



Faculty of Engineering

**Computational blast response of tin slag polymer concrete bunker
sandwiched by carbon fibre reinforced polymer skins**

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**Master of Engineering
2025**

Computational blast response of tin slag polymer concrete bunker sandwiched by carbon
fibre reinforced polymer skins

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A thesis submitted

In fulfillment of the requirements for the degree of Master of Engineering

(Civil Engineering)

Faculty of Engineering
UNIVERSITI MALAYSIA SARAWAK
2025

DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ACKNOWLEDGEMENT

I would like to express my heartfelt gratitude to my supervisor, Associate Professor Dr. Ahmad Kueh Beng Hong, for his invaluable guidance and support throughout the process of completing this report. I am deeply grateful for his trust in me and his unwavering encouragement until the completion of the report. His mentorship has been instrumental in shaping my understanding of research work. Additionally, I extend my sincere thanks to my senior who assistance in progressing through the writing process, particularly in defining property concepts. I am also thankful to all my friends who have served as my support system, providing encouragement and motivation throughout this endeavour. My sincere gratitude to the Centre for Graduate Studies, for the advice and support given during my period of study in Universiti Malaysia Sarawak.

Finally, I would like to thank the management of the Universiti Malaysia Sarawak for making it possible for me to complete my study here in Sarawak. Thank you all.

ABSTRACT

Motivated by the increasing threats of terrorist activities and the urgent requirement to protect civilian buildings from explosive events, this study aims to evaluate the blast-resistant characteristics of sandwich polymer concrete bunkers (SPCB) with tin slag as material inclusion which is externally strengthened by carbon fibre-reinforced polymer skins. The performance of the SPCB was compared with that of the sandwiched conventional reinforced plain concrete bunkers (SCB). The research utilized ABAQUS/CAE 6.14 software with the CONWEP function to analyse the effects of 1kg, 5kg, 10kg, and 25kg TNT charges from various blast points that are referred to as stand-off distances of 0.1, 0.25, 0.5, 1, 2 and 2.5 meters from SPCB with core thicknesses of 200 mm, 250mm, 300mm, and 500 mm. The results found that enhanced TNT charge and shorter distances caused an increase in deflection, von Mises stress, principal stress, and damage. Notably, a 200 mm thick SPCB exhibited a perforation size of only 0.28 m², compared to 1.14 m² in SCB representing 75.44% reduction in damage. A 250 mm and 500 mm SPCB did not fail under heavy blast load. The trend indicates that as the core thickness increases, the blast resistance improves. In contrast, a 500 mm thick SCB sustained 34.8% perforation damage under a 25 kg TNT blast at a 1-meter distance, while the SPCB showed no damage. Hence, it is proven that polymer concrete with CFRP shell as bunker is high blast-resistant. Mathematical models have been proposed to predict maximum von Mises and principal stress based on TNT charge, stand-off distance, and concrete core thickness. The study confirms that the SPCB design provides superior blast resistance compared to SCBs, making it suitable for high-risk blast-resistant facilities.

Keywords: Blast resistance; polymer concrete; sandwich bunker; CFRP skin; TNT mass

**TINDAK BALAS LETUPAN KOMPUTASI BAGI KUBU KONKRIT POLIMER
SANGA TIMAH YANG DIAPIT OLEH KULIT POLIMER BERTETULANG
GENTIAN KARBON**

ABSTRAK

Didorong oleh peningkatan ancaman aktiviti pengganas dan keperluan mendesak untuk melindungi bangunan awam daripada kejadian letupan, kajian ini bertujuan untuk menilai ciri-ciri tahan letupan kubu konkrit polimer terapit (SPCB) dengan sanga timah sebagai kandungan bahan diperkukuh oleh kulit polimer bertetulang gentian karbon. Prestasi SPCB dibandingkan dengan kubu konkrit konvensional bertetulang yang diapit (SCB). Penyelidikan menggunakan perisian ABAQUS/CAE 6.14 dengan fungsi CONWEP untuk menganalisa kesan cas TNT 1kg, 5kg, 10kg, dan 25kg daripada pelbagai titik letupan yang dirujuk sebagai jarak pemisah, 0.1, 0.25, 0.5, 1, 2 dan 2.50 m, dan SPCB dengan ketebalan teras 200, 250, 300, dan 500 mm. Keputusan mendapati bahawa cas TNT yang dipertingkatkan dan jarak yang lebih pendek menyebabkan peningkatan dalam pesongan, tegasan von Mises, tegasan prinsipal dan kerosakan. Terutama sekali, SPCB setebal 200 mm menunjukkan saiz tebuk hanya 0.28 m², berbanding 1.14 m² dalam SCB yang mewakili 75.44% pengurangan kerosakan. SPCB 250 mm dan 500 mm tidak gagal di bawah beban letupan berat. Corak keputusan menunjukkan bahawa apabila ketebalan teras meningkat, rintangan terhadap letupan turut meningkat. Sebaliknya, SCB setebal 500 mm mengalami kerosakan tebuk 34.8% di bawah letupan TNT 25 kg pada jarak 1 meter, manakala SPCB tidak menunjukkan kerosakan. Oleh itu, terbukti bahawa konkrit polimer dengan selaput CFRP sebagai kubu adalah tahan letupan tinggi. Model matematik telah dicadangkan untuk meramalkan tegasan maksimum von Mises dan prinsipal berdasarkan cas TNT, jarak pemisah, dan ketebalan teras konkrit. Kajian ini mengesahkan bahawa rekabentuk SPCB

memberikan rintangan letupan yang unggul berbanding SCB, menjadikannya sesuai untuk kemudahan tahan letupan berisiko tinggi.

Kata kunci: *Rintangan letupan; konkrit polimer; kubu terapit; kulit CFRP; tebuk; jisim TNT;*

TABLE OF CONTENTS

	Page
DECLARATION	i
ACKNOWLEDGEMENT	ii
ABSTRACT	iii
<i>ABSTRAK</i>	iv
TABLE OF CONTENTS	vi
LIST OF TABLES	x
LIST OF FIGURES	xi
LIST OF ABBREVIATIONS	xv
LIST OF SYMBOL	xvi
CHAPTER 1: INTRODUCTION	1
1.1 Study Background	1
1.2 Problem Statement	6
1.3 Objectives	9
1.4 Hypothesis	9
1.5 Scope of study	10
1.6 Summary	11

CHAPTER 2: LITERATURE REVIEW	13
2.1 Overview	13
2.2 Polymer Concrete	14
2.3 Fibre	15
2.3.1 Fibre Reinforcement Polymer Composites (FRPC)	15
2.3.2 Mechanical Properties of Advanced Polymer Composites	17
2.3.3 Carbon Fibre	19
2.4 Tin Slag	23
2.5 Bunkers	27
2.6 Blast Loading	30
2.6.1 Classification of Explosions and TNT Equivalence	30
2.6.2 Blast Scaling Laws and Stand-off Distance (SOD)	32
2.6.3 Effect of Strain Rate on Materials	34
2.6.4 Blast Interaction with Structures	35
2.6.5 Blast Loading on Composite and Sandwich Structures	36
2.7 Behaviour of Polymer Concrete under Compressive Test	37
2.8 Simulation of Blast Loading on Reinforced Concrete Panels	41
2.9 Effect of Explosive Charge Weight on RC Panel Performance	53
2.10 Blast of concrete with different standoff distances	59
2.11 Research gaps of literature review	62

2.12	Blast Parameters Gathered from Literature	65
2.12	Summary	65
CHAPTER 3: RESEARCH METHODOLOGY		69
3.1	Overview	69
3.2	General Finite Element Modelling Procedure	70
3.2.1	Part	74
3.2.2	Property	75
3.2.3	Polymer Concrete	75
3.2.4	Carbon Fibre Reinforced Polymer (CFRP)	79
3.2.5	Steel (Reinforcement)	81
3.2.6	Assembly and Contact	82
3.2.7	Step Manager	83
3.2.8	Interaction and Boundary Condition	85
3.2.9	Meshing	85
3.2.10	Job Module	88
3.2.11	Visualization and Result Plotting	89
3.3	Verifications	90
3.4	Regression Analysis	91
3.5	Summary	93

CHAPTER 4: RESULT AND DISCUSSION	96
4.1 Overview	96
4.2 Verification Result	96
4.3 Blast displacement of conventional against polymer sandwich bunkers	98
4.4 Principal stress distribution of SCB against SPCB	105
4.5 Damage pattern on SPCB	114
4.6 Damage areas comparison of SCB against SPCB	127
4.7 Regressed prediction	132
4.8 Summary	136
CHAPTER 5: CONCLUSION AND RECOMMENDATIONS	138
5.1 Conclusion	138
5.2 Recommendations	139
REFERENCES	141
APPENDICES	152

LIST OF TABLES

	Page
Table 2.1 Mechanical properties of unidirectional composites	18
Table 2.2 Properties of carbon fibres	20
Table 2.3 Properties of different grades of carbon	27
Table 2.4 Chemical composition of tin slag	20
Table 2.5 Properties of tin slag compared to granite	23
Table 2.6 Finite element predictions and comparison with test data	44
Table 2.7 Comparison between numerical results and test results	57
Table 2.8 The comparisons between the numerical and experimental results of the RC board damaged contour	59
Table 2.9 Summary of the experimental program of concrete slab under various TNT mass	61
Table 2.10 Summary of Key Studies on RC Panel Blast Performance	63
Table 2.11 Summary of Existing Studies on Blast Response of RC Panels	66
Table 3.1 Concrete damaged plasticity parameters.	77
Table 3.2 Properties of CFRP material parameters in ABAQUS	81
Table 3.3 Summary of the converged node and element numbers of bunkers with different core thicknesses.	87

LIST OF FIGURES

	Page
Figure 1.1 Massive explosion that occurred at the Port of Beirut, Lebanon	3
Figure 1.2 Alfred P. Murrah Federal Building after the explosion	4
Figure 1.3 Slab failure under blast loading	5
Figure 2.1 Typical Carbon fibres (CFRP)	25
Figure 2.2 General outlook of tin slag	25
Figure 2.3 Comparison of 3.36 – 6.3 mm and 3.36 – 6 mm Particle Size Sample	21
Figure 2.4 Entry to pillbox, Northumberland	28
Figure 2.5 A bunker in South Dakota	29
Figure 2.6 Shelter finite element model by WAI-MAZ	30
Figure 2.7 Pressure with time history curve that represents an ideal far-field blast wave	33
Figure 2.8 Stress-strain curves of concrete at different strain rates	35
Figure 2.9 Graph of stress-strain response of group A, B, and C unconfined samples.	39
Figure 2.10 Graph of PC compressive strength and modulus variation with aggregate size.	40
Figure 2.11 Typical stress-strain relationships for epoxy and polyester polymers (a) compressive strain (b) flexural strain	41
Figure 2.12 Reflected overpressure-time profile of panel (a) Panel 3 and (b) Panel 4	43
Figure 2.13 A panel response for 5-kg charge weight at 0.3 m stand-off distance	45
Figure 2.14 A panel response under blast effect which create the localize punching mode	45
Figure 2.15 Damage patterns. (a) experimental study and (b) numerical analysis of RC slab	47

Figure 2.16	Damage produced by the ball bearing impacts on the plain concrete block	48
Figure 2.17	The upper surface damage of the RC slabs	50
Figure 2.18	The bottom surface damage of the RC slabs	51
Figure 2.19	Comparison of experimental results and numerical simulation	53
Figure 2.20	Damage modes of RC slab	54
Figure 2.21	Failure mode of fabricated concrete slab	55
Figure 2.22	Displacement time history for different explosive charge on RC slab	56
Figure 2.23	(a) The explosion experiments setting and (b) the geometry of the reinforced concrete board	57
Figure 2.24	Schematic of the slab support and the geometry of the warhead	60
Figure 2.25	Comparison of the numerical and experimental results of the RC slab damage contour	62
Figure 3.1	Flowchart in modelling by using ABAQUS/CAE 6.14.	72
Figure 3.2	(a) Bunker sketch and (b) Bunker model by ABAQUS.	73
Figure 3.3	All parts of SPCB for ABAQUS modelling.	75
Figure 3.4	Complete assembly of the bunker.	83
Figure 3.5	Converging maximum displacement at the centre of the SPCB-200.	86
Figure 3.6	Complete meshing for the bunker SPCB-200.	88
Figure 3.7	Job Manager.	89
Figure 3.8	Visualization and Result Plot.	90
Figure 3.9	Blast on reinforced concrete panel (units: mm).	91
Figure 3.10	Response Surface Methodology (RSM) flowchart Using Minitab	92
Figure 4.1	Verification of blast modelling technique (a) Deflection-time curves (b) i Model result of Shishegaran (b) ii present Model.	97
Figure 4.2	Maximum vertical displacement of (a) SCB and (b) SPCB models.	102
Figure 4.3	Displacement of SCB and SPCB models.	104

