Effect of polyurea interlayer on ballistic performance of ceramic armor module against long rod impact

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**Effect of Polyurea Interlayer on Ballistic Performance of
Ceramic Armor Module against Long Rod Impact**

LUO BOYANG

**SCHOOL OF MATERIALS SCIENCE AND ENGINEERING
2020**

Effect of Polyurea Interlayer on Ballistic Performance of Ceramic Armor Module against Long Rod Impact

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SCHOOL OF MATERIALS SCIENCE AND ENGINEERING

A thesis submitted to the Nanyang Technological University in
partial fulfilment of the requirement for the degree of
Master of Engineering

2020

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Abstract

Improvement of ballistic resistance of ceramic armour against long rod impact is of great interest to armor designers and researchers. Spray-coating of a layer of polyurea on the front and/or back surfaces of metallic armor have been widely investigated to improve the protective performance of the metallic armor subjected to projectile impact. However, the study on the application of polyurea in ceramic armor for ballistic performance enhancement against long rod impact at high impact velocity (> 1000 m/s) is still lacking.

This project investigates the effects of mechanical properties of polyurea on the ballistic resistance of ceramic armor modules against long rod projectile impact. The effects of the strength and thickness of polyurea on the ballistic resistance of ceramic armor modules were studied through experiments and numerical simulations.

Two types of polyurea (PUK&PUD) were successfully synthesised in Ma Jan High-Speed Dynamics Lab. Quasi-static tensile, compression and shear tests were carried out to compare the mechanical properties of PUD and PUK polyurea. It reveals that PUK polyurea has a higher yield strength of 10 MPa and lower elongation of 360%. PUD polyurea has a lower yield strength of 0.8 MPa and higher elongation of 500%. Significant increment of shear stress and shear modulus were observed with applying compressive stress for both types of polyurea.

This study investigated the effect of two primary factors of polyurea on the ballistic performance of ceramic armor modules; (1) strength of polyurea, (2) thickness of polyurea interlayer.

The mass efficiency of ceramic target module increased from 1.59 to 1.85 when 2 mm PUK polyurea was used as an interlayer between ceramic and cover plate. In contrast, the mass efficiency decreases from 1.85 to 1.68 with reducing the flow stress of polyurea from 9.8 MPa to 1 MPa.

The mass efficiency of ceramic armor module varies with increasing polyurea interlayer thickness from 0 to 6 mm. Ceramic armor module with 2 mm polyurea interlayer has

the highest mass efficiency. The mass efficiency reduced with increasing the thickness of polyurea.

Through these experiments, it can be concluded that: (1) polyurea could improve the ballistic performance of ceramic amour module by influencing the dwell time. (2) Polyurea with higher strength would have better ballistic performance. (3) The optimised thickness of polyurea interlayer is 2 mm.

Simulations for the two types of polyurea under dynamic load were validated through the quasi-static test, SHPB test and ballistic experiment. It was found that the simulation model of the ceramic module with polyurea as an interlayer has acceptable accuracy. According to the simulation results, it has been confirmed that the polyurea interlayer could enhance the ballistic resistance of ceramic armor module by influencing the dwell time. With polyurea interlayer, the shock wave caused by projectile impacting ceramic tile can be attenuated. So the dwell time is increased with proper choice of the material and thickness.

Lay Summary

Large number of research have been carried out to understand the application of polyurea coating in blast mitigation. Some researchers investigated the effect of polyurea coating in enhancing the ballistic resistance of aluminium armour and ceramic armour at a velocity lower than 1000 m/s. Limited researches are available for the investigation of the ability of polyurea interlayer in a ceramic armor subject to high-velocity impact (> 1000 m/s) of long rod projectiles.

This study attempted to address the gap in knowledge by examining the ability to use polyurea coating as an interlayer to enhance the ballistic resistance of ceramic armor module.

The effect of polyurea interlayer in enhancing the ballistic resistance of ceramic armor modules was investigated by correlating ballistic experiment results and computer simulation.

This study investigated the effect of two primary factors of polyurea on the ballistic performance of ceramic armor modules; (1) strength of polyurea, (2) thickness of polyurea interlayer.

Two types of polyurea (PUD&PUK) were successfully synthesised. Through ballistic experiments, it was found that polyurea could improve the ballistic performance of ceramic amour module by influencing the dwell time. The key finding of this study was to correlate mechanical properties of poylurea interlayer with ballistic resistance of ceramic armor modules against long rod projectile impact. Increased polyurea strength could improve ballistic resistance of ceramic armor by extending the dwell time. The optimised thickness of polyurea interlayer is 2 mm.

Simulations for the two types of polyurea under dynamic load were validated through the quasi-static test, SHPB test and ballistic experiment. It was found that the simulation model of the ceramic module with polyurea as an interlayer has acceptable accuracy.

Accordingly, the ceramic armor module using this simulation model can be used to optimise the module design.

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Abbreviations

AD	Area Density
AISI	American Iron and Steel Instituted
DOP	Depth of Penetration
ME	Mass Efficiency
FEM	Finite Element Method
SPH	Smooth Particle Hydrodynamics
RHA	Rolled Homogenous Armor
SiC	Silicon Carbide

Chapter 1 Introduction

This chapter gives a brief introduction to the development of ceramic armor and application of polyurea. The objectives and outcomes of this study are also explained in this chapter.

1.1 Background

Armor protection is one of the most important elements for the survivability of soldiers in combat. Gen Shergill [1] pointed out that human life has been considered a precious commodity. Therefore, creative design and armor module optimisation was needed to provide better protection. Tanks were first used to provide protection for soldiers in World War I and were widely used in World War II. In the beginning, engineers improved the protection of tanks by increasing rolled homogenous armor (RHA) thickness. Tanks with over 100 mm RHA front armor were widely used in the World War II, such as Tiger I, Tiger II and M4A3E2 Sherman Jumbo. As one of the main factors for combat effectiveness of tank was its mobility, the weight of the tank was limited by its power-to-weight ratio. [2]

Weight of armor system was reduced through the introduction of ceramic armor with metallic and polymeric materials and were widely used since the Vietnam War. [3-6] The properties of high hardness and low density made ceramic an attractive material in armor system. Rosenberg et al. was the pioneer in conducting a series of ballistic tests on ceramic. [7-10] The widely used material model for ceramics was derived by Johnson et al. and Holmquist et al. [11-14] These works laid the foundation for ceramics armor system design.

Polyurea is an elastomer material invented in 1959. This material is the reaction product of synthetic resin and isocyanate component. Taking the advantages of high elongation, high strain rate sensitivity, fast reactivity and relatively low moisture sensitivity, polyurea was widely sprayed as a coating or interlayer for protective applications in the past a few decades. [15]

However, most researches on polyurea focused on blast mitigation. [16-22] The few studies which applied polyurea for improving the ballistic performance of armor [23-25] focused on projectiles with impact velocity under 1000 m/s. Study for its role in higher impact velocity is unavailable, but has become increasingly important. Therefore, in this study, the application of polyurea as an interlayer in ceramic armor against long rod projectile penetration with a nominal impact velocity of 1250 m/s will be investigated.

Specifically, the effects of mechanical properties (elongation, strength) and layer thickness of polyurea on ballistic resistance of ceramic target module will be investigated. As an increase of polyurea strength would reduce its elongation and vice versa, identifying their roles in ceramic armor is essential for design optimisation. On top of that, polyurea layer thickness study will be carried out for further optimisation. The investigation will provide vital information to armor designers to select suitable polyurea interlayer for ceramic armor modules.

1.2 Hypothesis

“This thesis tests the hypothesis that the strength of polyurea interlayer could affect the ballistic performance of ceramic armor modules.”

1.3 Objective and Scope

The objective of the research is to

“The present research is concerned with the experiment and simulation to investigate correlation between polyurea interlayer mechanical properties and ballistic performance of ceramic armor modules.”

This study aims to investigate the effects of mechanical properties of polyurea and the interlayer thickness on the ballistic resistance of ceramic armor module.

The work of scope covers

- (1) Quasi-static tensile, compression and shear tests, Split Hopkinson Pressure Bar (SHPB) tests, ballistic experiments, and computer simulation were used to achieve these objectives. The mass efficiency (ME) was used to assess the ballistic resistance of ceramic armor module.
- (2) The strengthening mechanism of ballistic resistance of ceramic armor modules was assessed through computer simulations. With the investigation of the effect of polyurea strength and thickness in ceramic armor modules, the author seeks to provide practical guidelines for using polyurea to improve the resistance of ceramic

armor modules to high-speed projectile penetration.

1.4 Dissertation Overview

The thesis addresses:

Chapter 1 presents an overview of polyurea and ceramic armor development and gaps observed by the authors and then followed with hypothesis and objectives.

Chapter 2 reviews the literature with regards to polyurea and ceramic armors. This chapter discusses the defeating mechanism of long rod projectile against ceramic armors, followed with the effect of the cover plate in ceramic armor modules. This chapter also discusses the mechanical properties of polyurea and the application of polyurea in protection applications. Then, the simulation models used in this study are discussed.

Chapter 3 provides the experimental methodology used in the study; including quasi-static tensile, compression & shear test, dynamic Split Hopkinson Pressure Bar test and ballistic tests. The detailed simulation model is also described in this chapter.

Chapter 4 presents the experimental results and simulation results. The correlation between polyurea strength & thickness and ballistic performance of ceramic armors are discussed. This chapter also presents the strengthening mechanism of using polyurea as an interlayer in ceramic armor modules through simulation.

Chapter 5 concludes the findings of this study. Recommendations for future work based on the drawn conclusions are discussed.

1.5 Findings and Outcomes

This research leads to several different outcomes by:

1. Synthesis and optimised two types of polyurea in Ma Jan High Speed Dynamic lab. Ballistic experiments show that PUK could enhance the ballistic resistance of ceramic armor module when it is used as the interlayer.
2. Established the correlation between the ballistic resistance of ceramic armor module with polyurea strength.
3. Established the correlation between the ballistic resistance of ceramic armor module with polyurea interlayer thickness.
4. Verified the simulation model of ceramic armor module with polyurea as an interlayer. Researchers could optimize the ceramic armor design using the verified simulation model.

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Chapter 2

Literature Review

In this chapter, the literature review is carried out on the design of ceramic armors. The first part summarizes the state-of-the-art research work on ceramic armor against long rod projectile impact test methods for armor study and theories of long rod projectile and ceramic armors. The second part of this chapter covers the experimental works of polyurea for protective applications. The last part of this chapter explains the simulation models for ceramics, metals and polyurea, laying down the foundation for simulation work in this study.

