bangunan yang dikenakan oleh serangan pengganas. Penyelidikan ini boleh memberi ilmu yang baru mengenai keselamatan manusia terhadap kaca.

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APPROVAL

The Examination Committee has met on 17th June 2020 to conduct the final examination of Lee Wei Szer on her master thesis entitled ' Behaviour of Laminated Glass Panels Subjected to Impact and Air Blast Loading'.

The committee recommends that the student be awarded the Master of Science (Civil Engineering).

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DECLARATION OF THESIS

Student's full name : Lee Wei Szer

Date of birth : 15th October 1991

Title : Behaviour of Laminated Glass Panels Sebjected to Impact and Air Blast Loading

Academic Session : 2018 - 2020

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LIST OF ABBREVIATIONS

C4	Composition C-4
EVA	Ethyl Vinyl Acetate
PVB	Poly Vinyl Butyral
SGP	Sentry Glas® Plus
PU Resin	Polymer Resin
LG EVA	Laminated Glass with EVA interlayer
LG PVB	Laminated Glass with PVB interlayer
LG SGP	Laminated Glass with SGP interlayer
LG PU Resin	Laminated Glass with PU Resin

CHAPTER 1

INTRODUCTION

1.1 Introduction

Natural glass scientifically known as obsidian, and had been utilised by man since prehistoric days. Glass was discovered in the Middle East around 7000 BC and have been in use in Egypt since 3500BC (Tsampiri, 2018). Later, glass bottles were developed in Egypt in 1500 BC. During the era of the Renaissance, coloured glasses, crystals and mirrors had all been developed and made in Venice (Adam et al., 2013). Glass is arguably, the most remarkable material ever discovered (Michael, 2014). Glass has been used in construction since 2000 years ago (Fatemeh, 2016). While in recent years, the application of glass in the field of construction has been widely developed because of the advantages of using glass has over other materials in building construction. The use of glass as a component of a building structure has been increasing since its initial introduction as a building material as windows in the early 19^{th} century (Kashif, 2018). In response to the highly demanding market forces, new glass types have emerged in spot applications over the past two decades. It includes the high compressive strength, which has the ability to resists corrosion (Hess, 2004).

A revolution in the production of flat glass began in 1959 by Pilkington Ltd in Britain. Various architectural designs with the addition of intelligent engineering solutions have resulted in lots of stunning buildings all over the world. For example, The National Grand Theatre of China or also known as Bird's Egg, is an opera house in Beijing. The titanium and glass building of this structure was designed by French architect Paul Andreu. The exterior of the National Centre for the Performing Arts, like a steel-structured oval shell, is an ingenious material integration of over 18,000 titanium plates and over 1,000 sheets of ultra-white glass, which creates a vivid visual effect as if the curtain is drawn apart slowly before your eyes. With the weight of 6,457 tons and the longest axis of 696 feet (212 meters), the steel-structured oval shell is the largest dome in the world at present (Schmich et al., 2008). The National Grand Theatre of China is shown in Figure 1.1.

Figure 1.1 National Grand Theatre of China (Larry, 2020)

Other than the National Theatre of China, the Agbar Tower from Barcelona, Spain sometimes also known as Torre Agbar is a 21st Century skyscraper. The tower is 142m in height and is the third tallest building in Barcelona. This tower consists of 4,400 windows and 56,619 transparent and translucent glass plates. The louvers are tilted at different angles that will deflect the sunlight (Layetana et al., 2005). The Agbar Tower from Barcelona, Spain is shown in Figure 1.2.

Figure 1.2 Agbar Tower from Barcelona, Spain (Layetana et al., 2001)

In addition to the stunning glass structure all over the world, the glass properties also need to be improved to withstand the blast and impact loading. This can be done by providing various method to strengthen the glass structure such as by tempering and laminating process. One of the most common method used widely is provided laminating using various types of interlayer such as Poly Vinyl Butyral (PVB), Ethyl Vinyl Acetate (EVA), Sentry Glas® Plus (SGP) and also Polymer Resin (PU Resin) to improve the blast and impact resistance of the glass (Nurhuda, 2011).