Figure 4.4	Principal stress distribution at distance 0.1 meter with 1 kg of TNT, (a) SCB-200-1, (b) SCB-250-1, (c) SCB-500-1 and (d) SPCB-200-1, (e) SPCB-250-1, (f) SPCB-500-1.	106
Figure 4.5	Principal stress distribution at distance 0.1 meter with 5 kg of TNT, (a) SCB-200-5, (b) SCB-250-5, (c) SCB-500-5 and (d) SPCB-200-5, (e) SPCB-250-5, (f) SPCB-500-5.	107
Figure 4.6	Principal stress distribution at distance 1 meter with 1 kg of TNT, (a) SCB-200-1, (b) SCB-250-1, (c) SCB-500-1 and (d) SPCB-200-1, (e) SPCB-250-1, (f) SPCB-500-1.	109
Figure 4.7	Principal stress distribution at distance 1 meter with 5 kg of TNT, (a) SCB-200-5, (b) SCB-250-5, (c) SCB-500-5 and (d) SPCB-200-5, (e) SPCB-250-5, (f) SPCB-500-5.	110
Figure 4.8	Principal stress distribution at distance 1 meter with 10 kg of TNT, (a) SCB-200-10, (b) SCB-250-10, (c) SCB-500-10 and (d) SPCB-200-10, (e) SPCB-250-10, (f) SPCB-500-10.	111
Figure 4.9	Principal stress distribution at distance 1 meter with 25 kg of TNT, (a) SCB-200-25, (b) SCB-250-25, (c) SCB-500-25 and (d) SPCB-200-25, (e) SPCB-250-25, (f) SPCB-500-25.	113
Figure 4.10	Tensile damage (DamageT) of SPCB under 1 kg TNT at 0.1 m blast distance.	114
Figure 4.11	Tensile damage (DamageT) of SPCB under 5 kg TNT at 0.1 m blast distance.	116
Figure 4.12	Tensile damage (DamageT) of SPCB under 10 kg TNT at 0.25 m blast distance.	118
Figure 4.13	Tensile damage (DamageT) of SPCB under 25 kg TNT at 0.25 m blast distance in the Z-axis cross-section.	120
Figure 4.14	Tensile damage (DamageT) of sandwich polymer bunkers under 25 kg TNT at 0.5 m blast distance in X- and Z-axes cross-section.	121
Figure 4.15	Tensile damage (DamageT) of SPCB under 25 kg TNT at 0.5 m blast distance.	122
Figure 4.16	Tensile damage (DamageT) of sandwich polymer bunkers under 25 kg TNT at 1 m blast distance on top view.	125
Figure 4.17	Tensile damage (DamageT) of SPCB under 25 kg TNT at 1 m blast distance (bottom view).	126
Figure 4.18	peak overpressure versus standoff distance with Tensile damage (DamageT).	126

Figure 4.19 Perforation area comparison of SCB models. 129

Figure 4.20 Comparison of predicted (a) σ_s and (b) σ_{Mises} Mises vs simulation data. 134

LIST OF ABBREVIATIONS

ACV	Aggregate Crushing Value
AIV	Aggregate Impact Value
APC	Advanced Polymer Composites
CFRP	Carbon Fibre Reinforced Polymer
FEM	Finite Element Method
FRP	Fibreglass Reinforced Plastic
PC	Polymer Concrete
PCB	Plain Concrete Bunkers
PCSP	Precast Concrete Sandwich Panels
SCB	Sandwich Concrete Bunkers
SOD	Stand-off Distance
SPCB	Sandwich Polymer Concrete Bunkers
TFV	Ten Percent Fine Value
TNT	Trinitrotoluene
CONWEP	Conventional Weapons Effects Program

LIST OF SYMBOLS

σ	Stress
σ_{Mises}	Von Mises Stress
σ_s	Principal Stress
ε	Strain
σ_{true}	True stress
$\varepsilon_{\text{true}}$	True strain
σ_y	Yield stress
σ_c	Compressive stress
σ_t	Tensile stress
σ_{max}	Maximum stress
ε_{max}	Maximum strain
ε_c	Compressive strain
ε_t	Tensile strain
ν	Poisson's Ratio
ρ	Density
d_c	Compressive damage parameter
d_t	Tensile damage parameter
f_t	Maximum tensile stress
$P_{r,\text{max}}$	Peak reflected overpressure
t_d	Positive phase duration
t'_d	Negative phase duration
E	Young's Modulus
U	Displacement

CHAPTER 1

INTRODUCTION

1.1 Study Background

Concrete is a very popular material in the construction industry because of being strong, durable and long lasting as such it is described to as an all-rounder building material. However, concrete may encounter demanding conditions throughout its life such as high-impact incidents like explosions or natural disasters. While conventional concrete made with cement, water and aggregates such as sand or crushed stone has high strength, it shows very little resistance to blast pressures. Exposure to high-energy shockwaves generated by explosions can cause conventional concrete to develop cracks and eventually disintegrate into rubble. This process poses serious risks of structural failure, endangering both human lives. To counter this, blast-resistant or anti-blast concrete, with its higher strength and enhanced durability, is increasingly used to effectively withstand explosive forces. The tougher these materials, the greater their resistance to explosive forces and potential benefits in shielding critical infrastructure. Public buildings have increasingly become targets of terrorist attacks in recent years, as these structures often fail to provide adequate protection against explosive events, resulting in severe risks to both occupants and infrastructure (Iannitti et al., 2018). Explosions often cause serious injuries or deaths, sometimes exceeding the harm caused by the extreme heat and pressure generated during the blast. The force of the explosion can lead to building collapse, resulting in additional damage and fatalities.

The blast, such as bombs and landmines, can cause significant damage to structures and infrastructure, as well as have a negative impact on the well-being of individuals and communities. Recent wars in Ukraine, Russia and Palestine provides a clear demonstration of the overwhelming capacity for destruction inherent within explosive TNT, as evidenced by significant harm caused to infrastructure that inevitably resulted in human fatalities. An essential strategy is to improve the blast resistance of materials, minimizing explosive weapons effects. Some specific materials can be engineered to withstand this extremely high pressure such as the design of some masonry is able to dissipate and absorb that energy in a way that has caused buildings not to collapse. Since explosive technology is evolving rapidly, countries must allocate maximum resources to the development of countermeasures for these dangerous weapons.

This damage usually caused by incidents with high explosive content, as shown in Figure 1.1 in catastrophic blast on August 4th, 2020 in Beirut Port, Lebanon. That explosion, caused by tons of ammonium nitrate stored in a warehouse there, devastated the city and left many dead or injured. It was revealed that inadequate safety measures and supervision involving storage of the ammonium nitrate had contributed to devastating accident outcomes. The blast, caused by hundreds of tons' worth of ammonium nitrate stored in a hangar, destroyed parts of the city and killed or injured dozens. These catastrophic event consequences have been made much worse because of the slipshod safety protocols and oversight related to ammonium nitrate storage. As

a result, calls for stricter safety regulations and improved storage practices to prevent similar tragedies from occurring again.



Figure 1.1: Massive explosion that occurred at the Port of Beirut, Lebanon (Yu et al., 2021)

A truck bomb containing approximately 4000 lb of ammonium nitrate soaked in fuel oil and detonated with a high explosive destroyed part of the Alfred P. Murrah Federal Building as shown in Figure 1.2 on April 19, 1995; this explosion damaged significant portions of the building and resulted in loss of life as well (168 deaths). Until September 11, 2001, it was the bloodiest act of terrorism ever committed on American soil. The Oklahoma State Department of Health conducted the epidemiologic research that showed 759 people were injured in the bombing (Teague, 2004).



Figure 1.2: Alfred P. Murrah Federal Building after the explosion (Teague, 2004).

Reinforced concrete structures are often used in the construction of blast-resistant buildings and other critical infrastructure. Researchers continue to explore the use of alternative materials to improve their strength and durability. The blast responsiveness of reinforced concrete structures is a multifaceted and complex subject. In other words, the size and weight of the explosive load together with distance from charge and concrete thickness all are essential when it comes to dynamic response of structure. The numerical simulation of reinforced concrete structures subjected to blast loads using the finite element method (FEM) has been proven an effective complement or alternative to experiments. Unlike expensive and time-consuming physical experiments, FEM allows the shaping of highly detailed complex structural behaviours investigated in a controlled and infinitely repetitive whitespace. Researchers can explore different parameters, optimize designs and predict failure modes which ultimately paves the route to more reliable solutions in structural engineering.

Reinforced concrete structures are used in construction because of their high-performance properties, but they do crush. A slab of concrete can fail for a number of reasons including inadequate design, poor construction errors, overloading or simply exposure to environmental factors that create corrosion and weathering. Other unexpected events like earthquakes, fires or explosions may also lead to concrete failure, as an example the reinforcement of a test slab (Figure 1.3) failing during blast procedures.



Figure 1.3: Slab failure under blast loading (Mendonça et al., 2018).

Concrete failure is a major problem that need to be considered in designing a concrete structure. Concrete failure can be caused by various factors such as the incident of explosion. According to Almustafa and Nehdi (2020), an explosion can create huge amount of pressure that can cause a permanent damage to the surrounding structure. Even with the high compressive strength, concrete cannot resist the amount of pressure produced by the explosive which will cause the concrete to fail.

The introduction highlights the vulnerability of civilian infrastructure to terrorist attacks, which can cause significant damage and fatalities. In response, various studies have been conducted to enhance the blast resistance of buildings, leading to the use of materials like polymer concrete, known for its superior mechanical and chemical resistance properties, including durability, damping, fracture toughness, and rapid curing. Although typically opaque due to its filler content, this study explores tin slag, a by-product of the tin smelting industry, as a key component in polymer concrete composites to enhance blast resistance. Incorporating tin slag not only supports sustainable construction by recycling industrial waste but also aids in developing high-performance materials with improved structural properties. This research investigates the potential of tin slag polymer concrete composites to absorb and dissipate energy under explosive loads, comparing their blast performance with that of conventional concrete. By examining factors such as explosive charge, slab thickness, and TNT distance using numerical models, the study aims to predict the maximum stress, deflection, and failure modes, offering valuable insights into the effectiveness of tin slag polymer concrete as a viable option for constructing blast-resistant structures.

1.2 Problem Statement

The concept of reinforced concrete remains unique in the field to improve the quality in term of the functionality, strength, and service time of structures. The emerge of new materials used in concrete such as tin slag will improve the quality of the concrete. Due to the improvement of the technologies in the last decade, there are many research involving the way to improve the quality of reinforced concrete structure. The study of blast behaviour in reinforced concrete slabs remains an active research area due to increasing concerns over safety from accidental or intentional explosions, as well as the need to evaluate new reinforcement materials like CFRP and fibre-reinforced concrete. The lack of standardized

design guidelines and the growing use of advanced experimental and numerical methods further drive continued investigation in this field (Draganić et al., 2025). Different blast loading energies cause varying responses in reinforced concrete slabs, ranging from minor surface cracks at low energy levels to severe damage or collapse under high-intensity blasts. As the blast energy increases, slabs may experience flexural cracking, spalling, scabbing, or even complete structural failure. The behaviour depends on factors such as explosive mass, stand-off distance, slab thickness, and reinforcement layout. Understanding these effects is vital for designing structures that can withstand different levels of blast impact, especially in safety-critical environments (Jaini et al., 2016).

The experiment is an essential component of the research process; nonetheless, it may be costly and time-intensive. A primary restriction of experimenting is the substantial expense, stemming from the need for specialized equipment, supplies, facilities, and proficient workers. Ultimately, replicability is crucial to the scientific method; nonetheless, it may be challenging to attain, since distinctive or intricate experiments may be difficult to duplicate owing to variations in circumstances or apparatus. These restrictions may be alleviated using alternate techniques such as simulations, theoretical analyses, or observational investigations; nevertheless, these approaches possess their own intrinsic limits and may not provide the same degree of confidence as direct testing.