2.1 Ballistic Test

There are many methods to evaluate the ballistic resistance of ceramic armor modules. Wilkins et al. developed the ballistic limit method in 1968 to evaluate the ballistic resistance of ceramic against 7.62 mm AP rounds. [1],[2] This method was to find out the required impact velocity to penetrate an armor module, [3]-[5], i.e. there is 50 % chance that an armor module would be penetrated at a particular velocity. To obtain this velocity, a series of experiments are required for each armor configuration due to material properties fluctuation. As a result, this method is time-consuming and costly.

To reduce the number of experiments required, another method, suggested by Bless et al. [6] and Rosenberg et al., [7] was widely used to assess the performance of ceramic armor modules. [8]-[18] In this method, one semi-infinite thick steel, also known as witness block, is placed behind the ceramic armor modules. The performance of ceramic armor module is evaluated based on the residual depth of penetration (DOP) of projectile into the thick backing. To define “semi-infinite” thick steel, Rosenberg carried out the simulation of tungsten-alloy long rod projectile at impact velocity of 1400 m/s to 2200 m/s.[19] A series of DOP tests of tungsten alloy long rod projectile were carried out by Littlefield et al. at impact velocity of 1500 m/s. [20] It was suggested that the diameter of witness block should be larger than 25 times of projectile diameter. Its thickness was required to be larger than 2 times of penetration depth.

2.2 Long Rod Penetrator

Long rod projectile has length/diameter (L/D) ratio larger than 10. They are made of high density metals such as tungsten alloy. The penetration of long rod projectiles into metallic material and ceramics had been systematically studied in the past decades. [21]-[23] In **Figure 2-1**, Christman et al. pointed out that the penetration process could be described by four stages: transient, primary, secondary and recovery. [24] In the transient phase, the projectile nose impacts the surface of target and generate high pressure shock wave. After the projectile penetrate into target with depth of few diameters of projectile, the projectile reaches the primary penetration phase. In this phase, the projectile has a constant penetration velocity. For long rod projectiles, the primary phase is relatively long and dominates the depth of penetration. The projectile

reaches the secondary penetration phase when it has completely deformed. In this phase, shear deformation takes place at the wall of crater and the crater expands. As the pressure decays in the secondary penetration phase, the strain rate response and strength of material are taken into account. When the energy density behind the expanding shock wave is insufficient to deform the backing material, the penetration process reaches the fourth phase: recovery phase. In the recovery phase, the crater contracts and brittle-type fracture takes place at the crater surface.

Figure 2-1: Four phases of high-velocity penetration process [24]

2.3 Ceramic Armors

It was found that by applying high hardness material as a coating on metals improved its ballistic performance during World War II. [25] As ceramics has high hardness and relatively low density, [26]-[31] ceramic-based armor had been developed and serviced to protect helicopter and aircraft since the Vietnam War. [32]-[35] Many different ceramic materials were used in armor applications, such as Alumina, Boron Carbide and Silicon Carbide. [36]-[39] In ceramic-based armor design, its ballistic performance, weight and manufacturing ability are usually considered. [40] Alumina has low cost as it could be fabricated by slip casting, pressing and injection moulding. [41] However, the density of alumina (3.95 g/cm^3) is relatively high compared to non-oxide ceramics. Boron carbide has a low density and excellent ballistic performance at low velocity. [[42]] However, the shear strength of boron carbide drops when the impact pressure

exceeds its Hugoniot elastic limit. [43]-[45] Chen et al. pointed out that this was due to localised amorphisation of boron carbide. [46] As a result, boron carbide is not suitable for high-velocity impact applications. Silicon carbide has a relatively low density and excellent physical properties. [47] The reaction-bonding method allows large-sized fabrication of silicon carbide with low cost. [48] In this report, silicon carbide grade F plus was used for the study.

2.4 Cover Plate in Ceramic Armor Modules.

Researchers investigated different configurations to enhance the ballistic resistance of ceramic armor modules in the past decades. In the study of Hauver et al. in 2005, it was found that the ballistic resistance of ceramic armor could be improved by applying a complex cover system. [50] As shown in Figure 2-2, the cover system includes a thick shock-wave attenuator followed with a metal layer. Weak material, such as graphite and polytetrafluoroethylene, was applied as an interlayer between the metal cover plate and ceramic tile. Also, lateral prestress was applied to the ceramic tile by shrink fit of ceramic tile with the steel frame at 538 °C. The authors pointed out that a certain level of prestressing could improve the dwell time of projectile. **Figure 2-3** compares the penetration process of the projectile into ceramic tiles. The top picture shows that the projectile directly erodes into the ceramic tile when 6 mm of ceramic was used as a cover plate. The bottom picture showed the dwell of the projectile when the heavy target configuration was used. In the study of Andersson et al., 7.5 mm of copper was used as a cover plate in the reverse ballistic experiments. [52] Holmquist used one copper plate as a cover plate in his experiment. The copper plate was 20 mm in diameter and 0.5 mm in thickness, expanding the central part of 5.71 mm in diameter and 8 mm in thickness.[51] It was found that 200 MPa of prestress on ceramic would increase the required surface load to create damage cone from 13 GPa to 26 GPa. In the study of Tan, G et al., 2 mm titanium cover with weak interlayer were applied to the ceramic armor module. [53] They pointed out that such a cover system could attenuate the dynamic load applied to ceramic tiles and reduce the initial damage on ceramic tiles. These studies show that a properly designed cover plate in ceramic armor structure could enhance the ballistic performance of ceramic armor module.

Figure 2-2: Heavy-target configuration to investigate interface defeat of projectile at ceramic surface [50]

Figure 2-3: Penetration process of the projectile into ceramics [50]

2.5 Polyurea for Protective Applications

Polyurea is known as elastomeric copolymer via the reaction between difunctional isocyanate and difunctional amine. The resulting molecular structure consists of soft segment and hard segment. [54] As the urea linkages are highly polar, hard segments are self-clustering. Consequently, bulk polyurea contains segregated hard domains which are surrounded with soft domains. The hard domains have a high glass transition temperature. Therefore, they are crystalline. The hard domains control the stiffness and strength of polyurea. The soft domains have a low glass transition temperature, which makes polyurea ductile. [55]

With proper surface preparation, polyurea could be bond well with metallic materials and concrete. Polyurea has been used as an outer coating or inter-layer material for protective applications since decades ago. [49] Xue et al. investigated the effect of polyurea coating on DH-36 steel plates against rigid projectile experimentally and numerically. [56] It was found that applying polyurea coating at the back surface can improve the ballistic resistance of DH-36 steel. Mohotti et al. investigated the effect of polyurea coating as backing and interlayer for aluminium plates against 5.56×45 mm projectile at a velocity of 970 m/s to 990 m/s. [49] They pointed out that the residual velocity of the projectile was reduced with increasing polyurea coating thickness on the back surface due to increment of energy absorption. In addition, using polyurea as an interlayer was less effective in reducing the residual velocity of the projectile. Roland et al. studied the ability to use polyurea coating to enhance the ballistic resistance of high hardness steel plates against projectile at a velocity of 1000 m/s. [57] It was pointed out that the ballistic limit velocity of steel plate could be increased by using polyurea coating as an inter-layer. Amini et al. and Nasser et al. studied the response of steel-polyurea bi-layer structure under impulsive load. It was found that the interface bonding strength between polyurea coating and steel was critical for the performance of steel-polyurea bi-layer structure. [58], [59] Ackland et al. reported that polyurea coating could be used to mitigate damage in steel and concrete induced by the blast. [60] Bahei-EL-Din et al. studied the blast mitigation effect of polyurea as interlayer material between fibrous laminate composite and structural foam core. [61], [62] It was found that polyurea interlayer could reduce 43% of peak kinetic energy and 38% of energy dissipated to the foam core compared with the conventional structure. In the study of Tekalur et al., [63] it was suggested that applying polyurea coating at the surface facing blast pressure has a better blast-resistance effect. Grujicic et al. applied

polyurea coating as a suspension pad material for helmets. [64] Their experiments show that the polyurea layer could reduce the peak load sustained by the brain from blast impact.

2.5.1 Effect of Hydrostatic Stress on Shear Yield Behaviour of Polyurea

Numbers of researchers have pointed out that the mechanical properties of polymers are dependent on the hydrostatic pressure applied. [65]-[70] With increasing the pressure, the stiffness and yield stress increased for polymethylmethacrylate, [65], [67] polypropylene [68] and polystyrene [69]. The fracture stress and strain of polymethylmethacrylate (PMMA) [65] and polystyrene [65],[70],[71] was found to increase with increasing hydrostatic pressure. Under high pressure, brittle-ductile transitions have also been found to have changed for various materials [68],[71]. In the study of Ainbinder et al. it was found that the tensile modulus of various materials increased with increasing hydrostatic pressure.[65] This increment of Young's modulus may be caused by three factors: 1) change in the interatomic distance, [72] 2) the decrease in specific volume and 3) the finiteness of deformation. [65] Base on the investigation of Grujicic et al. and Birch [73], [74], the relationship between hydrostatic pressure and Young's modulus can be expressed with the following equation when considering finiteness and deformation.

$$\frac{\Delta E}{E_0} = \frac{\sigma_r}{E_0} f(v) \quad (1)$$

where ΔE is the increment of Young's modulus, E_0 initial Young's modulus, σ_r is the hydrostatic pressure, and v the Poisson's ratio.

Figure 2-4: Shear Modulus of PMMA verses hydrostatic pressure [65]

In the study of Rabinowitz, as shown in **Figure 2-4**, the shear modulus of PMMA was found to increase from 953 MPa to 2179 MPa when the hydrostatic pressure was increased from 0 MPa to 196 MPa. The fracture stress was increased from 129 MPa to 250 MPa. [69] The yield stress of PMMA has a linear dependency with hydrostatic pressure, which is expressed with the following equation,

$$\tau = \tau_0 + \alpha P \quad (2)$$

In the study of Grujicic et al. in 2014, [74] pressure-shearing impact experiments and simulation were conducted to investigate the shear resistance of polyurea under high pressure and high strain rate. They pointed out that the shear resistance increases linearly with increasing of compressive stress in the range of 0 to 20 GPa. When the compressive stress exceeded 20 GPa, the increment of shear resistance deviated from the linear behaviour. According to the molecular level computational analysis, Grujicic et al. pointed out that the shear resistance of polyurea is dependent on the soft-segment molecular weight.