1.2 Problem Statement

Today, most of the amazing buildings' facades are constructed using ordinary glasses and without much protection from damages, especially from terrorist attacks. Terrorist attacks and bombings of buildings and infrastructures have become a global phenomenon. For examples of the terrorist attacks in Norway (2011), Belgium Airport (2017) and Sri Lanka (2019) shows that most of the building façades are not capable of withstanding the blast loading from the explosions. For example, in the Norway attack in year 2011 as shown in Figure 1.3. The blast pressure from the car bomb smashed nearly all the glass windows of the Oslo Executive Government Building. 209 out of 325 injuries were involved with glass shatters (Zhang et al., 2012). This results in glass breakages, thus producing sharp structures. Most of the building façades are made up of laminated annealed glasses and also tempered glasses. This type of glasses will break into pieces. Laminated glass with PVB interlayer (LG PVB) have potential to resist blast and most of the researches have investigated on the properties of LG PVB (Pilkington Group Limited, 2010). However, in the recent development of the laminated glass industry, there are also several interlayers which are commonly used nowadays such as EVA, SGP and PU Resin have been developed. Currently, there is only limited research conducted on the LG PVB, laminated glass with SGP interlayer (LG SGP) and laminated glass with PU Resin interlayer (LG PU Resin). However, there is no research conducted to study the impact and blast resistant of laminated glass with EVA interlayer (LG EVA), LG PVB, LG SGP and LG PU Resin as an interlayer. Therefore, this research will study the behaviour of the interlayer PVB, EVA, SGP and PU Resin subject to blast and impact loading. At the same time, also compare their performance when subject to blast and impact loading.

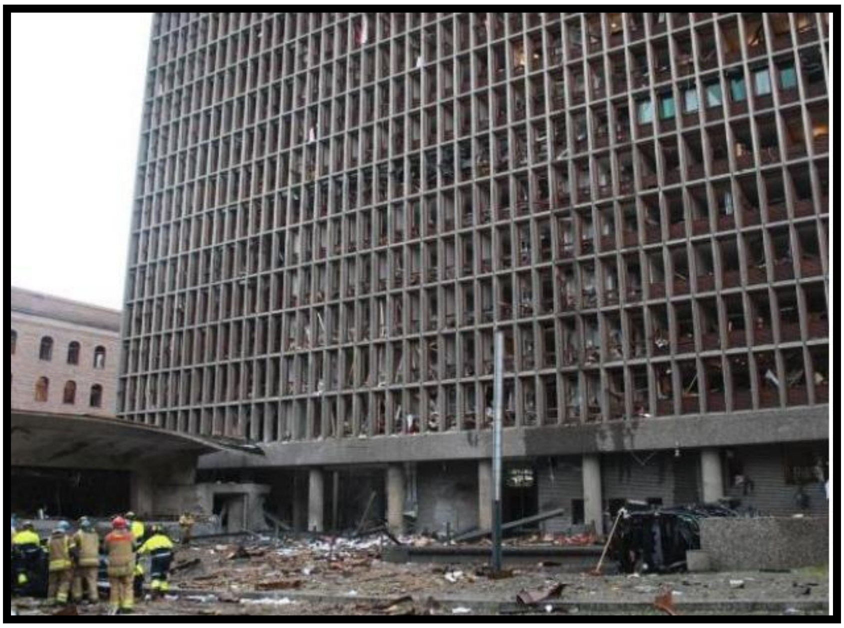

Figure 1.3 Oslo Executive Government Building in Norway attack (Zhang et al., 2017)

1.3 Objectives

The main objectives of this study are as follows:

1. To determine the mechanical properties which includes tensile, flexural and compressive of interlayer glass panel.

2. To investigate the performance for impact resistance of LG EVA, LG PVB, LG SGP and LG PU Resin which are subjected to air blast and impact loading.

3. To investigate the performance for air blast resistance of LG EVA, LG PVB, LG SGP and LG PU Resin which are subjected to air blast and impact loading.

1.4 Scope of Research

The scope of this research is limited to determine the mechanical properties of the four types of laminated glasses which are tensile strength test of interlayer, flexural test of laminated glass and compressive strength test of laminated glass. Tensile strength test of the interlayer was based on ASTM D638-10 while flexural test of laminated glass was based on ASTM C158-02. As for compressive strength test of laminated glass were based on the ASTM C39. Next, impact test was conducted based on EN 356 classes P1A to P5A. Lastly, field blast testing was carried out according to ASTM F 1642-04 to obtain the blast related data and also to investigate the behaviour of the 6.76mm of LG PVB, 6.76mm of LG EVA, 7mm of LG PU Resin and 6.89mm of LG SGP subjected to air blast loading.

1.5 Significance of Research

This research is expected to contribute new knowledge on safety to human as glass is widely used in all areas and the data on the impact and blast resistance behaviour of laminated glasses with different types of interlayer which include LG PVB, LG EVA, LG SGP and LG PU Resin.

1.6 Thesis Layout

This thesis dissertation consists of five chapters. Chapter one gives the reader an introduction to this study and all the objectives have been derived from the problem statement.