Numerous studies have shown that while reinforced concrete structures can resist normal compressive and tensile stresses, they are vulnerable to blast loads, which can cause cracking, spalling, scabbing, and even collapse. The severity of damage increases with the explosive charge, as confirmed by both experimental and numerical investigations. Previous studies have demonstrated that varying explosive charge weights result in different levels of damage to reinforced concrete structures (Draganić et al., 2025; Jaini et al., 2016). The

solution is the structures blast resistance can be controlled by adjusting its mass and strength with extra concrete and steel reinforcement. Unfortunately, this method can be costly, add significant structural load to the structure's foundations, and take a considerable amount of time. When concrete and masonry are exposed to blast loads, deformation and fragmentation can happen as well. So, another solution is finding new materials which is increase in the blast resistance. The discovery of new materials, such as tin slag used in polymer concrete, may offer a promising solution to enhance resistance against blast. Polymer concrete has high impact resistance and high compressive strength. This concrete is highly durable and highly resistant to freezing and thawing compared to conventional concrete. Previous research has consistently shown that the closer the explosive is to the reinforced concrete slab, the more severe the damage sustained by the slab (Holgado et al., 2024). Even with the use of minimal explosive weight in the research, it was sufficient to cause failure in the reinforced concrete slab. Most reinforced concrete slab failed in tensile failure. Therefore, the present research is focused on simulating the blast response of a sandwich polymer concrete bunker (SPCB), constructed with tin-slag polymer concrete as the core and CFRP as the skin on top and bottom of the bunker. The primary objective is to analyse the behaviour of tin slag polymer concrete sandwich bunkers under varying blast loads, including different TNT weights and standoff distances. ABAQUS/CAE software is utilized to simulate and study the response of the polymer bunker subjected to blast loading. This study aims to address the drawbacks of traditional experimentation, such as being time-consuming, labour-intensive, and costly, while also promoting material sustainability through the use of industrial waste like tin slag and tackling the complex blast behaviour of reinforced concrete (RC) structures.

1.3 Objectives

The objectives of the research are:

- i. To simulate the blast responses of tin slag polymer concrete bunkers sandwiched by carbon fibre-reinforced polymer (CFRP) skins, under varying explosive loads, standoff distances, and core thicknesses using numerical methods.
- ii. To evaluate the blast-resulted stress and deformation mode of tin slag polymer concrete bunkers sandwiched by CFRP skins compared to normal concrete sandwich bunkers under various blast conditions.
- iii. To formulate new generalized prediction equations for maximum principal stress and von Mises stress related to the blast responses, using the response surface method.

1.4 Hypothesis

The numerical model of sandwiched carbon fibre-reinforced polymer (CFRP) skins in reinforced polymer concrete bunkers can be accurately constructed using ABAQUS/CAE 6.14, incorporating the blast functionality of the CONWEP method to simulate explosive loading effects. ABAQUS is widely used for structural simulations due to its strong capabilities in material modelling, contact interactions, and customization through user subroutines. Despite these advantages, its capabilities in simulating complex behaviors, especially in layered structures like CFRP-skinned concrete bunkers require further detailed investigations. The blast response and deformation mode of tin slag reinforced polymer concrete bunkers with CFRP skins can be evaluated using a comparative approach versus those with normal concrete cores under identical blast conditions. Key parameters such as displacement, stress distribution, and damage extent are measured through simulations. This

approach enables the assessment of effectiveness of different concrete cores in enhancing blast resistance and contributes to the development of predictive models for structural performance. The effectiveness of such structures under TNT blast weights, core thicknesses, and standoff distances remains underexplored. The blast response of sandwiched carbon fiber-reinforced polymer (CFRP) skins in reinforced polymer concrete bunkers can be systematically formulated using the response surface method (RSM) to develop predictive models for structural performance forecast under explosive loading conditions.

1.5 Scope of study

The key steps and parameters involved in developing and assessing the performance of the sandwich polymer bunker with CFRP skins under explosive loads are as follows:

- i. Develop a model of the sandwich polymer concrete bunker with CFRP skins.
- ii. The sandwich bunker has a size of $10\text{ m} \times 6.5\text{ m} \times 3.5\text{ m}$.
- i. Polymer concrete is made from tin slag polyester concrete.
- ii. The polymer concrete reinforcement diameter will be 12 mm and the concrete cover of 40 mm.
- iii. The sandwich bunker is reinforced polymer concrete with fixed support.
- iv. The considered thicknesses of the polymer concrete are such as 200 mm, 250 mm, 300 mm, and 500 mm for the sandwich bunker.
- v. Various TNT masses, which are 1 kg, 5kg, 10 kg, and 25 kg, are applied for the structural assessment.
- vi. Various blast distances, which are 0.1-meters, 0.25 meters, 0.5 meters, 1 meter, 2 meters, and 2.5 meters are applied for the structural assessment.

- vii. The CFRP skin has a thickness of 3 mm on top and bottom.
- viii. The sandwich bunker model is simulated redundant ABAQUS/CAE 6.14 along with blast functionality CONWEP of ABAQUS.

1.6 Summary

Chapter 1 is devoted to providing an introduction to the study, emphasizing the application of concrete as a widely used material in construction due to its strength, durability, and cost-effectiveness. The chapter highlights the limitations of conventional concrete in resisting blast loads and stresses the need for improving blast resistance, especially in light of increasing threats and real-world incidents. It also explores the use of numerical simulations as a viable alternative to expensive experimental testing and introduces the use of tin slag in polymer concrete for enhanced blast resistance. The study's objectives include designing a CFRP sandwich polymer bunker and simulating its performance under various blast conditions using ABAQUS/CAE software.

Chapter 2 discusses the literature review, advanced polymer composites, examining polymer concrete, and the incorporation of tin slag as an aggregate. The review explores the benefits of using polymer-based materials in enhancing the durability and blast resistance of concrete structures. Additionally, it highlights the use of tin slag as an industrial by-product to improve the mechanical properties of concrete, including its ability to withstand extreme loads. The chapter also delves into the chemical activation processes that can further enhance the performance of these materials, providing a comprehensive overview of existing research and identifying gaps to be addressed in this study.

Chapter 3 explains the methodology used in the study, detailing the modelling and simulation of sandwich polymer concrete bunkers (SPCB) through ABAQUS/CAE. It

outlines the parameters analysed, such as explosive charge volume, slab thickness, and standoff distance, and predicts the structural responses, including stress, deflection, and failure modes. This chapter aims to develop prediction equations to guide the design of more blast-resistant structures.

Chapter 4 discusses the comparative analysis of SPCB (sandwich polymer concrete bunkers) and SCB (standard concrete bunkers) under blast loads. It examines the performance differences between these two types of bunkers, highlighting the enhanced blast resistance of SPCBs, and presents results for various blast distances and TNT masses.

Finally, Chapter 5 provides the conclusions of the study, summarizing the key findings regarding the effectiveness of SPCBs in improving blast resistance. It reflects on the practical applications of the research and offers recommendations for future studies and structural design improvements to enhance the durability and blast resistance of buildings.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter presents a comprehensive review of existing literature on the structural response of materials under blast loading, with a specific focus on polymer concrete, fibre-reinforced composites, and bunker systems. It examines past research relevant to the application of advanced composite materials in enhancing blast resistance and investigates how these materials behave under high strain-rate loading. The section also discusses different analytical and numerical approaches employed in the literature to assess blast performance and explores the mechanical characteristics of various composite constituents, such as tin slag and carbon fibres, which are central to this study.

The review begins by discussing the fundamentals of polymer concrete (PC), highlighting its superior mechanical properties, rapid curing, and durability under extreme conditions. It then introduces advanced polymer composites (APCs) like carbon fibre-reinforced polymer (CFRP), detailing their fabrication, structural advantages, and increasing use in protective structures. Emphasis is given to the inclusion of industrial waste, specifically tin slag, as an eco-friendly and sustainable alternative aggregate that contributes to the strength and mass of PC mixtures.

Additionally, the chapter covers the history, function, and development of bunkers, emphasizing their role in military and civil protection from blasts. It continues by assessing the behaviour of both conventional and advanced concrete systems under blast loading, focusing on the relationship between explosive mass, standoff distance, and material response.

2.2 Polymer Concrete

Polymer concrete (PC) is a type of composite material composed with synthetic polymer resins together with natural mineral aggregates. The concrete of this type is responsive to varying environmental service conditions and matrix materials that include both thermoset and thermoplastics as polymer (Yeon, 2010). Resin concrete provides an optimal combination of mechanical strength and chemical resistance, contributing to better in-service performance, and has good durability, damping properties, a wide range of modulus, and fast curing rates. The ratio of polymer in the mixture is relatively high due to the bonding of the aggregate by the polymer matrix, and the performance of the material depends on the type and mixed proportion of the resin and aggregate. Aggregate types include gravel, limestone, granite, clay, quartz, silica, calcium carbonate, and blast furnace slag. Common resin types are furan, polyester, epoxy, and carbamide (Wang et al., 2014). The mix design of the concrete utilizes aggregate size gradation to provide the least porous concrete and ensure the smallest amount of resin is used. Dirt and contamination-free aggregates ensure optimal bond strength with the resin. The processing of polymer concrete involves simple steps where a monomer, hardener, and catalyst are mixed with filler, and the amount of binder is determined based on the aggregate size. Normally, the polymer binder is present in the range of 5 to 15%, but in the presence of fine filler, it can go up to 30% (Hollaway, 2008).

PC is a type of composite material in which the traditional cement binder is replaced entirely or partially by polymer-based binders. According to Taha et al. (2019), PC exists in three main forms: polymer concrete (using polymer resin as the sole binder), latex-modified concrete, and polymer-impregnated concrete. Among these, polymer concrete, where the

polymer acts as the main binding agent for aggregates, offers superior performance characteristics compared to conventional cementitious concrete (Taha et al., 2019).

PC is widely used in harsh environments and structural repairs. Recent studies emphasize sustainable practices by incorporating recycled aggregates and industrial by-products, which improve performance and reduce environmental impact. The addition of nanomaterials like carbon nanotubes enhances PC's toughness and durability. However, PC's thermal resistance remains a challenge due to its sensitivity to high temperatures. Despite this, its lightweight nature, fast setting time, and potential for 3D printing make it promising for modern construction applications (Yelemessov et al., 2023).

2.3 Fibre

2.3.1 Fibre-Reinforced Polymer Composites (FRPC)

Fibre-reinforced polymer composites (FRPC) are materials made by combining a polymer matrix with high-strength fibres like carbon, glass, or aramid to enhance strength and stiffness. They have gained significant attention due to their unique properties, including a high strength-to-weight ratio and excellent corrosion resistance. These advantages make FRPCs suitable for a wide range of applications, including aerospace, automotive, marine, and construction industries (Hollaway, 2008).

In FRPCs, the polymer matrix is a thermoset or a thermoplastic. Thermoset matrices are cross-linked so they cannot be melted and reshaped once cured. Thermoplastic matrices are loosely bonded polymers that can be melted and reformed multiple times without undergoing permanent chemical change. FRPCs can be manufactured using a variety of techniques, including hand lay-up, filament winding, pultrusion. The manufacturing process used depends on the specific application and the desired properties of the final product.

One of the key advantages of FRPCs is their ability to be tailored to specific performance requirements. This is achieved by adjusting the type and amount of reinforcement material, the type of polymer matrix, and the manufacturing process used. By optimising these variables, FRPCs can be engineered for a range of mechanical properties, including strength, stiffness, and durability (Ilki et al., 2008). While there are numerous advantages of FRPCs, using them will also present many challenges. FRPCs, for a comprehensive list of example design are generally expensive to fabricate and their mechanical properties can be very process dependent. Furthermore, the use of some reinforcement materials such as carbon fibre could produce environmental issues on account of high-energy production and possibility for waste.

Carbon, glass and aramid are the highly demanded fibres for structural applications. Strength of these fibres is of the same order although they differ in stiffness. The higher the stiffness of the fibre, higher will the value of stiffness of composite. Carbon fibre is the most demanded for structural rehabilitation because of high stiffness (220-300 GPa). Glass fibre is also an option because of economic and environmental considerations. Ultra-high stiffness carbon fibre is not used because of low value of ultimate strain (0.4%). The higher the amount of fibre, higher will be the strength of composite. However, there should be an optimum amount as an excess of fibre amount will lead to poor impregnation by matrix and shear failure. A fibre weight fraction of 55- 60% is used for renovation of structural members (Hollaway, 2003).

Fibre orientation affects the tensile strength and Elastic modulus value of composite. For rehabilitation and retrofitting of columns, continuously wound fibres in hoop direction are applied to column with a slight positive angle. These fibres confine the concrete as the

fibre can resist much higher tensile stress compared with that of concrete column. This will increase compressive load bearing capacity.

In conclusion, FRPCs offer a range of advantages over traditional materials, with the potential to bring transformative changes across various industries, particularly in construction, aerospace, automotive, and marine engineering. Nevertheless, research and development must continue to address those challenges of their application in order for the benefits associated with these materials to be realized fully.

2.3.2 Mechanical Properties of Fibre-Reinforced Polymer Composites

As the properties result from a complex interplay of material characteristics, fibre orientation and manufacturing techniques, composite will incorporate all these factors while giving mechanical performance. Table 2.1 gives the properties of epoxy impregnated composites with different fibres prepared through pultrusion. Fibre weight fraction is 0.6 for all composites.