2.5.2 Effect of Strain Rate on Polyurea

Mechanical properties of polyurea are known to be dependent on strain rates. Numerous studies were carried out to characterise polymer mechanical behaviour concerning strain rate [75]-[81]. In the study by Qi et al., it was found that the majority of the irreversible strain of polyurea after unloading would vanish after post-unloading time [83]. It indicates that polyurea has viscoplastic behaviour. They pointed out that the probability for thermally activated processes, which results in plastic deformation, would be reduced with increasing strain rate. At the same time, the elastic response is increased. Amirkhizi accounted for the strain rate dependency of polyurea with the time-temperature superposition principle. [82] The material is un-relaxed when the imposed deformation is shorter than the relaxation time. Hence, the material shows strain rate dependency. In the study of Jiao et al. in 2009 [84], they found that, at a high shearing rate of 10^{-5} s^{-1} , the shearing resistance was not sensitive to the shearing rate. On the other hand, the shear resistance of polyurea increased with increasing of pressure.

2.6 Constitutive Models for Polyurea, Ceramics and Metals

In this section, the material models for simulation work in this study are described. Johnson Holmquist model was used for ceramics, Johnson-Cook model for metals, and Mooney Rivlin model for polyurea in the study.

2.6.1 Johnson Holmquist Model (JH-1)

There are two widely used model developed by Johnson Holmquist for ceramics: JH-1 and JH-2. JH-2 model provides a dimensionless description of strength for ceramics, while JH-1 model gives a linear relationship between strength and pressure of ceramics. [85], [86] Some researches indicated that the JH-1 model was a more accurate representation of ceramic failure than JH-2 model. [85] In the research of Johnson et al. in 2001, they found that JH-1 model can provide a more accurate modelling of interface defeat of boron carbide target. [87], [88]

In this thesis, the JH-1 model was used for simulation of silicon carbide ceramics. The model can be summarised in **Figure 2-2**. The upper part of the figure shows the dependency of von Mises Stress (σ) of material with pressure (P), material damage (D) and normalised strain rate ($\dot{\epsilon}^*$). The material cannot sustain any plastic strain when it was under tensile pressure T. The strengths of intact material are S_1 and S_2 when it was

under compressive pressures, P_1 and P_2 . For intact material, its damage $D=0$; for partially damaged material, $0<D<1$; for fully damaged material, $D=1$. The maximum failure strength ($S_{\max}^f$) of fully damaged material is significantly reduced compared with intact material. The slope between strength of fully damaged material and its pressure is represented by α . Feng et al. [89] suggested a gradual softening for a partially damaged material. However, their data was inconclusive for the magnitude of softening. In the research of Grady et al. and Moody et al. [90], they pointed out that the strength of SIC was 12.9 GPa when the hydrostatic pressure was 32.2 GPa. In the research of Bassett et al. they found that the strength of SiC would reduce to 9.9 GPa when the hydrostatic pressure was increased to 34.2 GPa. These data suggested that ceramic softening occurred during damage accumulation. It was suggested by Holmquist et al. [85] that the softening during damage accumulation was not significant until the material was fully damaged ($D=1$).

The dependency of material strength with strain rate can be expressed with the following equation,

$$\sigma = \sigma_0(1 + C \ln \dot{\epsilon}^*) \quad (3)$$

where σ_0 is the strength of material when $\dot{\epsilon}^*=1$. C is the strain rate constant.

The accumulated damage for material D can be calculated with the following equations,

$$D = \sum \Delta \epsilon_p / \epsilon_p^f \quad (4)$$

$$\dot{\epsilon} = \frac{2C_B \epsilon_R(t)}{L_s} \quad (5)$$

During each cycle of integration, the equivalent plastic strain increment is represented with $\Delta \epsilon_p$. The ϵ_p^f is the equivalent plastic strain of material at failure when it is under pressure of P . It can be found that the equivalent plastic strain of material reaches its maximum when the pressure is increased to P_3 as shown in Figure 2-5.

The hydrostatic pressure P of material is illustrated in the lower right of **Figure 2-5**. When the material is intact or partially damaged ($D<1$), the value of P can be calculated with the following equation

$$P = K_1 \mu + K_2 \mu^2 + K_3 \mu^3 \quad (6)$$

where K_1 was the bulk modulus of material. K_2 and K_3 were constants. The value of volumetric strain $\mu = V_0/V - 1 = p_0/p - 1$. V_0 is the original volume and V the current volume

of material. Similarly, ρ_0 is the original density and ρ the current density. When the material is fully damaged ($D=1$), P can be calculated with adding the additional incremental pressure ΔP . The ΔP could be obtained from energy considerations.

$$P = K_1\mu + K_2\mu^2 + K_3\mu^3 + \Delta P \quad (7)$$

Figure 2-5: Description of JH-1 Model for brittle materials (a) strength model, (b) damage model of ceramic, (C) pressure model [85]

2.6.2 Johnson Cook Model (JC)

Johnson and Cook first reported their model for A36 hot rolled steel in 1983 which was known as Johnson Cook model. [91] Since then, JC model had been widely used for simulation of metallic materials, such as steel, aluminium and titanium in ballistic experiments. The JC Model was expressed in the following equations,

$$\sigma = [A + B * \epsilon_{eff}^n][1 + C * \ln \dot{\epsilon}][1 - (T_H)^m] \quad (8)$$

$$\dot{\epsilon} = \frac{\dot{\epsilon}_{eff}}{\dot{\epsilon}_0} \quad (9)$$

$$T_H = \frac{T - T_R}{T_M - T_R} \quad (10)$$

where ϵ_{eff} is the effective plastic strain, $\dot{\epsilon}$ the normalised strain rate, and $\dot{\epsilon}_0$ the reference effective plastic strain rate ($\dot{\epsilon}_0 = 1$). T_H is the normalised temperature and T , T_M , T_R are instantaneous temperature, melting temperature and room temperature respectively. A , B and C are yield stress coefficient, strain hardening coefficient and

strain rate coefficient, respectively. m and n are the temperature softening exponent and strain hardening exponent of the material. The first bracketed term in Equation (8) represents the strain hardening effect for yield stress of the material. The second bracketed term includes the effect of increasing strain rate on yield stress. The third bracketed term takes into account the softening effect of the yield stress, which is induced by localised temperature increase. In the research of Hancock et al., they found that the fracture strain of material decreases with increasing the hydrostatic tensile stress. [92] Based on their theory, Johnson and Cook further expanded the previous equations by adding damage parameters for fracture in 1985. [93] The JC model had been widely used by many researchers to simulate the behaviours of metallic materials, such as aluminium, steel and titanium, in ballistic experiments and yielded good results. [94]-[101]

2.6.3 Mooney Rivlin Model (MR)

The Mooney Rivlin model has been wide used to simulate the behaviours of rubber like hyper-elastic materials. [102], [103] In the past decades, researchers had modified the MR model to describe non-linear behaviour of these materials based on different assumptions. [104]-[109] However, in the simulation hydrocode of LS-Dyna, the original version of MR model are employed. [110]

In the MR model, the strain energy of material was derived in terms of principle strain invariants, which is as shown in the following equations: [102], [103]

$$W = \sum_{i,r=0}^N C_{ir} (\bar{I}_1 - 3)^i (\bar{I}_2 - 3)^r + \sum_{K=1}^M D_K (J - 1)^{2K} \quad (11)$$

$$\bar{I}_1 = J^{-2/3} * I_1 \quad (12)$$

$$\bar{I}_2 = J^{-4/3} * I_2 \quad (13)$$

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \quad (14)$$

$$I_2 = (\lambda_1 \lambda_2)^2 + (\lambda_1 \lambda_3)^2 + (\lambda_2 \lambda_3)^2 \quad (15)$$

where W is strain energy, C_{ir} are the material constants, which would be obtained empirically; $\bar{I}_1$ and $\bar{I}_2$ are the first and second principle strain invariant; J is the determinant of elastic deformation gradient and D the incompressibility parameter of

the material. For incompressible materials, J is set as 1. The parameter λ is known as the extension ratio which is equal to $(1+\varepsilon)$.

Xue et al. pointed out the two parameters version of MR model could be used to predict the behaviour of polyurea material as interlayer under impulsive loads.[56] By letting $N=1$, $J=1$ and $C_{00}=C_{11}=0$ in Equation 11,

$$W = C_{10}(\bar{I}_1 - 3) + C_{01}(\bar{I}_2 - 3) \quad (16)$$

In the case of one-dimensional extension, $\lambda_2 = \lambda_3 = \frac{1}{\lambda_1}$. Therefore, the engineering stress σ of material could be expressed as

$$\sigma = 2(\lambda - \lambda^{-2})(C_{10} + C_{01}\lambda^{-1}) \quad (17)$$

where C_{10} and C_{01} are constants, they could be obtained by data fitting from experiments.

2.6.4 Piecewise Linear Plasticity Model

One main drawback of Mooney Rivlin model is that it could not predict the strain-rate and pressure dependency of polymers. To include these effects, Piecewise linear plasticity model, which is widely used in simulations to describe rate-dependent phenomena of polymers, can be adopted. In this model, one arbitrary stress-strain curve is defined to describe the behaviour of the material at the lowest strain rate of interest. The strain-rate effect is accounted for with Cowper Symonds model in the followed equation,[104]

$$\sigma_y(\varepsilon_{eff}^P, \dot{\varepsilon}_{eff}^P) = \sigma_y^S(\varepsilon_{eff}^P) + SIGY \left(\frac{\dot{\varepsilon}_{eff}^P}{C} \right)^{\frac{1}{P}} \quad (18)$$

where C and P are constants, and could be obtained from a series of mechanical tests under different strain rates. In this report, Mat_24 PIECEWISE_LINEAR_PLASTICITY in LS-Dyna was used for the simulation of polyurea in ballistic experiments.

2.7 Hydrocode Simulation

The finite element method (FEM) has been widely used for investigating material response under high-velocity impact by solving partial differential equations. In LS-Dyna, the momentum equations are solved by satisfying displacement boundary conditions and traction. The energy equations are used for evaluating the equation of state, and to keep global energy balance. [111], [112] Thus, the displacement and deformation of material could be well tracked with using FEM.

However, the FEM is limited by the time step during integration. The time step should be small enough to ensure that the wave is within one element in each integration step. When solving large deformation problems, the time step is required to be extremely small, otherwise the accuracy of result would be affected. To overcome this kind of problem, the Smoothed Particle Hydrodynamics (SPH) method has to be used. The SPH method was first developed by Lucy et al. for solving of astrophysical problems. [112]-[117] The behaviour of SPH is governed by a few conservation equations. These SPH nodes would be stable for large deformation and the accuracy depends on the smoothing function used. [118] The SPH method has the following advantages: (1) it could solve large deformation problems with simple and accurate solution; (2) it would be simpler for discretisation of complex geometries and (3) determination of free surface and deformable boundaries would be simpler. However, since the interaction of SPH particles is calculated individually, the SPH method would require more resources compared with FEM.