Chapter two shows an overview of the laminated glasses used in this research project which is manufacturing process of glass, mechanical properties of interlayers, types of laminated glasses, laminated glass materials used for impact loading, air blast loading, the prediction of blast loading, experiments that have been conducted by other researchers previously, standard use for mechanical properties, impact loading test and blast test.

Chapter three discusses on the methodology and materials used in this research project. A specific approach in conducting the experimental works, preparation of materials and field blast tests is discussed in this chapter.

Chapter four presents the results for experimental work and then discusses the experimental work in this chapter.

Chapter five presents the conclusion obtained from this research and also the recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Glass is manufactured from some cheap raw materials which is easily available in large quantity and most importantly glass can be recycled and often considered as environmental friendly. Besides, the majority of glass used nowadays is either sheet glass or glass moulded into jars or bottles. About 95 % of sheet glass is used for glazing in houses and factories, with the remaining 5 % used for making mirrors or are toughened materials for the use in domestic appliances such as ovens and nearly 40 % of the total glass wares are exported (Stephanie et al., 2002).

2.2 Glass

According to Lenntech (2018), the term ‘glass’ is often referred as a hard material, but it is normally fragile and transparent. It is composed mainly of sand or silicates, SiO_2 and an alkali. These materials are fused together at a high temperature and cooled rapidly to form a rigid structure.

However, glass does not have enough time to form regular crystalline structure. The composition of glass and its cooling rate depends on the final use and the application of glass which will achieve the adequate properties for the specific application.

Silica based materials are the most popular chemical used to manufacture glass. This type of glass is also suitable to be used in designing architectural and automotive glasses, containers, table glassware, glass wool for heat insulation and decorative objects. However, glass nowadays is made basically from many different compositions using a wide variety of processes in giving the end products with better properties and applications (Lenntech, 2018). Table 2.1 shows the chemical composition of silicon-soda-lime glass according to European construction standards.

Table 2.1 Chemical Composition of Soda Lime Silica Glass*

Silica sand	SiO_2	71 – 73%
Soda	Na_2O	11 - 12.2
Boron-oxide	B_2O_2	7 – 15 %
Potassium oxide	K_2O	0 – 2 %
Alumina	Al_2O_3	0 – 8 %
Calcium oxide	CaO	12 – 14 %
Magnesium oxide	MgO	1.1 – 2.0 %
Iron oxide	Fe_2O_3	0 – 2 %

* Adapted from Kumar et al. (2002)

2.3 Production of Glass Panels

Glass is produced by the float process, which was introduced by Pilkington Brothers Ltd in the 1950s (Olive et al., 1985). The production of glass panel consists of four main steps which are batching, melting, fining, and forming. These processes are shown in Figure 2.1.

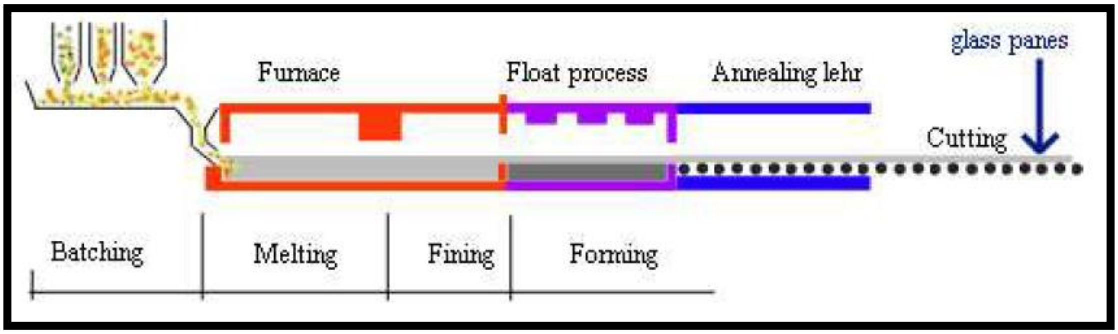

Figure 2.1 Production process of glass (Lam et al., 2011)

According to Lam et al. (2011) initially glass making was a batching process. In this process, all the raw materials such as sand, soda ash, limestone, dolomite and alumina were selected and weighed accordingly in the batching process and soda ash was added. The purpose of adding soda ash is to expedite the melting process. The function of the limestone is to make the glass become more durable. In addition, the function of the dolomite is to increase the working and weathering properties.

Next is the melting process. In this process, all the raw materials are melted in a furnace at 1500°C. Finally, the melted raw materials go through the fining process. At this stage of the fining process is to produce a homogenous and bubble free molten gas, which can be obtained by regulating the temperature and adding of fining agents.