In applications where structural elements are subjected primarily to compressive forces such as in columns, struts, and load-bearing panels, the compressive strength of composite materials becomes more critical than their tensile strength. The integrity of the composite under compression is crucial because fibre buckling can lead to premature failure. In such cases, the matrix plays a vital role by providing lateral support to the fibres, helping to prevent local buckling. Furthermore, the quality of the interface between the fibre and the matrix significantly influences the composite's compressive performance, as poor bonding can lead to delamination or fibre misalignment under load.

Table 2.1: Mechanical properties of unidirectional composites (Hollaway, 2008).

Composite material	Specific weight	Tensile strength (MPa)	Tensile modulus (MPa)	Flexural strength (MPa)	Flexural modulus (GPa)
E-glass	1.90	750-1050	40.0	1450	40
S-2 glass	1.80	1650	55	-	-
Aramid 49	1.45	1150-1400	70-110	-	-
Carbon (PAN)	1.60	2670-1950	150-220	1600	-
Carbon (pitch)	1.80	1400-1500	280-350	Failure strain = 0.40 >330	

However, aramid fibre composites exhibit non-linear stress strain behaviour under compression, even at low stress levels, making them less suitable for structural applications that require high compressive strength. Typical compressive strength of glass, aramid and carbon fibre-based composites are 55%, 20% and 78% less than the tensile strength of these composites.

Polymer being visco-elastic in nature undergoes creep under the action of load. Fibres, on the other end, do not have creep component. Therefore, fibres reduce the creep of viscoelastic polymers by acting as reinforcement, resulting in significantly lower long-term deformation in FRPCs compared to pure polymers. Creep value of FRPCs depends on several factors that include fibre volume fraction, fibre orientation and type of fibre used. FRPCs for strengthening have two features that make the creep in composite negligible. First, the stressed state in fibre does not exceed 20 to 25% of ultimate value. Second, composite contains high weight fraction of fibre that makes creep phenomenon in composites negligible (Ilki et al., 2008).

Fatigue in composite materials develops gradually over time due to repeated loading and unloading cycles. It often leads to failure in the fibres themselves or within the stacking sequence (the arrangement of fibre layers). Although the fatigue loads are usually much lower than the materials ultimate strength, carbon and glass fibre composites generally perform well under such conditions. Most fatigue failures are initiated in the matrix or at the interface between the matrix and fibres. A strong fibre matrix interface can significantly delay damage, such as fibre buckling or matrix cracking along the fibres, thereby enhancing the composite's fatigue life (Yeon, 2010).

2.3.3 Carbon Fibre

The processing of carbon fibres involves stabilisation, carbonisation, graphitisation, and surface treatment, which include pyrolysis and crystallisation of organic precursors (Bengtsson et al., 2022). During these processes, most non-carbon elements are removed, and carbon crystallites align along the fibre's length. At temperatures above 2000°C, the crystallites grow larger and become more oriented. Carbon fibre filaments typically range from 5 to 8 µm in diameter, with tows comprising 5000 to 12000 filaments that can be twisted into yarns or woven. Common precursors include PAN, pitch, or rayon.

The main raw material for producing carbon fibre is the precursor, with about 90% made from polyacrylonitrile (PAN), while the rest come from rayon or petroleum pitch. Carbon fibres are known for their high tensile strength, low density, excellent thermal and chemical stability (in non-oxidising environments), and good electrical conductivity. They also offer strong compression resistance, making them ideal for structural applications. Although more expensive than other fibres, carbon fibres are widely used across industries

including aerospace, military, medical, automotive, sports, and construction due to their superior strength-to-weight ratio and high modulus (Vinod et al., 2023).

Table 2.2 compares the properties of Pitch, Rayon, and PAN carbon fibres. Pitch has the highest density (2.0 g/cm^3), followed by PAN (1.8 g/cm^3) and Rayon (1.7 g/cm^3). Rayon shows the highest Young's Modulus ($415\text{--}550 \text{ GN/m}^2$), while PAN offers the greatest tensile strength ($2.48\text{--}3.10 \text{ GN/m}^2$). Pitch has the lowest tensile elongation (1%), with PAN ranging from 0.6–1.2%, and Rayon lacking data. Due to brittleness at high modulus, joint and connection design becomes critical, making adhesive bonding preferable for carbon composite laminates (Sett and Vipulanandan, 2013).

Table 2.2: Properties of carbon fibres (Vinod et al., 2023).

Typical Properties	Pitch	Rayon	PAN
Density (g/cm^3)	2.0	1.7	1.8
Young's Modulus (GN/m^2)	380	415-550	200-345
Tensile Strength (GN/m^2)	1.55	2.07-2.76	2.48-3.10
Tensile Elongation (%)	1	-	0.6-1.2

Durability is a major concern when using externally bonded FRP systems for strengthening reinforced concrete, especially regarding the FRP material and its bond with concrete (Bengtsson et al., 2022). A 1.5 mm FRP thickness minimises contact stress and delamination risk, while thicker layers increase contact friction stress, thus a thinner FRP is recommended (Gupta and Doddamani, 2018).

Figure 2.1 illustrates typical carbon fibres used in carbon fibre-reinforced polymer (CFRP) materials. CFRP is a composite material consisting of a polymer matrix reinforced with carbon fibres, which are known for their high strength-to-weight ratio, stiffness, and resistance to corrosion. The unidirectional or woven carbon fibres shown in the Figure 2.1 endow a composite with excellent tensile modulus and rigidity. The properties of CFRP make it an attractive material in many applications that need high strength to weight ratios, as well as a damage tolerant design: including whole body armour, bullet-proof vests functional parts for aircraft and spacecraft (including propellant tanks), ducted fan housing. Turbine housings such power generator casings; hypodermic syringes; tubes requiring high stiffness and low mass.

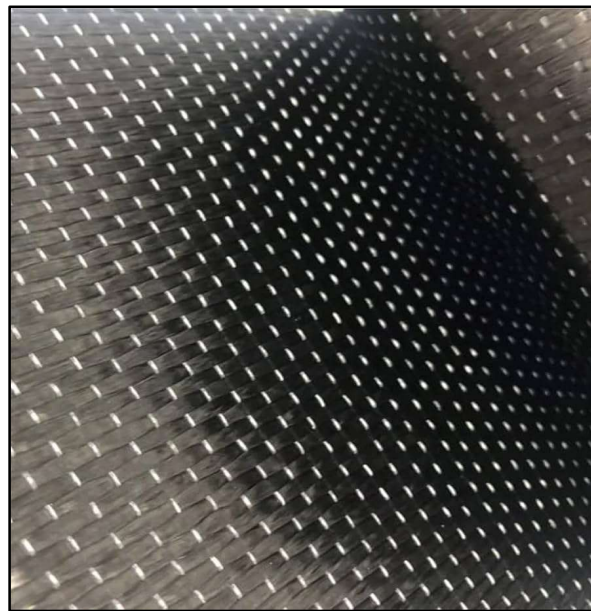


Figure 2.1: Typical carbon fibre-reinforced polymer (Falah, 2016).

Carbon fibre exhibits elastic behaviour up to failure at ambient temperatures and is highly resistant to creep and fatigue. It is chemically inert except in strong oxidative environments and also demonstrates high damping properties. Carbon fibres are high-

performance materials derived from PAN, pitch, or rayon precursors, which are heat-treated to produce strong, lightweight fibres with excellent tensile stiffness and strength.

Table 2.3 highlights the mechanical properties of various carbon fibre types, categorized into PAN-based and pitch-based fibres, each with standard, intermediate, and ultra-high modulus grades. Ultra-high modulus fibres offer exceptionally high tensile modulus (up to 882.5 GPa for pitch-based fibres) but have low elongation, indicating high stiffness and limited flexibility. In contrast, intermediate modulus fibres provide a balanced combination of strength and ductility, making them suitable for a broader range of applications (Srivatsan, 1995).

Carbon fibres have several disadvantages like brittleness, poor durability against impacts, low elongation, low strength at compression, and a small ratio of linear expansion. Despite these limitations, they are nevertheless a flexible, high-performance material utilized in a variety of applications. Their characteristics vary depending on the precursor material and the production technique. While PAN-based carbon fibres are the most prevalent, pitch-based, rayon-based, and vapor-grown carbon fibres each have distinct properties that make them ideal for certain applications.

Table 2.3: Properties of different grades of PNA based Fibres (Ahmad et al., 2020; Srivatsan, 1995).

Fibre Type PNA based Fibres	Tensile Strength, MPa	Tensile Modulus, GPa	Elongation to Break, %
Standard modulus	3447	228	1.6
	4502	234	1.8
	3530	228	1.5
Intermediate modulus	5378	276	2.1
	6067	290	2.1
	924	297	2.2
Ultra-high modulus	3447	441	0.5
	4413	441	1.0
	3820	586	0.7
Standard modulus	1903	379	0.5
Intermediate modulus	2103	517	0.4
Ultra-high modulus	3620	724	0.5
	3633	883	0.4

2.4 Tin Slag

Tin slag is a by-product of smelting process of tin. In this process, cassiterite (SnO_2) is reduced to get tin from ore. The temperature is in the range of 1200-1300°C and an atmosphere of carbon is maintained. Special furnaces known as reverberator furnaces are utilized to re-smelt tin slag for further tin recovery, with the smelting process taking

approximately 10 to 12 hours; after this period, the batch is tapped into a settler, where the slag overflows. Then, slag is granulated using water and solidified into a material which seems glass-like. Slag consists of a number of elements and compounds including silica, lime, iron, uranium and thorium (Shakil and Hassan, 2020) . Typical chemical composition of tin slag is given in Table 2.4.

There has been little interest in finding the properties of tin slag so far. There can be many reasons for this lack of attention including non-ferrous slag does not constitute appreciable portion of slag by-products produced worldwide. Most of the attention is received by slag products that are larger in production volume such as steel slag.

Table 2.4: Chemical composition of tin slag (McCallion, 1969; Rustandi et al., 2018).

Properties	Percentage (%)
Calcium oxide (CaO)	16-20
Silicon dioxide (SiO ₂)	28-32
Aluminium oxide (Al ₂ O ₃)	10-13
Magnesium oxide (mgO)	2-4
Iron (FeO)	13-18
Wolfram oxide (WO)	2.0
Aesenic (As)	< 0.01
Lead (Pb)	< 0.01
Cadmium (Cd)	< 0.0001
Titanium Dioxide (TiO ₂)	4-5
Zinc (Zn)	< 0.3
Tin (Sn) Properties Value (%)	< 1.4

Most of tin slag is being produced in developing countries where there has been little incentive in recycling the by-product for further use. Also, environmental regulations are not stringent enough to act as stimulus for environmental related research.

Particles of raw tin slag procured from industry are shown in Figures 2.2 and 2.3 where the look of tin slag is blackish and glassy. The general outlook of tin slag is granular. Density of tin slag is of the same order as other slags such as steel and copper slag. However, when densities of natural aggregates such as granite and limestone are compared with tin slag, density of tin slag is higher than them. This indicates that a high density mixture will result when tin slag is used as aggregate in polymer or hydraulic concrete (Iannitti et al., 2018; McCallion, 1969).



Figure 2.2: General outlook of tin slag (Abd and Yusof, 2005).

The two most dominant shapes are the triangle and circle, as seen in Figure 2.3, it is in general, less than 6.3 mm and consists of needle like particles. The density of tin slag was evaluated under all these conditions.

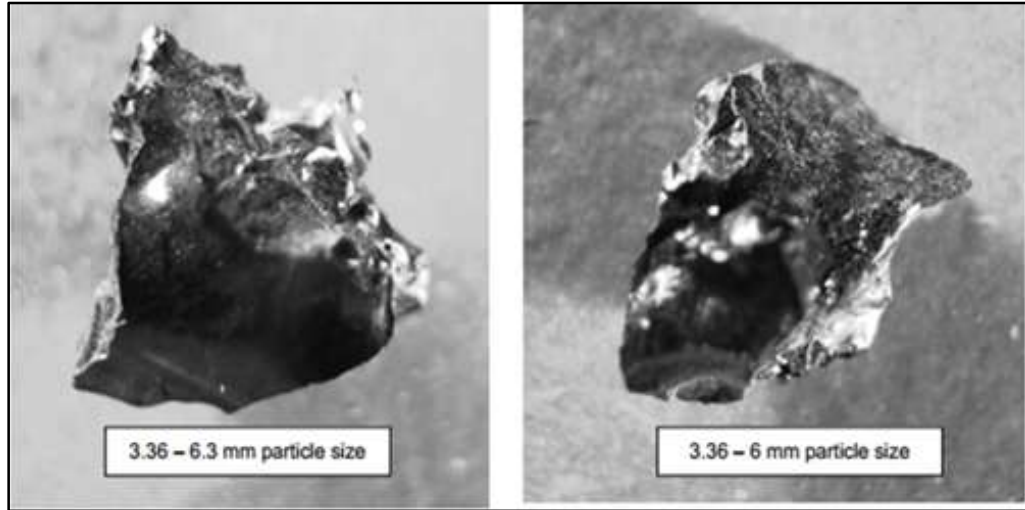


Figure 2.3: Comparison of 3.36 – 6.3 mm and 3.36 – 6 mm Particle Size Samples (Abd and Yusof, 2005)

Mechanical properties of tin slag include aggregate crushing value (ACV), ten percent fines value (TFV) and aggregate impact value (AIV). For comparison, values of ACV obtained from testing tin slag is compared to granite, another construction aggregate, to appreciate the differences in properties. All values from these tests are given in Table 2.5.