Another method to overcome the limitations of FEM and SPH was developed in LS-Dyna named DEFINE_ADAPTIVE_SOLID_TO_SPH. [119] In this method, SPH particles are coupled with FEM elements. The FEM elements are used for small deformation. FEM elements would then be converted to SPH when the FEM elements are highly distorted. Using this scheme, the computation efficiency can be improved. [120]-[122]

2.8 Gap of Research

As mentioned in the above sections, most of the previous studies had focused on the use of polyurea coating for blast mitigation applications. Some researchers investigated the application of polyurea for enhancing the ballistic resistance of ceramic armor at a velocity lower than 1000 m/s. Limited researches are available for the investigation of the ability of polyurea interlayer in a ceramic armor subject to high-velocity impact (> 1000 m/s) of long rod projectiles. This study attempted to address this gap in knowledge by examining the ability to use polyurea coating as an interlayer to enhance the ballistic resistance of ceramic armor module.

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Chapter 3

Experimental Methodology

In this chapter, synthesising of PUD & PUK polyurea is discussed in the first section. The second section discusses the quasi-static tensile, compression & shear test, hardness test and split Hopkinson pressure bar test for polyurea. Then the method of ballistic experiment and the equipment used for the ballistic experiment are explained in the third section of this chapter. In the fourth section, the methods of establishing the simulation model and material model used for hydrocode simulation are described.

3.1 Material Preparation

There are two different types of commercially purchased isocyanate used in this study: Dragonsshield and Isonate 143L. The polyamine used in this study is commercially purchased Versalink P-1000. The detailed chemicals and its weight percentage are listed in Tables 3-1, 3-2, and 3.3.

Table 3-1: Chemical contents in Dragon shield Part A

Name	Weight Percentage (%)
Isocyanates, low monomer toluene diisocyanate (TDI)	50-80
2,4-Diphenylmethane diisocyanate	1-10
4,4'-Diphenylmethane diisocyanate	1-10
2,2-Diphenylmethane diisocyanate	1-10
Propylene carbonate	1-10

Table 3-2: Chemical contents in Isonate 143L

Name	Weight Percentage (%)
Methylenediphenyl diisocyanate	65-70
4,4' -Methylenediphenyl diisocyanate	61-66
Methylenediphenyl diisocyanate, homopolymer	28-33
Triethyl phosphate	2

Table 3-3: Chemical content in Versalink P-1000:

Name	Weight Percentage (%)
Polytetramethyleneoxide-di-p-aminobenzoate	100

In this study, two types of polyurea were synthesised: PUK and PUD. PUK was synthesised with Isonate 143L and Versalink P-1000 with weight ratio of 3:7. PUD was synthesised with Dragon Shield Isocyanate and Versalink P-1000 with weight ratio of 1:1.

The viscosity of isocyanate under room temperature is 5.7 cPs, and that of Versalink P-1000 under 40 °C is 3000 cPs. To achieve a better mixture, both chemicals were heated to 70 °C to reduce the viscosity before putting into the mixer. The mixture was placed in a Kakuhunter vacuum mixer (specifications of the mixer will be provided in the next section) for 180s. During the mixing, a vacuum level of 0.5 kPa was kept to

remove bubbles in the product. The revolution and rotation speed were set as 580 rpm and 1700 rpm, respectively.

Polyurea was poured into an aluminium mould with the dimension of 250×250×20, as shown in **Figure 3-1**. The thickness of the cavity varies from 7 to 11 mm to control the thickness of polyurea interlayer. After being poured into the mould, polyurea was cured at 90 °C for 24 hours.

Figure 3-1: Polyurea in aluminium model after the mixture

3.1.1 Planetary Mixer

The mixing of polyurea was carried out using a Kakuhunter SK-300TVSII mixer from Shashin Kagaku Pte Ltd, Japan. The Kakuhunter SK-300TVSII mixer was revolution-rotation mixer with a vacuum level of 0.1 kPa (**Figure 3-2**). The maximum revolution speed and rotation speed are 1700 rpm and 1160 rpm, respectively. Bubble burst effect would be induced by the revolution-rotation design under vacuum. As a result, material would be well mixed and degassed simultaneously.

Figure 3-2: Illustration of the Kakuhunter vacuumed mixer working mechanism

3.1.2 Preparation of Cover Plate

To increase the adhesion between polyurea interlayer and cover plate, sandblasting at grit 90 was applied to cover plates. The average surface roughness was 145 microns. It was found that the adhesion strength was increased from 0.39 MPa to 3.7 MPa with sandblasting on the cover plate. Then, the cover plates were heated up to 70 °C with the aluminium module. Based on experimental trials, delamination would occur at the polyurea-cover plate interface if the polyurea mixture was transferred onto cover plates without pre-heating. Comparison between the heated condition and room temperature condition is as shown in **Figure 3-3**.

Figure 3-3: Comparison of process polyurea between the heated condition and room temperature condition

3.2 Material Characterisation

3.2.1 Quasi-Static Tensile, Compression & Shear Test

The tensile test of polyurea was carried out using Instron 5500R mechanical test machine with 30KN load cell as shown in **Figure 3-4**. The polyurea specimen was cut to size according to ASTM-D638 standard. The dimensions of the specimen are illustrated in **Figure 3-5**. The gauge length and width of specimens are 9.53 mm and 3.18 mm respectively. To ensure the test was in a quasi-static process, the strain rate of the tensile test was set to be 10^{-4} s^{-1} . A set of tested polyurea specimens are shown in **Figure 3-6**. A typical tensile stress-strain curve for plastics is shown in **Figure 3-7**. [1] The Young's modulus, yield strength, failure strain and its fracture stress can be obtained based on the test results. One cylindrical cutter with 6mm inner diameter compressed with hydraulic compressor was used to prepare specimens for compression tests. The cutter and prepared specimens are shown in **Figure 3-8**.

The quasi-static shear test was conducted with the jig shown in **Figure 3-9**. Cylindrical specimens for the shear test were fabricated with 5 mm in diameter. The Instron mechanical tester recorded the cutting force in the vertical direction. One 2 kN load cell shown in **Figure 3-10** was used to record the compressive & tensile force in the horizontal direction.

Figure 3-4: Experimental setup for the tensile test

Figure 3-5: Drawing of ASTM-D638 tensile test specimen where dimensions were given in mm

Figure 3-6: Test specimens of PUD & PUK polyurea

Figure 3-7: Typical tensile test result of polymers

Figure 3-8: Cylindrical cutter for compression test

Figure 3-9: Jigs for the shear test

Figure 3-10: Load cell used in the mechanical tests

3.2.2 Hardness Test

The hardness of polyurea sheet was tested with Teclock durometer type-A according to ASTM-D-2240. The drawing for the durometer is shown in **Figure 3-11**. [16] When the durometer was applied on the surface of polyurea, the indenter would pressurise the spring behind it, then pressurised force by the spring would deform the polyurea, where larger force corresponds to higher hardness. Different types of durometer are used for different material characteristics and shape of surface. The differences are in the springs and indenter shape.

Figure 3-11: Drawing for Teclock durometer type-A [16]

3.2.3 Split Hopkinson Pressure Bar (SHPB)

For ballistic experiments, the materials would undergo very high strain rate $> 1000 \text{ s}^{-1}$. As polyurea has a high sensitivity to strain rate, the dynamic properties of polyurea would be different with that obtained in quasi-static tests. [2] The dynamic properties of material could be obtained with SHPB test. The experimental setup is illustrated in **Figure 3-12** The SHPB consists of striker bar, incident bar, transmission bar and momentum bar. The material is AA 6061 and the bars diameter are 20 mm. The length of these four bars are 800 mm, 2000 mm, 2000 mm and 300 mm respectively. The striker bar is propelled with gas gun with pressure of 2 - 7 MPa. When the striker bar impacts the incident bar, a pulse of compressive wave is generated. The compressive wave will be transmitted to the specimen through the incident bar. After the compressive wave propagates through the specimen, it will be transmitted through the transmission bar and then the momentum bar. Finally, the compressive wave will be carried with the momentum bar to the shock absorber.

The measurement system consists of strain gauge, Wheatstone bridge circuit, amplifier and oscilloscope. The strain gauges are adhered at the center of incident bar and transmission bar to measure the strain during stress wave propagation. The strain gauges used for the experiment are purchased from Tokyo Sokki Kenkyujo Co. Ltd with gauge resistance of 120Ω and gauge factor of 2.18. The measured signal from strain gauge is transmitted to the Wheatstone bridge, as shown in **Figure 3-13**. The signal is amplified with an amplifier before sent to an oscilloscope.

Figure 3-12: Experimental setup of Split-Hopkinson Pressure bar for dynamic compressive test

Figure 3-13: Illustration of opposite half bridge setup for strain gauge and Wheatstone bridge [3]

Before experiment, the alignment of bars was checked with blank test without specimen. With good alignment of bars, the compressive stress wave would propagate through the incident bar and transmission bar and single pulse of signal would be recorded. If misalignment exists, reflected pulse would be recorded in the incident bar. One set of recorded stress wave in incident bar with and without good alignment are shown in **Figure 3-14**.

Figure 3-14: (a) Compressive stress wave in bars with good alignment and (b) stress wave in bars with misalignment [4]

Assuming no dispersion of stress waves, the recorded strain by strain gauges were equal to the strain at bar ends. Based on 1-dimenssional stress wave theory, the stress strain and strain rate could be calculated with following equations

$$\dot{\epsilon} = \frac{2C_B \epsilon_R(t)}{L_S} \quad (19)$$

$$\epsilon = \frac{2V_B \int_0^t \epsilon_R(t) dt}{L_S} \quad (20)$$

$$\sigma = \frac{A_B}{A_S} E_B \epsilon_t(t) \quad (21)$$

$$\dot{\epsilon} = \frac{2C_B \epsilon_R(t)}{L_S} \quad (22)$$

where ϵ_R and ϵ_t are the recorded reflected strain in incident bar and transmitted strain in transmission bar respectively; the E_B , V_B and A_B are the Young's modulus, sound speed and cross-sectional area of the aluminium bars; A_S and L_S are the cross-sectional area and length of specimen respectively.

3.3 Ballistic Experiment

3.3.1 Two-Stage Gas Launcher

The two-stage gas launcher, shown in **Figure 3-15**, was fabricated by Thiot Ingenierie and used for ballistic experiments. High purity helium gas was used to drive the gas launcher. The projectile was loaded at the left end of launch tube while a 9 kg piston was loaded at the end of reservoir and the pump tube was vacuumed to 0.1 mbar. Then, the pump tube and reservoir were filled with 6 bar and 200 - 300 bar of high purity helium, respectively.