The aggregate crushing value test is the ability of aggregates to resist crushing under increasing burden. The test method consists in compacting a specimen introduced on the steel (ASTM D-6925) cylinder with plunger. The procedure applies a standard loading regime and this crushes the aggregate to different degrees depending on their crushing resistance. Here, the sieving test is used to establish the degree/resilience.

According to the values reported in Table 2.5, ACV for tin slag is 31.4 and for granite, 11.6. This indicates that tin slag is approximately three times weaker than granite in crushing strength. Aggregate impact value test is to measure resistance of an aggregate or particle to sudden impact or force. Test method is simple that involves compacting specimen in steel cup followed by sudden impact from dropping weight. Breakage of aggregates gives an

indication of the degree of resistance to impact load. The degree is assessed by sieving test. A lower value obtained points out to higher toughness and wear resistance (Tylecote et al., 1989). Tin slag is at least two times weaker in impact value test than granite.

Table 2.5: Properties of tin slag compared to granite (Abd and Yusof, 2005).

Property	Tin Slag	Granite
Aggregate Crushing Value, ACV (%)	31.4	11.6
Aggregate Impact Value, AIV (%)	24.9	10.4
Ten Percent Fine Value, T _{FV} _{dry} (kN)	22.1	100.0

The impact value test reveals that tin slag is at least two times weaker than granite, indicating its relatively lower strength. The ten percent fines value (TFV) test is often employed to assess aggregate strength, where a specimen is compacted in a cylinder, followed by applying a load through a plunger, resulting in the crushing of the aggregate. The degree of crushing is then measured through a sieve test, and the procedure is repeated until a force level is reached that produces 10% of material finer than 2.36 mm. The TFV results show that tin slag has values around five times lower than granite, further highlighting its significant weakness compared to granite (Olukotun et al., 2021).

2.5 Bunkers

Bunkers have long been integral to military strategies, serving as strategic constructions aimed at safeguarding individuals and valuable materials from explosions or assaults. This role was particularly pronounced during major global conflicts like World War II and the Cold War. During these times, bunkers were not merely passive shelters but served as

command centres, weapons depots, and distribution hubs, contributing significantly to strategic defence and operational continuity across various theatres of war.

Figure 2.4 shows the entrance to a pillbox bunker in Northumberland, a defensive structure designed to protect against enemy attacks. Bunkers like these were integral to military strategy during the Second World War, providing fortified positions that could withstand bombardment.



Figure 2.4: Entry to pillbox, Northumberland (Bennett, 2011).

Figure 2.5 depicts a bunker in South Dakota, illustrating how bunker preparation has evolved over time. Initially designed during World War II and the cold war primarily for protecting military personnel and infrastructure, contemporary bunker use has shifted to a broader and more community-focused approach.



Figure 2.5: A bunker in South Dakota (Garrett and Klinke, 2019).

Bunkers are designed to withstand bomb blasts, nuclear attacks, and shockwaves, with reinforced entrances and ventilation for prolonged occupancy. Besides military use, they also protect weapon facilities and offer shelter during natural disasters like tornadoes (Ghamry Metwally et al., 2017).

Figure 2.6 illustrates, the standard approach to structural analysis across different loading scenarios heavily relies on finite element software programs, especially for typical structures such as buildings. However, structures engineered to endure blast loads necessitate specialized software due to their intricate dynamic responses. Blast field experiments are costly, dangerous, and often limited in scope, leading researchers to adopt sophisticated finite element software like LSDYNA and WAI-MAZ. In a case study involving an aircraft shelter exposed to a general-purpose bomb, both software tools produced comparable displacement responses. This underscores their credibility and effectiveness in analysing structures subjected to blast loads (Ghamry Metwally et al., 2017).

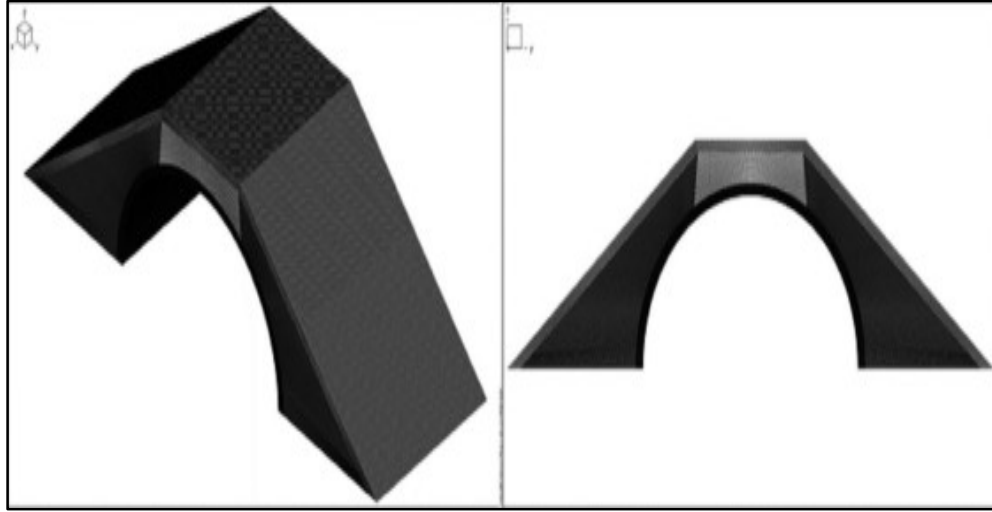


Figure 2.6: Shelter finite element model by WAI-MAZ (Ghamry Metwally et al., 2017).

2.6 Blast Loading

2.6.1 Classification of Explosions and TNT Equivalence

Explosions are rapid releases of energy that can be classified into physical, chemical, nuclear, and electrical events depending on their source. Physical explosions occur due to phenomena such as the rupture of compressed gas cylinders, volcanic eruptions, or sudden phase changes, releasing energy through physical processes. Nuclear explosions, though less common in civilian engineering, release vast amounts of energy through fission or fusion, causing widespread destruction. In engineering applications, chemical explosions are the most critical, as they involve rapid oxidation of elements like carbon and hydrogen, producing supersonic shock waves capable of devastating structural systems. High explosives such as TNT, RDX, or ANFO fall into this category and are frequently used as reference materials in blast research (Ngo et al., 2007). Electrical explosions, on the other hand, result from sudden discharges in electrical systems, though their structural impact is

usually less significant. Explosions are also distinguished by the extent of confinement, which directly influences pressure build-up and blast propagation. Unconfined explosions include free-air bursts, surface bursts, and air bursts, where the explosive detonates without significant containment. In contrast, confined explosions occur in enclosed or partially vented spaces, amplifying overpressure effects due to reflections and restricted venting (Shirbhate & Goel, 2021). The classification of explosions is vital for structural engineers because both the type of explosive and the degree of confinement dictate the blast characteristics, influencing the resulting loads, structural response, and potential failure mechanisms. Understanding these classifications provides a foundation for accurate blast load analysis and the development of mitigation strategies.

Complementary concept is TNT equivalence, which standardizes different explosives by converting their energy output into the equivalent mass of TNT. This enables the use of empirical predictive tools, such as CONWEP or Blast-X, that rely on TNT-based data (Shirbhate & Goel, 2021). Blast parameters governed by scaling include peak overpressure, positive and negative phase durations, and impulse, the latter being the time-integrated pressure load. Importantly, scaling laws are effective in simple, unimpeded environments but their accuracy diminishes in complex urban or confined conditions, where wave reflections, shielding, and channelling alter blast propagation (Ngo et al., 2007). Nevertheless, scaling laws and TNT equivalence remain foundational tools in blast engineering, forming the basis for risk assessment, protective design, and validation of advanced numerical simulations.

2.6.2 Blast Scaling Laws and Stand-off Distance (SOD)

The severity of a blast event depends largely on two fundamental parameters: the charge weight (W) of the explosive and the stand-off distance (R) from the target. To enable meaningful comparisons across different explosive events, researchers apply the Hopkinson Cranz cube-root scaling law, defined as $Z = \frac{R}{W^{\frac{1}{3}}}$, where Z is the scaled distance. This principle allows results from small-scale laboratory tests to be extrapolated to full-scale explosions, with studies confirming that differences in peak overpressure between scaled and full-scale tests can be as low as 3%. Such scaling laws are critical in both experimental and computational blast research, where full-scale testing is often impractical or unsafe (Ratcliff et al., 2023).

Blast waves are characterized by a rapid rise to a peak overpressure, followed by an exponential decay and subsequent negative phase, as illustrated in Figure 2.7. The pressure time history curve typically shows the peak reflected overpressure ($P_{r,max}$), the positive phase duration (t_d), and the negative phase (t'_d). To enable comparison of different explosive events, blast wave scaling principles are applied. According to the Hopkinson Cranz scaling law, two geometrically similar shock waves will behave identically if the scaled distances and control parameters are the same, regardless of explosive mass. This cube-root scaling has been widely adopted in blast studies as it allows experimental and numerical results to be generalized across different charge sizes, thereby simplifying blast wave prediction and structural response analysis.

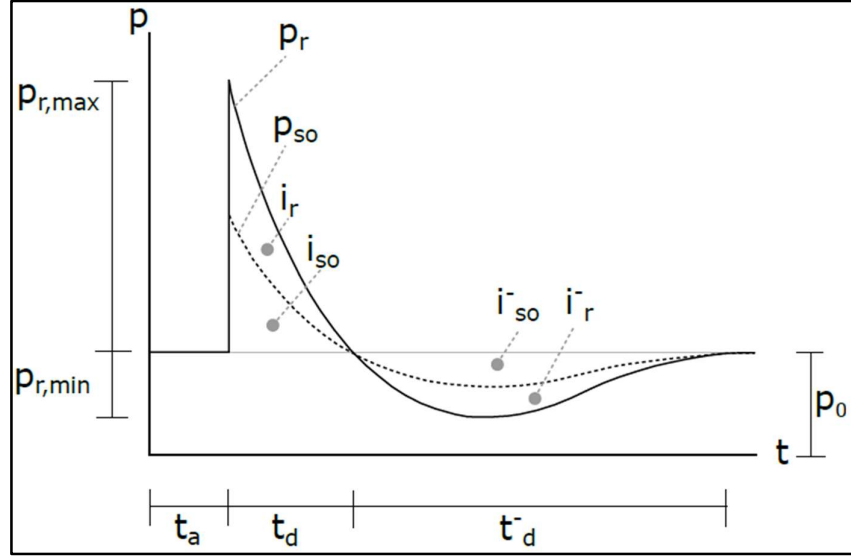


Figure 2.7: Pressure with time history curve that represents an ideal far-field blast wave (Rigby et al., 2014).

Across materials and systems, Stand-off Distance (SOD) strongly modulates dynamic demand and probability of limit-state exceedance. For steel moment-resisting frame buildings, increasing SOD systematically reduces blast fragility (failure probability at a given intensity measure), underscoring SOD as a first-order risk lever for performance-based design and urban risk management. Close-in detonations (small SOD) push members into highly nonlinear regimes with significant local damage and connection demands (Ngo et al., 2007; Zhang et al., 2024). For reinforced-concrete (RC) components, experiments and validated simulations show that as SOD increases, peak mid-span displacement and residual damage reduce markedly; reinforcement ratio, axial force state, and detailing interact with SOD to shape failure mode transitions from punching/scabbing to flexural responses. For advanced concretes, small-SOD (including contact) testing of UHPC slabs demonstrates substantially improved damage thresholds compared to normal RC, but still reveals sensitive

failure-mode boundaries at very low SOD where near-field effects dominate (Peng et al., 2025).

2.6.3 Effect of Strain Rate on Materials

Blast loading subject's materials to extremely high strain rates, often several orders of magnitude higher than those encountered in conventional static or quasi-static loading. Under such conditions, most construction materials, including steel, concrete, and composites, exhibit strain rate sensitivity, where their mechanical properties such as strength, stiffness, and ductility vary with the rate of loading. For instance, concrete demonstrates an increase in apparent compressive and tensile strength under high strain rates, a phenomenon often attributed to the reduced time available for micro-cracks to propagate (Ratcliff et al., 2023). Similarly, steel shows enhanced yield strength and strain hardening behaviour under dynamic loading, which can significantly influence the energy absorption capacity of structural members. While strain rate effects can initially appear beneficial by increasing material resistance. Brittle fracture, spalling, and localized shear failure are more likely under blast conditions due to rapid stress wave propagation and inertial effects (Shirbhate & Goel, 2021).