The firing process was separated into two stages. In the first stage, the high-pressured helium gas in the reservoir was released to propel the 9 kg piston to velocity of 150 m/s. At the same time, the piston compressed the helium gas in pump tube into high pressure section (HP). The pressure in high pressure could be compressed to 3000 bar when the piston reaches the high-pressure section. In the second stage, the exceptionally high pressure in HP would propel the projectile to accelerate in the launch tube. The maximum velocity of the projectile was 1400 m/s. To reduce the yaw of projectile, the expansion chamber and target chamber were vacuumed to 200 mbar during the test.

Software Cesar32 was provided by Thiot Ingenierie to predict projectile velocity by counting parameters including the weight of the projectile package, weight of the piston, pressure in pump tube and reservoir and pump tube friction coefficient.

Figure 3-15: Drawing of two stage gas launcher in Ma Jan High Speed Dynamics Laboratory

3.3.2 Experimental Setup of Ballistic Test

The experimental setup of ballistic test in Ma Jan High-Speed Dynamics Laboratory can be illustrated in **Figure 3-16**. The ceramic target module was placed at the middle of the target chamber with one piece of steel 4340 block, which is 150 mm in diameter and 80 mm in thickness. An additional ten pieces of 10 mm thick steel plates were fixed behind for protection purpose. To protect equipment from flying fragments during ballistic tests, the chamber was fabricated using one piece of rolled steel 20 mm in thickness. At the same time, one piece of 30 mm ballistic resistance glass was used at the viewing window for protection.

There are four diagnostic systems for the two-stage gas launcher: (1) Laser aiming system; (2) Velocimeter; (3) Flash X-Ray system; and (4) High-speed camera.

Figure 3-16: Experimental setup of ballistic test

3.3.2.1 Aiming System

The ceramic target module was placed at the centre of the target chamber, 5 m away from the muzzle. An aiming system was placed at 1.5 m away from the end of reservoir. As shown in **Figure 3-17**, the aiming system consists of three parts: laser beam, laser mount and mounting stage. The laser beam used here was 850 nm-3mw-CW circular beam laser diode module purchased from Edmund Optics. The laser beam was fixed to one tri-directional adjustment laser mount with one piece of cylindrical aluminium jig. Then the laser mount was fixed to the mounting stage which can be adjusted both in

horizontal and vertical direction. Calibration test was carried out by marking the laser point on a steel 4340 target for the DOP test. By comparing the position of crater and the marking on the target, a precision of $\pm 3\text{mm}$ from impact point was expected. **Figure 3-18** shows the laser beam indicating the impact point of projectile on the target.

Figure 3-17: Image of the aiming system

Figure 3-18: Image of target with aiming the impact point

3.3.2.2 Velocimeter

VMS 600 velocimeter shown in **Figure 3-19** was used to measure the velocity of projectile at the muzzle of launch tube. To measure the velocity of projectile, two sets of parallel laser beams were mounted to one steel tube which was placed at a distance of 500 mm from the muzzle of launch tube. The two sets of laser beams were separated in distance of 200 mm as shown in **Figure 3-20**. When the projectile passing through one

set of the laser beams, laser between the two beams would be blocked by the projectile. At the same time, a signal pulse would be sent to the machine. By recording the time interval of two signals, the velocity of projectile can be calculated by the equipment.

Figure 3-19: Image of VMS 600 velocimeter for measuring the projectile velocity

Figure 3-20: Schematic illustration of velocimeter

3.3.2.3 Flash X-ray System

As shown in **Figure 3-16**, one set of X-ray tubes were vertically located at 2 meters in front of the target to capture the yaw of projectile. Another set of flash X-ray tubes were located at 100 mm behind the target. The flash X-ray system used in the experiment was SCF 150 flash X-ray purchased from Scandiflash AB, Sweden. The generated flash X-ray is able to penetrate a 3 mm steel plate. The X-ray images of projectile were captured with reusable X-ray film purchased from Durr NDT, Germany.

An electronic triggering system was designed to capture the image of projectile. As shown in **Figure 3-21**, one printed circuit was used as the trigger foil. The trigger foil was printed with two sets of electrical pathways and was separated with 2 mm gaps.

One 12 V constant voltage source was applied at the two terminals of the trigger foil. When the projectile perforated the trigger foil, the projectile would connect circuits as a bridge. Then one trigger pulse would be generated to the control panel to activate the flash X-ray system. The first set of X-ray tubes was triggered at 3 μs after receiving the signal. This set of X-ray tubes can capture the pitch and yaw of the projectile. It was suggested that the total yaw of projectile should go below 2° . [5][6] To ensure the validity of experimental results, one 3 mm steel reference bar, which had been calibrated with laser system, was placed at side of image film. The second X-ray tube was triggered at 900 μs after the first set of X-ray tubes. The third X-ray tube was triggered at 960 μs after the first set of X-ray tubes. This set of X-ray tubes can capture the residual projectile, which provides the residual velocity and residual length of projectile. The residual velocity could be calculated by dividing the distance between two images of the residual projectile with the delayed time (60 μs). A typical post penetration image is shown in **Figure 3-22**. The post penetration image could be used to evaluate the performance of armor modules by comparing the residual length and residual velocity of the residual projectile. Software D-Tect was used to measure the pitch/yaw of projectiles.

Figure 3-21: The trigger foil for flash X-ray system

Figure 3-22: X-Ray Image for post penetration analysis

3.3.2.4 High Speed Camera

High speed camera was used to capture the penetration progress of projectile into ceramic armor modules. This high-speed video could provide information such as penetration time of projectile, deformation profile of cover and backing plate. The high-speed camera used in experiments was Photron model SA5 from Japan. As an example, the image shown in **Figure 3-23** was recorded at 150,000 fps and resolution of 256×144 pixels. The recording time was set as 2 seconds to provide sufficient window to capture the penetration process. To provide clear high-speed video, non-flicker LED light was used to illuminate the target. A white Styrofoam was placed behind the target to increase the contrast.

Figure 3-23: Image of recorded high-speed video

3.3.3 Projectile

Dimensions of conical nosed tungsten alloy long are rod shown in **Figure 3-24**. The tungsten alloy long rods were 8.3 mm in diameter and 115 mm in length, giving the L/D ratio of the projectile to be 13.8. The tungsten alloy was fabricated with 93% of tungsten, 3% of iron and 4% of nickel. This tungsten alloy has a typical elongation of 25% and yield strength of 700 MPa.

Figure 3-24: Schematic of conical nosed tungsten alloy long rod

As shown in **Figure 3-25**, the projectile package consists of one tungsten alloy long rod, 4 pieces of sabots, one piece of baser and one piece of pusher. The pusher fabricated with nylon would be propelled by compressed helium gas in high pressure section during firing. A baser fabricated with AA 7075 was placed between projectile and pusher to prevent the pusher from yielding during acceleration. Sabots were fabricated with polycarbonate to guide the projectile to accelerate in the launch tube. After the projectile was propelled out of the muzzle of launch tube, sabots would be separated symmetrically by air in expansion chamber. One typical opening of sabots in expansion chamber is shown in **Figure 3-26**.

Figure 3-25: Projectile package for the ballistic experiment

Figure 3-26: Image of projectile in expansion chamber captured by high speed camera

3.3.4 Target Fabrication

The configuration of ceramic target module is illustrated in **Figure 3-27**. The ceramic target module consists of four main parts: cover plate, polyurea interlayer, silicon carbide ceramic tile, and backing plate. The thickness of each component is listed in the **Table 3-4**.

Table 3-4: Thickness of cover plate, interlayer, ceramic tile and backing plate.

	Oblique test	Nominal test
Component Name	Thickness (mm)	Thickness (mm)
Cover plate	5	5
Polyurea Interlayer	0-3	0-6
Ceramic Tile	20	20
Backing plate	7	10

Figure 3-27: Sectioned view of ceramic target module for ballistic test

The cover plate for the nominal impact test was fabricated with AISI 4340 steel plates. According to preliminary simulation results, the projectile could not penetrate the ceramic armor module using 5 mm AISI 430 steel plate cover plate. So, the cover plate for the oblique test was fabricated with grade 5 Titanium alloy which has a yield strength of 828 MPa and elongation of 10%. Silicon carbide ceramic tiles grade F plus from 3M Technical Ceramics, Germany were used for this study. The backing plates of ceramic target modules were fabricated with AISI 4340 steel.

Before the assembling of the target module, sandblasting at grit 90 was carried out on the cover plates and AISI 4340 steel backing plates for better adhesion. The average surface roughness was 145 microns. Then the mixed polyurea was poured into the Aluminium mould as shown in **Figure 3-1** with placing the cover plate at the bottom.

The Loctite EA9309.3NA two-part epoxy adhesive was used for adhesion between ceramic tile and backing plate. The part A and part B of adhesive were mixed to the weight ratio of 100:22 using the planetary mixer, which was discussed in section 3.1.2, for 3 min.

Hydraulic press from Enerpac shown in **Figure 3-28** was used to apply a load of 1 kN onto ceramic tile during fabrication of target module. This is to control the thickness of adhesive layer between silicon carbide and backing plate to 0.13 mm. The load was held for one hour to prevent air gap formation between ceramic tile and backing plate.

The adhesive was cured at 82 °C for 3 hours. Then it was cooled down to room temperature and held for 12 hours before testing.

Figure 3-28: Figure of hydraulic press to compress ceramic into target module

3.3.5 Ballistic Performance of Ceramic Armor Module

The depth of penetration (DOP) test is widely used to investigate the performance of ceramic armors. [7 - 9] With the result from DOP tests, Mass Efficiency (ME) [10] was calculated with the Equation (23) to evaluate the performance of ceramic armor module

$$ME = \frac{\rho_s P_{ref}}{AD_{module} + \rho_s P_{ref}} \quad (23)$$

where ρ_s is the density AISI 4340 steel block; P_{ref} and P_{res} are the reference DOP and residual DOP. The value of $AD_{module} = \frac{m}{A}$ is the area density of the ceramic armor module. m is the mass of ceramic armor module, and A is the area of the ceramic armor module. To find the reference DOP, Goh W.L and Y. Zheng did a series of DOP tests of long rod projectile against AISI 4340 steel semi-infinite targets in the velocity range of 1000 m/s to 1400 m/s. They found the relationship between DOP and impact velocity could be calculated with Equation 24:

$$DOP = 0.1091V - 71.52 \quad (24)$$

where V is the impact velocity.

To obtain the residual DOP of the test, one piece of AISI 4340 block, which was 150 mm in diameter and 80 mm in thickness, was placed at back of ceramic armor module as the witness block. The residual DOP is calculated with following equation, [10]

$$P_{Res} = t_b - t_r \quad (25)$$

where t_r and t_b were the residual thickness and the total thickness of the witness block, as illustrated in **Figure 3-29**.