Figure 2.8 highlights the dynamic strengthening effect of concrete, where compressive strength and ductility improve with increasing strain rate. This behavior is important in blast, impact, and seismic applications, as it shows that concrete structures can withstand much higher stresses when subjected to rapid loading. However, it also indicates that design approaches based solely on static properties may underestimate concrete's resistance under high strain-rate scenarios.

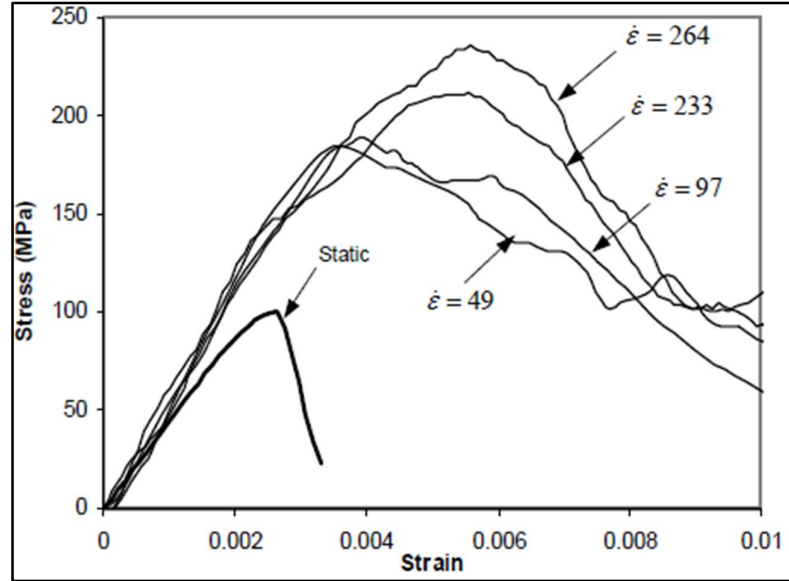


Figure 2.8: Stress-strain curves of concrete at different strain rates (Ngo et al., 2004a).

2.6.4 Blast Interaction with Structures

Composite and sandwich structures are increasingly studied for their blast-resistant properties due to their high strength-to-weight ratios, energy absorption capacity, and tailored failure mechanisms. Unlike conventional reinforced concrete or steel, composites such as fibre-reinforced polymers (FRP) and sandwich panels with lightweight cores can dissipate blast energy through progressive damage modes, including delamination, fibre breakage, and core crushing (Peng et al., 2025; Shirbhate & Goel, 2021). These mechanisms prevent catastrophic failure by spreading loads over larger areas and absorbing significant amounts of energy. Research shows that sandwich panels with polymeric or metallic cores reduce transmitted loads and mitigate localised failures under blast pressures. Similarly, CFRP-strengthened reinforced concrete elements demonstrate improved ductility, delayed cracking, and enhanced residual capacity when subjected to high strain rates. Experimental studies confirm that fibre orientation, matrix properties, and core thickness strongly

influence the blast performance of such structures. However, while composites improve resistance, they remain sensitive to strain rate effects and localized failures. Numerical models indicate that improper bonding between layers or premature delamination can reduce their protective effectiveness. To overcome these challenges, hybrid systems combining concrete with FRP skins or sandwich facings have been proposed as more reliable solutions for critical infrastructure (Ratcliff et al., 2023; Shirbhate & Goel, 2021).

2.6.5 Blast Loading on Composite and Sandwich Structures

Composite and sandwich structures are increasingly studied for their blast-resistant properties due to their high strength-to-weight ratios, energy absorption capacity, and tailored failure mechanisms. Unlike conventional reinforced concrete or steel, composites such as fibre-reinforced polymers (FRP) and sandwich panels with lightweight cores can dissipate blast energy through progressive damage modes, including delamination, fibre breakage, and core crushing (Peng et al., 2025; Shirbhate & Goel, 2021). These mechanisms prevent catastrophic failure by spreading loads over larger areas and absorbing significant amounts of energy. Research shows that sandwich panels with polymeric or metallic cores reduce transmitted loads and mitigate localised failures under blast pressures. Similarly, CFRP-strengthened reinforced concrete elements demonstrate improved ductility, delayed cracking, and enhanced residual capacity when subjected to high strain rates. Experimental studies confirm that fibre orientation, matrix properties, and core thickness strongly influence the blast performance of such structures. However, while composites improve resistance, they remain sensitive to strain rate effects and localized failures. Numerical models indicate that improper bonding between layers or premature delamination can reduce their protective effectiveness. To overcome these challenges, hybrid systems combining

concrete with FRP skins or sandwich facings have been proposed as more reliable solutions for critical infrastructure (Ratcliff et al., 2023; Shirbhate & Goel, 2021).

2.7 Behaviour of Polymer Concrete under Compressive Test

Despite the increasing interest in polymer concrete (PC) as a sustainable and high-performance alternative to conventional cement-based materials, there remains a notable lack of critical and systematic reviews focusing on its behaviour under compressive loading. Most available literature tends to be descriptive, presenting experimental outcomes without in-depth analysis of failure mechanisms or design implications. One of the few significant studies in this area was conducted by Shakil and Hassan (2020) who investigated the compressive performance of tin slag-based polymer concrete using an Instron 600 kN Universal Testing Machine at a loading rate of 1 mm/min. Their study examined unconfined specimens with three different aggregate sizes (AU, BU, CU), and results indicated that the AU sample achieved the highest compressive strength. The stress strain curve showed a typical three-zone behaviour: an initial linear rise (Zone 1), a plateau near peak load (Zone 2), and a post-peak descending branch (Zone 3), where cracking and interfacial failure between aggregate and matrix occurred. However, the study lacked deeper analysis into factors such as porosity, interfacial bonding, and the microstructural influence of aggregate grading. Similarly, follow-up studies with confined specimens demonstrated strength enhancements through the use of fibre-reinforced polymers (FRP) or metallic tubes, yet failed to isolate the contribution of confinement versus interfacial shear resistance. Importantly, these studies did not address key factors such as strain-rate effects, long-term durability under thermal or moisture exposure, or environmental degradation of the polymer matrix. Moreover, comparisons across studies are limited by inconsistent reporting of critical parameters such as resin type, curing conditions, and mix composition. The absence of high-

strain-rate data is especially concerning given the intended use of polymer concrete in protective and blast resistant applications. There is also a significant gap in modelling efforts, with limited numerical studies incorporating experimentally validated damage or failure parameters. In conclusion, while polymer concrete particularly tin slag-based variants show promising compressive strength and potential for structural use, the current body of work lacks the depth, standardisation, and critical evaluation required to fully understand and exploit its mechanical behaviour. Future research should adopt a multiscale approach integrating material characterisation, durability testing, and advanced modelling to establish a comprehensive framework for its structural application.

According to Shakil and Hassan (2020) compressive strength continuously increases with the highest value of 37.7 MPa for sample AU. Figure 2.9 shows the graph of compressive modulus and the compressive strength of the samples. Shakil and Hassan (2020) stated that there are two factors contributing to the effective distribution of finer size in granular skeleton that contribute to the increment of compressive strength, which are angular shape and higher concentration.

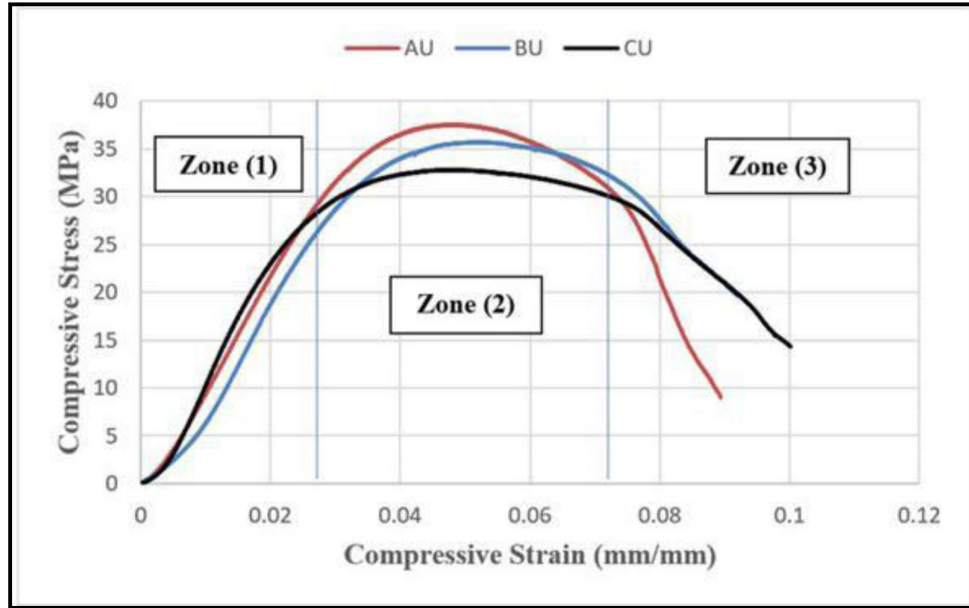


Figure 2.9: Graph of stress-strain response of group AU, BU, and CU unconfined samples (Shakil & Hassan, 2020).

Figure 2.10 highlight, the graph of polymer concrete compressive strength and modulus variation with aggregate size indicates that a decrease in aggregate size leads to an increase in the modulus of the polymer concrete. The reason for this rise in modulus is the volumetric increase in the inter-phase, which increases with the size of the surface area. According to Shakil and Hassan (2020), this relationship has been stated in an analysis of polymer cement compounds where modulus is assumed to be the result of two phases: aggregate and interphase. The contrasting relationship between strength and modulus is clearly caused by difference in aggregate size. According to Shakil and Hassan (2020), the study of polymer concrete under compressive load. They study five types polymer concrete which have different ratios of concrete mix design. Sample AC (AC define as a sample name) has the highest compressive strength with 58.21 MPa and follows by the other sample. In the research, it states that the AC sample has the highest compressive strength due to higher

bonding area provided between the resin and the particle size. It also stated that the average weight ratio is 30% resin to 70% tin slag.

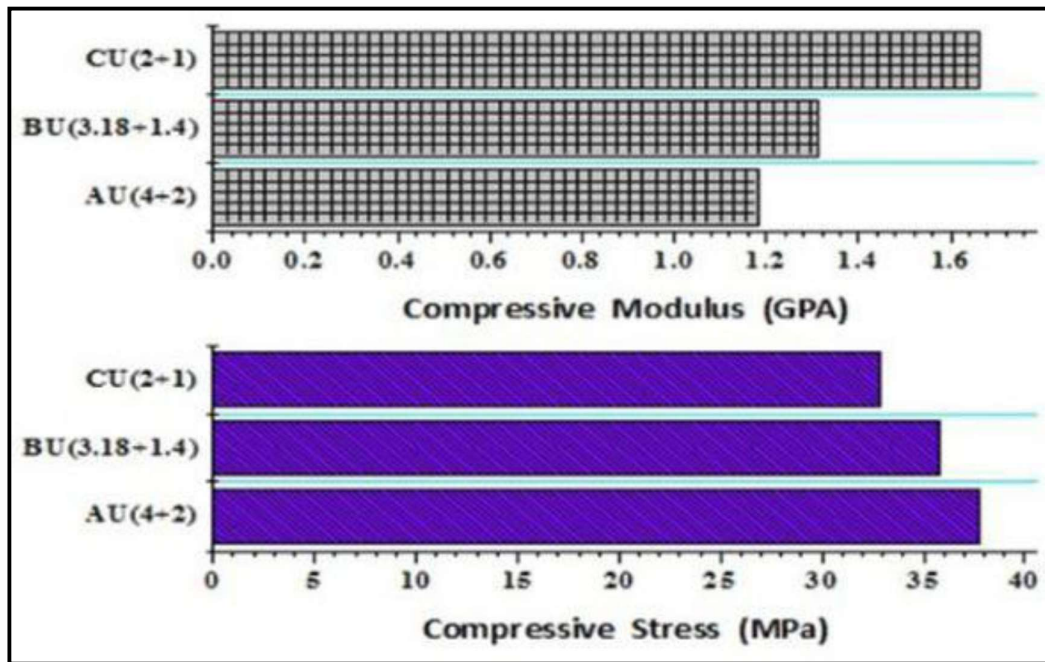


Figure 2.10: Graph of PC compressive strength and modulus variation with aggregate size.

The compressive and flexural stress strain responses of epoxy and polyester polymer concrete (PC) exhibit distinct behaviors influenced by resin type, resin content, and temperature variations. As depicted in Figure 2.11, the stress-strain curves for both epoxy and polyester polymer concretes reveal that an increase in the fiber reinforcement in resin content and temperature has a more pronounced effect on flexural strength, stiffness, and the overall stress-strain relationship than on compressive behavior.