Figure 3-29: Illustration for measurement of DOP [10]

3.4 Hydrocode Simulation

The ballistic experiments were examined with explicit finite element method carried out with LS-Dyna version 8.0 by LSTC, USA. LS-Dyna pre-post software was used for model building, post simulation analysis.

3.4.1 Simulation Model for Materials

FEM and SPH were used for building simulation model of ballistic experiments. An overview of simulation model is shown in **Figure 3-30**. The projectile was built with SPH with diameter of 0.4 mm. The armor model and witness block were built with FEM elements with element size of 1 mm. The polyurea interlayer was built with FEM elements which has an element size of 0.5 mm. For cover plate and ceramic block, they were built with both FEM and SPH with using keyword “DEFINE_ADAPTIVE_SOLID_TO_SPH”. SPH nodes were coupled with FEM elements at beginning. When deletion criteria of FEM elements were reached, the SPH

nodes replace FEM and carried on the simulation continually after transferring information from FEM to SPH. This method would maintain the confinement pressure of surrounding elements when FEM elements are deleted. As a result, the accuracy of simulation would be improved as ceramic strength is pressure dependent.

The keywords `CONTACT_ERODING_SURFACE_TO_SURFACE` and `CONTACT_ERODING_NODES_TO_SURFACE` were used for the contact between parts in simulation. The keyword `CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK` was used to represent the adhesion between ceramic and backing plate/polyurea interlayer and cover plate. The nodes of interface were joined together at the beginning. The joint surfaces were separated when the tensile stress reached 200 MPa.

All simulations were carried out with half model with assuming symmetric penetration process. The computation time for each simulation was 10-12 hours.

Figure 3-30: Image of a simulation model for ballistic experiment

3.4.2 Simulation Model

The parameters of materials used in simulation are listed in this section.

3.4.2.1 Metallic Materials

The JC model was used for tungsten alloy, titanium and AISI 4340 steel in simulations. The parameters of tungsten alloy were obtained from the Hokinson Bar test carried out by Goh et al. [10] An empirical relationship between parameters of steel and its hardness was established by Deniz et al. [11] In this study, the AISI 4340 steel with hardness of 30 HRC was used. The parameters were obtained accordingly. The material parameters of titanium alloy were obtained from the work of Hubert, [12] Dandikar [13] and Burkins [14].

These parameters are listed in the Table 3-5.

Table 3-5: Parameter of metallic materials in simulation

Parameter	AISI 4340	Tungsten alloy	Titanium alloy
A (MPa)	719	697	896
B (MPa)	456	1160	656
C	0.008	0.056	0.0128
M	1.03	1	0.8
N	0.093	0.626	0.5
Density (g/cm ³)	7.85	17.6	4.43
Young's Modulus (GPa)	201	320	113.8
Shear Modulus (GPa)	78	160	42.4
Melting Temperature (K)	1723	1730	1605
Poisson's Ratio	0.29	0.29	0.342

3.4.2.2 Silicon Carbide

The JH-1 model was used for the simulation of silicon carbide in this study. The parameters of SiC used in simulation were obtained from literature. [15] The tensile strength of SiC F plus used in experiment was chosen to be 450 MPa after validation with reference experimental data. The detailed parameters are listed in the Table 3-6.

Table 3-6: Parameters of JH-1 model for Silicon Carbide F Plus tiles

Parameters	SiC F Plus
Intact Strength Constant, S_1 (MPa)	7100
Intact Strength Constant, S_2 (MPa)	12200
Intact Strength Constant, P_1 (MPa)	2500
Intact Strength Constant, P_2 (MPa)	10000
Strain Rate Coefficient, C	0.01
Tensile Strength, T (MPa)	450
Maximum Fracture Strength, S_{max}^f (MPa)	1300
Failed Strength Constant, α	0.4
Damage Constant, ε_{max}^f	0.8
Damage Constant, ϕ	0.8
Damage Constant, P_3	99750

3.4.2.3 Polyurea

The MAT_024 piecewise linear plasticity in LS-DYNA was used for the simulation of polyurea interlayer in this study. A set of SHPB tests were conducted to obtain the dynamic behaviour of polyurea. As shown in **Figure 3-31**: Flow stress of polyurea at 20% strain under different strain rates were used to find the strain rate effect coefficient in the piecewise linear plasticity module through data fitting. The fitting result is displayed in **Table 3-7**

Figure 3-31: Flow stress of polyurea at 20% strain under different strain rate**Table 3-7:** Parameters of Piecewise Linear Plasticity for PUD & PUK polyurea

Parameter	PUD	PUK
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C	0.043	23.36
P	3.09	2.69

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Chapter 4

Results and Discussion: Experiment

In this chapter, quasi-static tensile, compression and shear test, SHPB test are applied to two types of polyurea materials: PUD and PUK polyurea. From the results, it shows that both types of polyurea have high strain rate sensitivity. PUK polyurea has a higher strength, and PUD polyurea has a larger elongation. Ballistic experiments were conducted to investigate the accuracy of simulation modelling and the effect of polyurea as inter-layer in ceramic armors. The results show that polyurea can improve the ballistic performance of ceramic armor module when used as the interlayer.

4.1 Quasi-static Test and Hardness Test Results

A series of quasi-static tensile & compression tests were carried out under a strain rate of $6 \times 10^{-4} \text{ s}^{-1}$ using Instron mechanical test machine. The effect of the weight percentage of isocyanate and the effect of curing temperature were investigated to provide suitable polyurea mechanical properties for this study.

4.1.1 Quasi-static Tensile Test

A series of quasi-static tensile tests were conducted to investigate the effect of weight ratio between isocyanate and polyamine. It was found that, for PUD which was synthesised with Versalink P-1000 and dragon shield isocyanate, the optimised weight ratio is 1:1. When the weight percentage of dragon shield isocyanate was higher than 55%, the synthesised PUD polyurea could not be fully cured after 24 hr under 60 °C. The synthesised PUD polyurea would have bubble after 24 hr of curing under room temperature when the weight percentage of dragon shield isocyanate was lower than 45%. As shown in Table 4-1, the weight percentage of Isonate 143L was varied from 20% to 50% to optimise the mechanical property of PUK polyurea. All tested samples were cured under 90 °C for 24 hours.

Table 4-1: Weight percentage of Isonate 143L for four types of polyurea materials

Test set number	Weight percentage of Isonate 143L (%)
S1	20
S2	30
S3	40
S4	50

Figure 4-1: Quasi-static tensile test results for various weight percentage of Isonate 143L

Figure 4-2: Quasi-static tensile test results for 30% Isonate 143L PUK polyurea cured under different temperatures for 24 hours

Figure 4-3: Quasi-static tensile test results for 40% Isonate 143L PUK polyurea cured under different temperatures for 24 hours

Figure 4-4: Quasi-static tensile test results for PUK and PUD

The flow stress of polyurea at 100% tensile strain is used in this section for comparison. The experimental results in **Figure 4-1** show that the mechanical property of polyurea varies with changing weight percentage of Isonate 143L in polyurea. Polyurea has the

highest elongation at 20% of Isonate 143L. The flow stress of polyurea increases significantly when Isonate 143L is higher than 20%. Two sets of experiments were carried out, using 30% and 40% of Isonate 143L, to investigate the effect of curing temperature. **Figure 4-2** displays the stress-strain curve of S2 PUK polyurea samples with 30% of Isonate 143L cured under 25, 90, 100, and 120 °C for 24 hours. It shows that the elongation was slightly reduced from 460% to around 350%, while the flow stress was increased from 13.4 MPa to 19.2 MPa with increasing curing temperature from 25 to 100 °C. The polyurea showed a high elongation and ultimate tensile strength when it was cured under 90 °C for 24 hours. The flow stress of samples which cured under 90°C to 120°C is very close. The set of S3 PUK polyurea, with 40% of Isonate 143L, were cured under 25°C, 60°C, 90°C and 120°C. **Figure 4-3** shows that, with curing, strength and elongation of polyurea increased obviously. The sample cured under 90°C has the best performance. It has a flow stress of 20 MPa, elongation of 470% and ultimate tensile strength of 55 MPa. In this study, the weight percentage of Isonate 143L for PUD polyurea was chosen to be 30%. **Figure 4-4** compares the quasi-static tensile test results of PUK and PUD polyurea. It shows that PUK polyurea has a flow stress of 19.8 MPa and ultimate tensile strength of 66 MPa. On the other hand, PUD polyurea has higher elongation of 500% and much lower yield strength of 3.1 MPa.

4.1.2 Quasi-static Compression Test

Quasi-static compression test was carried out for PUD and PUK polyurea. The compression test results in **Figure 4-5** show that the flow stress at 20% strain for PUK polyurea is 4.6 MPa. That of PUD polyurea is 0.95 MPa. Overall, the PUD polyurea has much lower strength than that of PUK polyurea. This quasi-static compression test results are consistent with the previous quasi-static tensile test results.

Figure 4-5: Quasi-static compression test results for PUK and PUD

4.1.3 Quasi-static Shearing Test

Quasi-static shear test for the two types of polyurea was carried out to investigate the shear behaviour of polyurea under pressure. The experimental results in **Figure 4-6** reveal that the strength and shear modulus of PUK polyurea increased with increasing applied compressive pressure. Test result in **Figure 4-8** shows that the ultimate shear stress slightly increased when tensile strength was applied to PUK polyurea, while the shear modulus decreased slightly when tensile pressure was applied. **Figure 4-7** shows that there is no significant yield stress for the PUD polyurea. However, apparent yield strength was obtained when the compressive load was applied to the PUD polyurea. The shear modulus of PUD polyurea linearly increased with increasing applied compressive pressure. As shown in **Figure 4-9**, the ultimate shear stress slightly increased when a tensile pressure was applied. The fracture shear strain was significantly reduced from 80% to 44%. The test results show that the shear modulus increase with increasing applied compressive stress. PUD has higher sensitivity compared with PUK polyurea. The mechanical property of polyurea did not change much when tensile strength was applied. This was due to that the applied tensile strength was low compared with compressive stress. It was challenging to increase the

applied tensile stress as the strength of polyurea was low for both types of polyurea. Large deformation was observed when 5 MPa of tensile pressure was applied.

Figure 4-6: Quasi-static shear test results for PUK polyurea under pre-compression

Figure 4-7: Quasi-static shear test results for PUD polyurea under pre-compression

Figure 4-8: Quasi-static shear test results for PUK polyurea under pre-tension

Figure 4-9: Quasi-static shear test results for PUD polyurea under pre-tension

4.1.4 Hardness Test

The hardness of the two types of polyurea were tested using a Teclock durometer type A hardness tester, the results are listed in **Table 4-2**. It reveals that the PUK has higher hardness value. This hardness test results are consistent with the previous compression test results.