Polymer concrete typically fails in shear under uniaxial compression, and although the strength and modulus ratios generally increase with rising temperature, the compressive strain ratio remains relatively constant. Figure 2.11 further illustrates that temperature significantly impacts the flexural behavior of PC, aligning with typical polymer

characteristics. Among the materials tested, epoxy PC demonstrated the highest strength and stiffness at room temperature, with maximum compressive yield strengths of 62 MPa at 22°C and 40.7 MPa at 80°C. In contrast, polyester PC showed a maximum compressive yield strength of 35.2 MPa at 22°C, slightly decreasing to 33.8 MPa at 110°C. These findings highlight the temperature-dependent nature of polymer concrete, particularly its flexural properties (Palamarchuk et al., 2024).

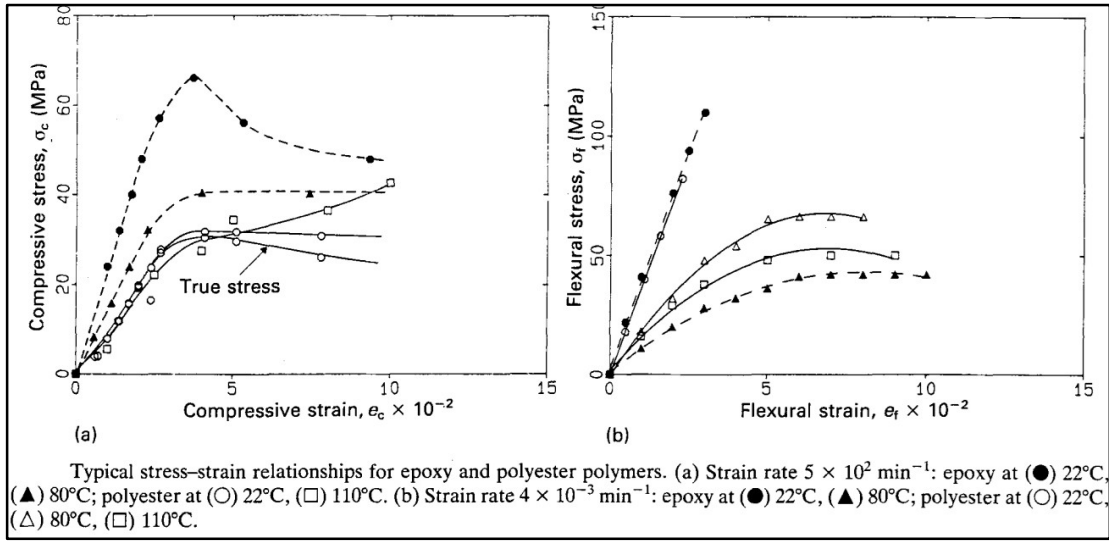


Figure 2.11: Typical stress-strain relationships for epoxy and polyester polymers (a) compressive strain (b) flexural strain (Vipulanandan et al., 1988).

2.8 Simulation of Blast Loading on Reinforced Concrete Panels

A research work on response of reinforced concrete panel under blast loading using modelling method has been done by Lin et al. (2014) where steel reinforcements are represented using the Plastic Kinematic Model (MAT3) in LS-DYNA, which effectively simulates both isotropic and kinematic hardening plasticity, with options to include rate effects. This model allows for varying the hardening parameters between 0 and 1 to capture different levels of material response.

Concrete within the model is represented using Solid 164 elements, an 8-node constant stress hexahedron brick element, with Lagrangian formulation applied. This approach attaches the numerical mesh nodes to the material, allowing them to move and deform with it. Blast pressure time histories are computed using the CONWEP code in LS-DYNA. This empirical blast loading function is based on extensive experimental data and is represented through high-order polynomial equations that model the pressure decay over time, following an exponential decay pattern. This model effectively captures the pressure history typical of free-air explosions, allowing for accurate simulations of blast effects on the reinforced concrete structures.

The modelling or numerical method is used to predict the response of reinforced concrete panel under blast loading. The peak reflected overpressure and the maximum deflection of reinforced concrete panel are always related to the arrival time of the blast wave on the reinforced concrete surface. Overpressure can be defined as pressure cause by a shockwave above normal atmospheric pressure. A TNT explosion will create overpressure which will damage the surface reinforced concrete panel. The lower the reflected overpressure, the lower the chance of blasted products getting damage and the longer time of shockwave to arrive. Figure 2.12 shows the result of reflected overpressure against arrival time which the weight of TNT is different with constant standoff explosive distance.

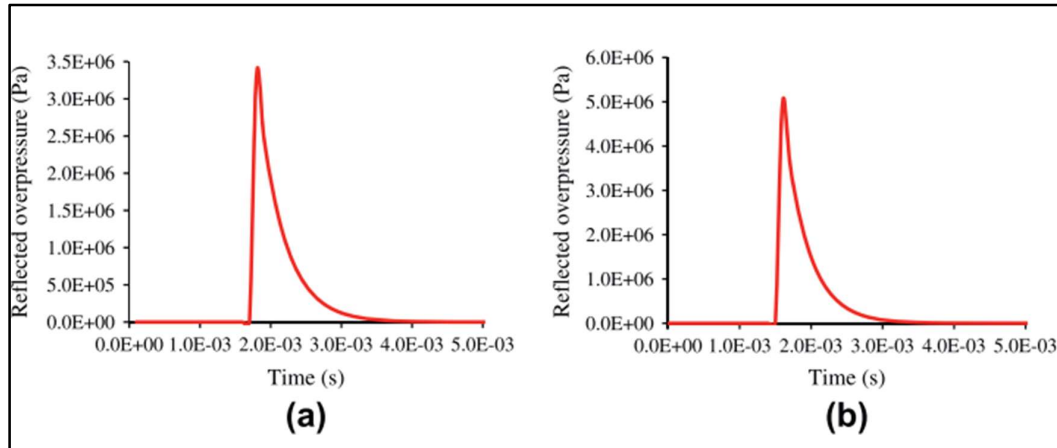


Figure 2.12: Reflected overpressure-time profile of panel (a) Panel 3 and (b) Panel 4 (Lin et al., 2014).

Panels 3 and 4 represent reinforced concrete panels subjected to 22.4 kg and 33.4 kg ANFO blast loads, respectively, with higher charge resulting in greater peak overpressure and deflection. The simulation results closely matched experimental data, confirming the model's reliability in predicting blast response and damage. The predicted reflected overpressure versus time histories for reinforced concrete Panels 3 and 4 are illustrated in Figure 2.12(a) and Figure 2.12(b), respectively. As shown in Table 2.6, the maximum deflections at the centres of Panel 3 and Panel 4, derived from the numerical model, are 7.72 mm and 11.10 mm, respectively (Lin et al., 2014). These values align closely with the test data, exhibiting only minor errors of 7.3% and 2.0%, respectively, demonstrating the accuracy and reliability of the numerical model in predicting the panels behaviour under blast loading (Ghani Razaqpur et al., 2007).

Table 2.6: Finite element predictions and comparison with test data (Lin et al., 2014).

No	ANFO charge mass (kg)	Peak reflected overpressure (kPa)	Arrival time (ms)	The maximum central deflection (mm)
Panel 3	22.4	3443	1.79	7.72
		3842		8.33
Panel 4	33.4	5076	1.59	11.1
		5283		11.33

Syed et al. (2018) investigated the failure behaviour of reinforced concrete panels under blast loading, focusing on predicting the failure modes based on the plastic strain profiles at different stages. The aim of this research work is to investigate the failure behaviour of reinforced concrete panels under the blast effect. The research included two full-scale open-air blast trials: one conducted in a far-field condition with a 40 m standoff distance, and another in a near-field condition with standoff distances at 2 m. The RC panels, designed without considering extreme loading, were subsequently modelled and analysed using the non-linear finite element (FE) software LS-DYNA. Figure 2.13 shows a panel response for a 5kg charge weight as close as 0.3m standoff. Syed et al. (2018) examined the blast creates maximum incident angle of 66.9 and punching mode is found to dominate the response. Figure 2.14 shows the response of the panel under blast effect which create the localized punching mode which dominate the response.

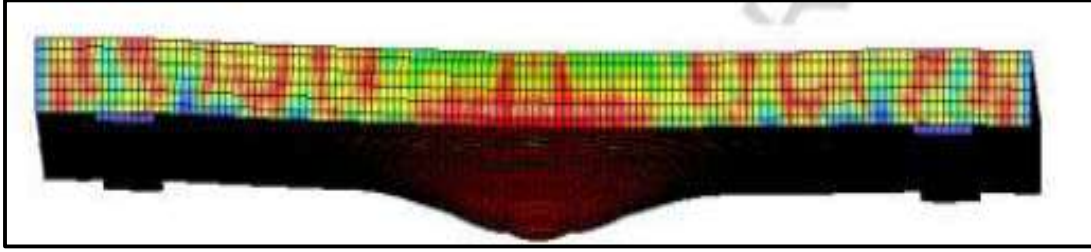


Figure 2.13: A panel response for 5-kg charge weight at 0.3 m stand-off distance

(Syed et al., 2018).

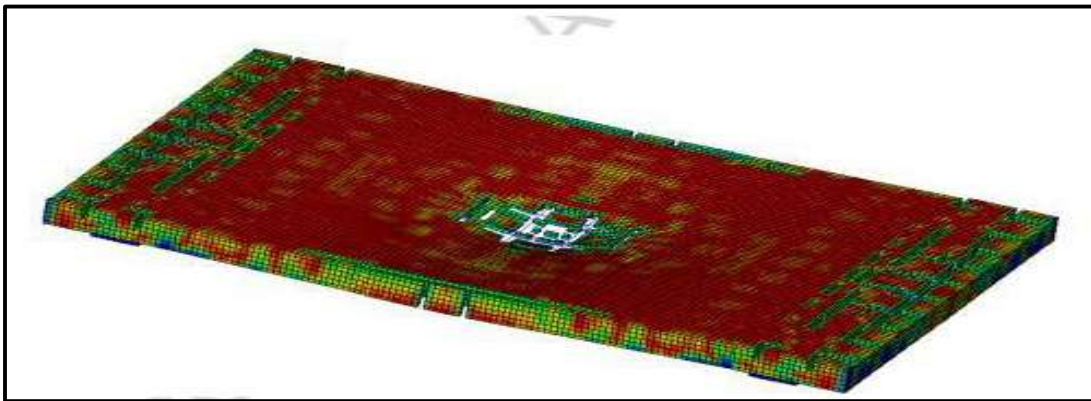


Figure 2.14: A panel response under blast effect which create the localize punching

mode (Syed et al., 2018).

Çankaya (2020) conducted a study to simulate and investigate the behaviour of a reinforced concrete (RC) panel under blast loading using the non-linear finite element software LS-DYNA. The simulation was based on an experimental study by Ghani Razaqpur et al. (2007). The RC panel, with dimensions of 1000×1000×70 mm, was subjected to a blast generated by a 33.4 kg ammonium-nitrate/fuel-oil (ANFO) explosive from a 3-meter standoff distance. In the model, solid elements were used to discretize the concrete, while beam elements were used for the reinforcement bars. The WINFRITH CONCRETE (MAT084) material model was implemented to simulate the concrete under blast loading.

The numerical model captured the crack profile accurately, reproduced the peak reflected pressure within 20 % of the test value (good agreement), and predicted the mid-point deflection with a 35 % deviation (reasonable agreement).

A comparison between the damage profiles from the test and numerical analysis, shown in Figure 2.15, reveals that LS-DYNA successfully predicted a circular damage pattern on the front face of the panel, similar to the experimental observations. The numerical analysis indicated the specimen was divided into four parts from the bottom face, with diagonal damage initiation also observed, closely matching the 4 mm crack width detected in the test. However, the simulation estimated the maximum pressure to be 20% lower than the test results, and the central deflection had a 35% error (Çankaya, 2020). These discrepancies could be due to factors such as inaccuracies in pressure estimation, idealization of support conditions, and mesh density in the model.