Table 4-2: Shore hardness test results for three types of polyurea materials

Name of material	Shore hardness (Type A)
PUD	77
PUK	97

4.2 SHPB Test Results

SHPB test was conducted on the two types of polyurea listed in the previous section to investigate their mechanical properties under dynamic loading.

Figure 4-10: SHPB test results for PUK polyurea

Figure 4-11: SHPB test results PUD polyurea

Figure 4-12: Flow stress of two types of polyurea at the strain of 20%

The SHPB test results for PUK polyurea in **Figure 4-10** show that the strength of polyurea increased with increasing the strain rate from $1 \times 10^{-4} \text{ s}^{-1}$ to 6500 s^{-1} . Significant strain rate hardening effect was observed for PUK polyurea. According to the results in **Figure 4-11**, the strength of PUD polyurea also increased with increasing the strain rate from $1 \times 10^{-4} \text{ s}^{-1}$ to 5600 s^{-1} . The flow stress of both types of polyurea at 20% is shown in **Figure 4-12**. Strain rate hardening effect for both PUD and PUK polyurea is significant under dynamic condition. The PUK polyurea has higher strength compared with that of PUD polyurea.

4.3 Ballistic Experimental Results

In this study, nominal impact ballistic experiments were carried out to investigate the effect of polyurea strength and thickness on the ballistic performance of ceramic armor modules. Also, oblique impact experiments were carried out to investigate the ballistic resistance of ceramic armor modules with polyurea interlayer.

4.3.1 Nominal Impact Experiment

To investigate the effect of polyurea as an interlayer in ceramic armor module, two sets of nominal impact ballistic experiments were carried out under the impact speed of 1250 m/s. The experimental set up is illustrated in **Figure 4-13**. The target module was placed 300 mm in front of the witness block. One set of X-ray tubes were placed in between to capture residual projectile images as shown in **Figure 4-14**. The target information and experimental results are listed in **Table 4-3**. As shown in **Figure 4-15**, by using the residual depth of penetration and impact velocity of each test, the mass efficiency of different targets are obtained.

Figure 4-13: Illustration of oblique ballistic experimental setup

Figure 4-14: X-ray image for post penetration

Figure 4-15: Ballistic experimental results

Figure 4-16: Witness block for the reference test and PUK6 test

Table 4-3: Ballistic test results of normal impact test

Test name	Interlayer Thickness	Impact speed	Depth of Penetration	Mass efficiency	Residual Length	Residual Velocity
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	(mm)	(m/s)	(mm)		(mm)	(m/s)
Reference	0	1215	15.23	1.59	35.99	1108
PUK2	2	1248	11.6	1.85	N.A	N.A
PUK3	3	1246	12.98	1.77	N.A	N.A
PUK6	6	1264	14.4	1.74	36.1	1166
PUD2	2	1263	16.1	1.68	N.A	N.A
PUD3	3	1274	18.3	1.62	33.74	1091

The crater on the witness block for the PUK6 test shows that the impact angle of residual projectile is large. In the study of Lee et al., they pointed out that the depth of penetration decreases with increasing impact angle. [1] One relationship between the depth of penetration and impact angle is illustrated as in **Figure 4-17**. In this case, the test result of PUK6 is corrected by the residual velocity and length of residual projectile. According to the crater shape of reference test, it is reasonable to assume that the impact angle, in this case, was close to 0. The X-ray image of post penetration shows that the residual velocity and residual length for the reference test and PUK6 are close to each other. According to simulation results with LS-Dyna, the corrected depth of penetration of PUK6 test is 16.1 mm. The mass efficiency of PUK6 is decreased from 1.74 to 1.66.

The result in **Table 4-3** shows that mass efficiency varied with increasing thickness of polyurea interlayer from 0 to 6 mm. For both types of polyurea, mass efficiency reached the maximum when the thickness of the polyurea interlayer was 2 mm.

Meanwhile, it reveals that the mass efficiency of ceramic armor module using PUK as interlayer is 10.1% and 9.25% higher than that with PUD polyurea interlayer when the interlayer thickness is 2 mm and 3 mm, respectively. As discussed in the previous section, PUK polyurea has a higher strength but a lower elongation at break. This implies that the strength of polyurea contributes more than that of elongation. With a higher strength, polyurea interlayer has a better ability to attenuate the shock wave, which results in longer dwell time of projectile. As a result, the ballistic resistance of ceramic armor target is better.

Figure 4-17: Impact Geometry and Normalized penetration versus yaw. Rod $L/D = 10$ at 1.4 km/s.[1]

4.3.2 Oblique Impact Experiments

To investigate the effect of polyurea in ceramic armor modules against oblique impact, one set of oblique ballistic tests were carried out under impact speed of 1250 m/s. The experimental setup is shown in **Figure 4-18**. The ceramic armor module was laid on a Styrofoam which was cut to a slop of 30 degrees. The target information and results are shown in

Table 4-4. It reveals that by adding 2 mm PUD polyurea as an interlayer in the armor module, the residual DOP decreased from 7.4 mm to 4.8 mm. The mass efficiency of armor module was increased from 2.56 to 2.78. It can be concluded that the polyurea interlayer can improve the ballistic resistance of ceramic armor target against oblique impact.

Figure 4-18: Illustration of oblique ballistic experimental setup

Table 4-4: Ballistic test results of oblique test

Target	Impact speed (m/s)	DOP (mm)	Differential mass efficiency
5mm Ti+20mmSic+7mm steel backing	1255	7.4	2.56
5mm Ti+2mm PUD+20mmSic+7mm steel backing	1252	4.8	2.78

Chapter 5

Results and Discussion: Simulation

In the first section of this chapter, the simulation of the quasi-static test, SHPB test and ballistic test are carried out. The simulation results are confirmed to have acceptable accuracy for predicting the performance of ceramic armor modules against the penetration of long rod projectile. In the second section of this chapter, the defeat mechanism of using polyurea as an interlayer in ceramic armor modules is discussed based on the ballistic impact simulation.

5.1 Simulation Results

5.1.1 Simulation Results of Quasi-static Compression and SHPB test

Based on the quasi-static compression and SHPB test, simulations were carried out using LS-Dyna. The material modelling parameters of the two types of polyurea were obtained in chapter 3. As shown in **Figure 5-1** and **Figure 5-2**, the simulation results show that the material model has reasonable accuracy for both types of polyurea. Due to the limitation of the simulation model, Young's modulus of polyurea does not increase with increasing the strain rate. The simulated flow stress of polyurea matches well with the experiment results when the compressive strain was over 5%.

Figure 5-1: Compression results of PUK polyurea where solid lines represent experimental results and dot lines represent simulation results

Figure 5-2: Compression results of PUD polyurea where solid lines represent experimental results and the dotted lines represent simulation results

5.1.2 Simulation Results of The Ballistic Experiment

Based on the ballistic test result, simulations were carried out using LS-Dyna. The material modelling parameters for tungsten, silicon carbide and steel 4340 were taken from literature as discussed in Chapter 3. Parameters for the material model of polyurea was obtained by SHPB test results, which was discussed in the previous chapter.

The simulation of the reference test and nominal impact test PUD3 & PUK3 were carried out to validate simulation parameters first. As shown in **Table 5-1** and **Table 5-2**, the simulation model for ballistic experiments under 1250 m/s had reasonable accuracy.

Table 5-1: Experimental and Simulation results for Nominal impact experiments

Target	DOP from Experiment (mm)	DOP form Simulation (mm)
Reference	15.23	15.05
PUK3	12.98	12.56
PUD3	18.3	16.9

Table 5-2: Experimental and Simulation results for oblique impact experiments

Target	DOP from Experiment (mm)	DOP form Simulation (mm)
Without Polyurea interlayer	7.4	6.24
With 2mm Polyurea interlayer	4.8	3

A series of simulations were then carried out to investigate the effect of polyurea thickness for nominal impact tests. The simulation results are illustrated in **Figure 5-3** and **Figure 5-4**. It reveals that the simulation has a similar profile of mass efficiency versus polyurea interlayer thickness as that of experimental results. The mass efficiency of ceramic armor module increases with adding polyurea as an interlayer. For PUD polyurea, the mass efficiency was slightly increased when the thickness of PUD polyurea was 2 mm. The mass efficiency was reduced when the thickness of polyurea was increased to 6 mm. For PUK polyurea, the mass efficiency was increased when the thickness of polyurea varied from 2 mm to 6 mm. The mass efficiency decreased significantly from 1.9 to 1.69 when polyurea interlayer increased from 2 mm to 4 mm. With further increasing the thickness of polyurea interlayer from 4 mm to 6 mm, the mass efficiency gradually decreased from 1.69 to 1.65.

Also, a series of simulation was carried out to investigate the effect of polyurea thickness in oblique impact experiments. The impact velocity of these simulations was set as 1250 m/s. As shown in **Figure 5-5**, the mass efficiency increases with increasing polyurea interlayer thickness from 0 to 2mm. The mass efficiency decreases when further increase of the polyurea interlayer thickness from 2 mm to 4 mm.

Figure 5-3: Simulation results of nominal impact experiments with different thickness of PUD polyurea interlayer

Figure 5-4: Simulation results of nominal impact experiments with different thickness of PUK polyurea interlayer

Figure 5-5: Simulation results of oblique impact experiments with different thickness of PUK polyurea interlayer

5.2 Defeat Mechanism

Simulation result in **Figure 5-6** shows that the long rod has dwelled on the surface of ceramic tile when polyurea was applied as an interlayer. On the contrast, expel of damaged ceramic around the impact area is found when the cover plate directly contacts with ceramic tile. It is reasonable to assume that such dwell of projectile contributes to the higher ballistic performance when polyurea is used as an interlayer.

Figure 5-6: Shape of the projectile at 24 μs

5.2.1 Shock Attenuation

The stress of ceramic was studied by the simulation to investigate the strengthening mechanism of polyurea in ceramic armor modules. As shown in left of **Figure 5-7**, the stress of one FEM element on the surface of ceramic was extracted from the simulations. The right of **Figure 5-7** illustrates the stress on ceramic by varying the thickness of PUK polyurea interlayer. It reveals that the stress applied to the ceramic increases to 9.2 GPa at 11 μs when the head of the projectile touches the surface of ceramic tile. When using polyurea as an interlayer between ceramic and cover plate, significant attenuation effect is observed. The stress is reduced from 9.2 GPa to 1.4 GPa when 2 mm of PUK polyurea interlayer is applied. Such attenuation effect could reduce the damage on ceramic tiles during the penetration process. As a result, the projectile would dwell on the surface of the ceramic tile.

Figure 5-7: Stress on ceramic tile versus different thickness of PUK polyurea interlayer

5.2.2 Effect of Polyurea Thickness

As discussed in the previous section, local pre-stress applied to ceramic tile by the cover plate would improve the ballistic performance of ceramic armor modules. **Figure 5-8** and **Figure 5-9** illustrate the stress of ceramic with different PUK polyurea interlayer thickness. It reveals that the prestress applied to ceramic decreases from 1.4 GPa to 326 MPa when the polyurea interlayer thickness increase from 2 mm to 6 mm. The stress applied to ceramic decreases significantly when the polyurea interlayer thickness increases from 2 mm to 4 mm. However, the difference in stress between 5 mm and 6 mm polyurea interlayer is negligible. **Figure 5-4** illustrates the mass efficiency of ceramic armor module with the thickness of PUK polyurea increase from 0 mm to 6 mm. Similar with the change of stress, the mass efficiency of ceramic armor module decreases significantly by increasing the thickness of polyurea interlayer from 2 mm to 4 mm. The change in mass efficiency is low when the thickness is higher than 4 mm.

Figure 5-8: Stress on ceramic tile versus different thickness of PUK polyurea interlayer

Figure 5-9: Stress on ceramic tile versus different thickness of PUD polyurea interlayer

5.2.3 Effect of Polyurea Strength

Figure 5-10 illustrates the stress applied to ceramic tile when two types of 3 mm polyurea interlayer are used. The simulation result shows that the pre-stress applied to ceramic at 11 μs are 1080 MPa and 419 MPa for PUK and PUD polyurea interlayer respectively. In the case of PUD polyurea interlayer, the stress increases from 419 MPa to 6.35 GPa within 2.5 μs . On the other hand, stress increases from 1.08 GPa to 4.29 GPa for PUK polyurea. It reveals that PUK polyurea provides a higher pre-stress before the head of the projectile reaches the surface of ceramic tile. Also, PUK polyurea has better stress attenuation effect compared with that of PUD polyurea. As a result, as shown in **Figure 5-11**, PUK polyurea interlayer provides a longer dwell time compared with that of PUD polyurea.

Figure 5-10: Stress applied to ceramic tile with 3 mm of polyurea interlayer

Figure 5-11: Dwell of ceramic armor module with different thickness of PUK & PUD polyurea interlayer.

According to the experimental results observed in the previous section, ceramic armor module with PUK polyurea interlayer has a better ballistic resistance than that of PUD polyurea. It can be concluded that polyurea elongation is not a critical material parameter in enhancing the ballistic resistance of ceramic armor modules in this study.

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Chapter 6

Conclusions and Recommendations for Future Work

This chapter concludes the works carried out and findings in this study. It summarises practical guidelines for using polyurea in improving the ballistic resistance of ceramic armor modules. Based on the findings in this study, future work is also recommended in this chapter.

6.1 Conclusions

Two types of polyurea (PUK&PUD) were prepared and optimized in Ma Jan High-Speed Dynamics Lab. Quasi-static tensile, compression and shear tests were carried out to compare the mechanical properties of PUD and PUK polyurea. It reveals that PUK polyurea has a higher yield strength of 10 MPa and lower elongation of 360%. PUD polyurea has a lower yield strength of 0.8 MPa and higher elongation of 500%. Significant increment of shear stress and shear modulus were observed with compressive stress is applied for both types of polyurea.

Split Hopkinson Split Bar tests were carried out at strain rate in the range of 1000 to 6500 s^{-1} for these two types of polyurea. It reveals that both types of polyurea have significant strain rate hardening effect. The PUK polyurea has a higher strength than PUD polyurea in the studied range of strain rate.

Ballistic experiments with an impact velocity of 1250 m/s were carried out. The nominal impact experiments show that PUK polyurea has better performance than that of PUD polyurea. This result shows that the strength of polyurea is more critical than elongation in improving the ballistic performance of ceramic armors. The ballistic resistance of ceramic armor module varies with changing the thickness of polyurea interlayer from 0 mm to 6 mm. Both types of polyurea gave the best ballistic resistance when the thickness of interlayer was 2 mm. Oblique experiments show that polyurea interlayer can also improve the ballistic resistance of ceramic armor modules against oblique impact.

Through data extracted from literature and our own SHPB tests, a simulation model for ceramic armor module was established. By comparing against experimental results, the simulation results had shown reasonable accuracy, thus validating the model used. Defeating mechanism of polyurea as an interlayer in ceramic armor modules is studied based on the simulation model. It reveals that polyurea interlayer

has a significant shock attenuation effect, which has induced the dwell of the projectile on the surface of ceramic tile. As a result, the ballistic resistance of ceramic armor is improved. Higher local pre-stress on ceramic is formed by using polyurea with a higher strength, which results with a longer dwell time. So higher ballistic performance could be achieved with using higher strength polyurea interlayer.

With previous experimental and simulation results, three directions of investigations would be proposed:

1. Effect of cover plate thickness on the ballistic resistance of ceramic armor module
2. Effect of cover plate material on the ballistic resistance of ceramic armor module.
3. Carbon fibre reinforcement of polyurea

6.2 Future Work

6.2.1 Optimization of The Cover Plate of Ceramic Armor Modules

Intensive studies have been devoted to developing lightweight armor for vehicles in the past few years. [1]-[5] It would be valuable to reduce the weight of ceramic armor modules by reducing the thickness of the cover plate or change the material of the cover plate from steel to titanium.

As shown in **Table 6-1**, a set of ballistic experiments could be carried out with varying the thickness of polyurea interlayer from 1 mm to 3 mm and the thickness of cover plate from 2mm to 3 mm. By comparing the mass efficiency of ceramic

armor module with different cover thickness and polyurea interlayer thickness, this study seeks to optimize the thickness of the cover plate and polyurea interlayer.

The oblique test result in the previous section shows that titanium could take the place of steel as the cover plate. Titanium has a relatively high yield strength of 900 MPa and a low density of 4.3 g/cm³. It would be valuable to investigate the effect of cover plate material on the ballistic resistance of ceramic armor modules. As shown in **Table 6-1**, ballistic experiments could be carried out with 2 mm of polyurea interlayer and 5 mm titanium cover plate. By comparing the mass efficiency of ceramic armor module with previous test results, this study seeks to enhance the mass efficiency of ceramic armor module by reducing the density of the cover plate.

Table 6-1: Experimental configurations for future work

Experiment S/N	Cover plate	Polyurea Interlayer	Ceramic tile	Backing plate
PUK-1	3 mm Steel	1 mm PUK	20 mm F+	7 mm steel
PUK-2	3 mm Steel	2 mm PUK	20 mm F+	7 mm steel
PUK-3	3 mm Steel	3 mm PUK	20 mm F+	7 mm steel
PUK-4	2 mm steel	1 mm PUK	20 mm F+	7 mm steel
PUK-5	2 mm steel	2 mm PUK	20 mm F+	7 mm steel
PUK-6	5 mm Ti	2 mm PUK	20 mm F+	7 mm Steel
PUK-7	5 mm Steel	1 mm PUK between SiC and backing plate	20 mm F+	7 mm steel
PUK-8	5 mm Steel	5 mm PUK behind backing plate	20 mm F+	7 mm steel
PUK-9	5 mm Steel	0.5 mm PUK between SiC tiles	20 mm F+	7 mm Steel

PUK-10	5 mm Steel	2 mm carbon fiber reinforce PUK	20 mm F+	7 mm Steel
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6.2.2 Effect of Polyurea Interlayer Position on Ballistic Resistance of Ceramic Armor Modules.

In the previous study, it shows that polyurea could improve the ballistic resistance of ceramic armor modules when it is used as an interlayer between the cover plate and ceramic tile. Researchers have been using polymer fibre lining as a backing material for a ceramic armor system. [6] It would be valuable to investigate the effect of polyurea as backing in ceramic armor modules. As shown in **Table 6-1**, ballistic experiments could be carried out with using polyurea as an interlayer between ceramic tile and backing and as energy adsorption layer behind backing material. By comparing the mass efficiency of ceramic armor modules with previous test results, this study seeks to establish the correlation between the ballistic resistance of ceramic armor modules with the position of the polyurea layer. With ballistic experiments above, simulations would be carried out to investigate the strengthening mechanism of polyurea as interlayer in ceramic armor modules.

6.2.3 Effect of Polyurea in Improving The Multi-hit Capability of Ceramic Armor Modules

In the study of Goh W.L in 2019, a ceramic module with multiple SiC F+ tiles was tested. [7] He pointed out the damage radius of SiC F+ tile was 420 mm. Tensile wave generated during the impact process is the main reason for the damage of neighbouring tiles. The study in previous sections has shown that polyurea could attenuate the shock wave from cover plate to ceramic tiles. It would be valuable to

investigate the effect of polyurea in improving the multi-hit capability of ceramic armor modules by reducing the damage radius. Ballistic experiment will be carried out with the armor module illustrated in **Figure 6-1**. 0.5 mm of polyurea will be used as an interlayer between ceramic tiles. By comparing the damage radius of ceramic armour module with the test result in the literature, the effect of polyurea interlayer in reducing the damage radius will be investigated.

Figure 6-1: Section view of 4 ceramic target module

6.2.4 Effect of Carbon Fiber Reinforcement on Polyurea Interlayer

As is discussed in the previous sections, polyurea with higher strength have better ballistic performance. Carbon fibre, which has a high strength to weight ratio, is desirable for mechanical reinforcement of polymers. [8] It would be valuable to investigate the effect of carbon fibre reinforced polyurea on the ballistic resistance of ceramic armor modules.

In the preliminary study, carbon fibre weave reinforced polyurea plate with 40% weight percentage of carbon fibre was fabricated. The quasi-static compression test result is illustrated shown in **Figure 6-2**. [9] It reveals that the carbon fibre reinforced polyurea has a higher young's modulus of 926 MPa and a yield strength of 167.8 MPa. In future work, the compressive property of carbon fibre reinforced polyurea will be studied with varying the percentage of carbon fibre and carbon fibre directions. As shown in **Table 6-1**, ballistic experiments will be carried out with 2 mm of carbon fibre reinforced polyurea interlayer. By comparing the mass efficiency of ceramic armor module with previous test results, this study seeks to investigate the correlation between strength of polyurea and ballistic resistance of ceramic armor modules.

Figure 6-2: Quasi-static compression test result for PUK polyurea with carbon fibre reinforcement and without carbon fibre reinforcement [9]

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