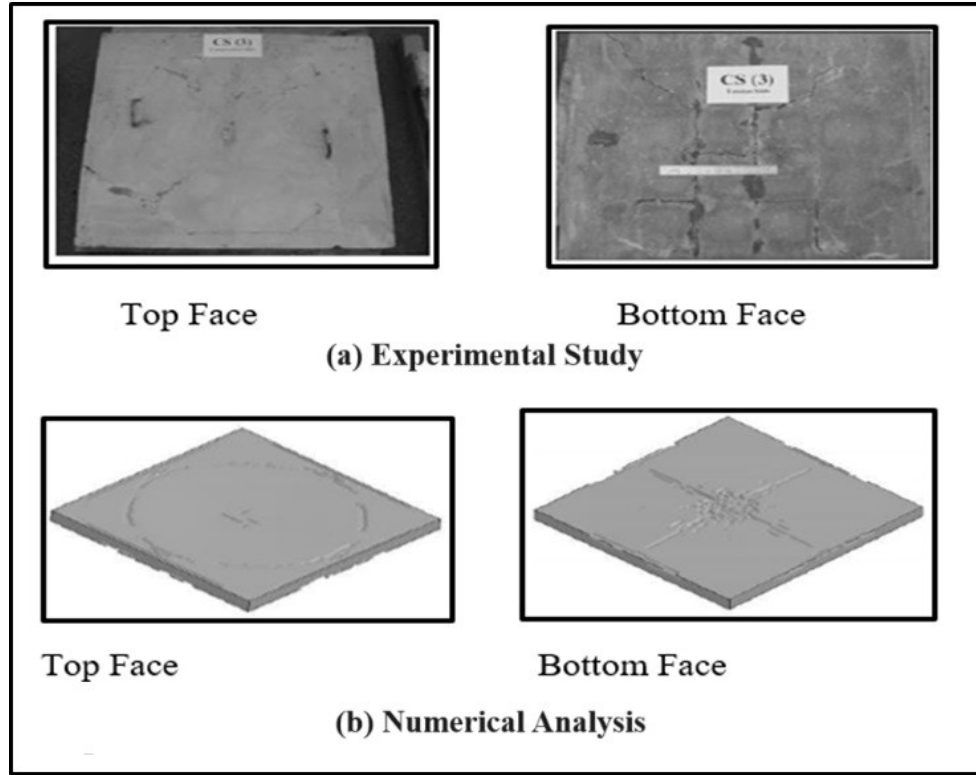


Figure 2.15: Damage patterns. (a) experimental study and (b) numerical analysis of RC slab (Çankaya, 2020).

The study conducted by Leppänen (2005) was crucial in validating a proposed fragment simulation method, which aimed to accurately model the interaction between explosive charges and concrete targets. The experiment involved discretizing a concrete block using a mesh of 10 mm cells, with gradual increases in mesh size toward the bottom to optimize computation time.

Figure 2.16 illustrates the model applied general material laws, adjusting the concrete's compressive strength to 31.2 MPa to better replicate the experimental conditions. The cylindrical charge was modelled using Lagrangian elements, with the explosives equation of state (EOS) and material constants set as specified (Leppänen, 2005).

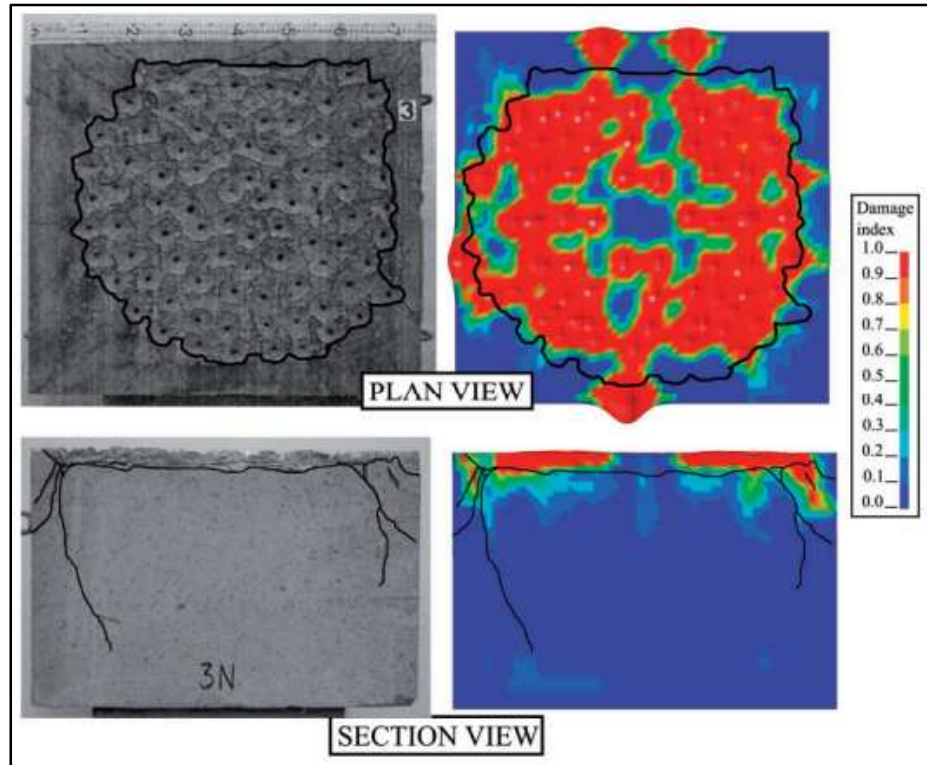


Figure 2.16: Damage produced by the ball bearing impacts on the plain concrete block (Leppänen, 2005).

The simulation incorporated Smooth particle hydrodynamics (SPH) particles to represent the ball bearings used in the experiment, which were accelerated by the explosion and subsequently interacted with the concrete block. Blast pressures were modelled using the CONWEP boundary condition. The simulations fragment velocities averaged 1570 m/s, closely matching the 1650 m/s recorded in the experimental results. The damage patterns on the concrete block, including the spread of fragment impacts and the thickness of the damaged layer, were accurately reproduced, closely aligning with experimental observations (Del Linz et al., 2021).

The successful validation of this modelling approach demonstrated its ability to realistically simulate the interaction between explosive fragments and concrete, accounting

for both initial impacts and subsequent structural responses. The results highlighted the importance of considering both fragment impacts and blast pressures in such simulations, as models including only one loading type failed to capture the full extent of damage observed in experiments. This comprehensive modelling approach provides a valuable tool for analysing combined blast and fragment scenarios, allowing for detailed assessments of damage evolution under varying conditions (Del Linz et al., 2021).

Figure 2.17 illustrates the damage observed on the upper surfaces of reinforced concrete (RC) slabs under blast loads, comparing experimental results by Wang et al. (2012) with finite element (FE) simulations conducted by Abada et al. (2021). Both the experimental and simulated results indicate that the extent of damage increases with the TNT charge. Specifically, for Panel A, subjected to a 0.13 kg TNT charge with a stand-off distance (SoD) of 0.3 m, no significant damage was observed, aside from minor cracks at the centre of the slab. Panel B, exposed to a 0.19 kg TNT charge at the same SoD, exhibited several small cracks in the centre, attributed to the high-pressure impact of the explosion. Panel C, under the influence of a 0.31 kg TNT charge with a 0.4 m SoD, developed a 3 mm crack along the mid-span of the slab. Panel D displayed circular and radial cracks with a small damaged area at the centre of the slabs upper surface, consistent with the experimental observations.

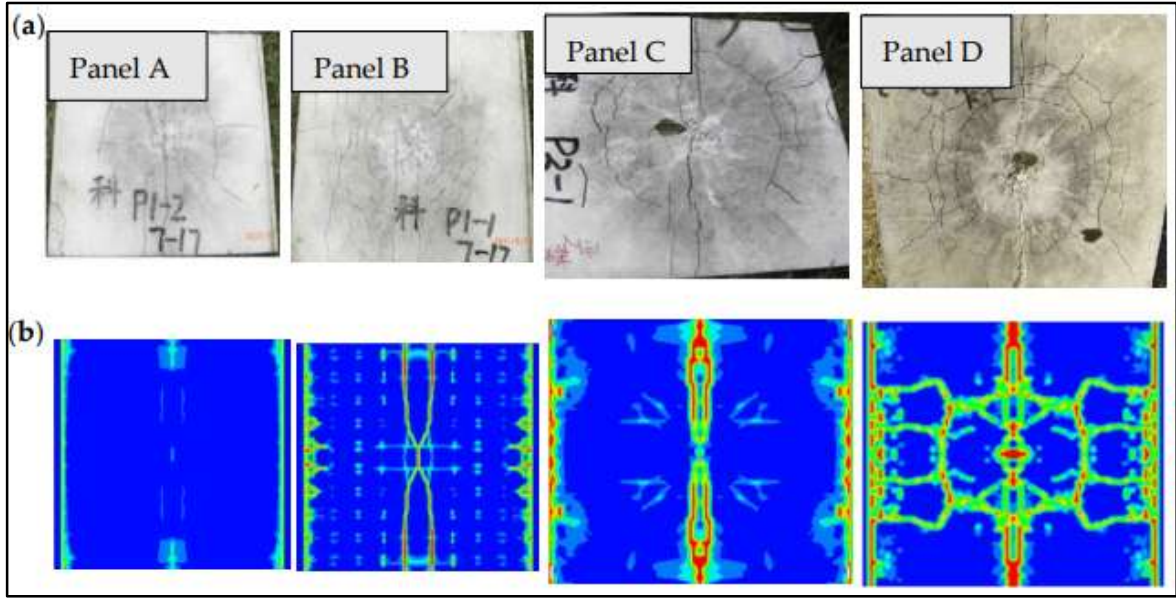


Figure 2.17: The upper surface damage of the RC slabs (a) Experimental examination (Wang et al., 2012) (b) FE simulations (Abada et al., 2021).

Figure 2.18 illustrates, the bottom surfaces of the slabs experienced more severe damage compared to the top, with spalling being the primary mode of failure. The numerical simulations produced damage radii that closely matched the experimental results, with slight differences caused by factors such as how severely damaged elements were removed in the model and the assumed material properties. These differences, however, were within acceptable limits, validating the accuracy of the finite element (FE) models in predicting blast-induced damage (Abada et al., 2021; Wang et al., 2012).

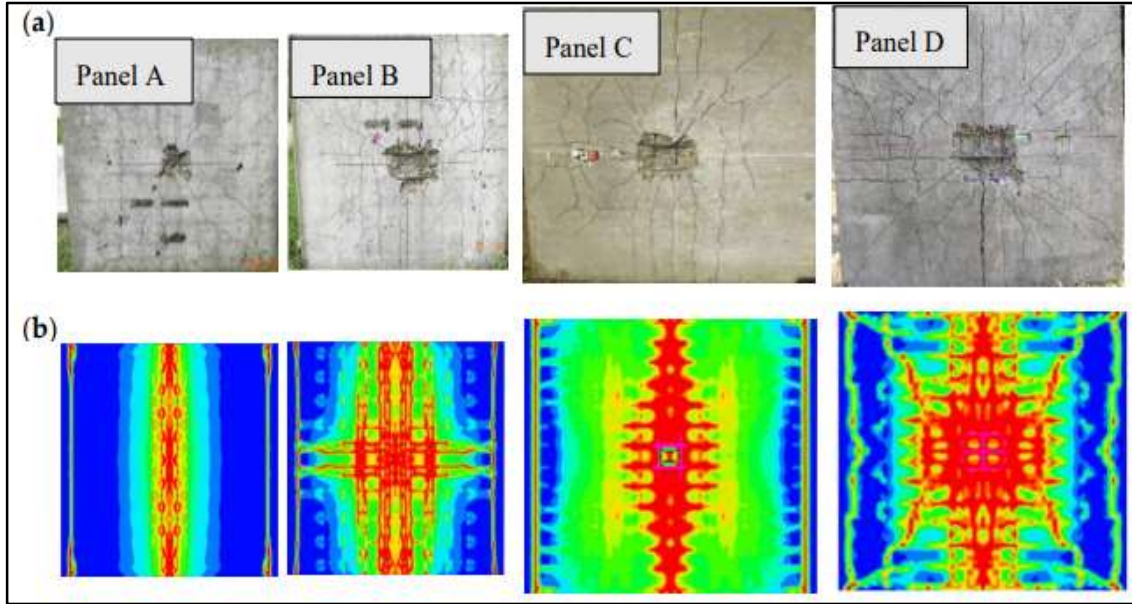


Figure 2.18: The bottom surface damage of the RC slabs (a) Experimental examination (Wang et al., 2012), (b) FE simulations (Abada et al., 2021).

Furthermore, the study explored the use of sacrificial cladding structures with different core configurations, Hexagonal Single-Celled Tube (H-SCT), Hexagonal Double-Celled Tube (H-DCT), and Hexagonal Quadruple-Celled Tube (H-QCT), to enhance the blast resistance of reinforced concrete (RC) panels. The findings demonstrated a substantial reduction in residual deformations, as the cladding structures effectively absorbed and dissipated a significant portion of the blast energy. Consequently, the damage patterns of the shielded panels improved notably, transitioning from severe structural damage to the presence of only minor surface cracks (Abada et al., 2021).

The blast testing of a sandwich panel, as described by Ye et al. (2021), involved a specimen with dimensions of 2000 mm × 800 mm × 120 mm, consisting of a front steel sheet, a core foam layer, and a rear reinforced concrete (RC) layer. The front steel sheet, with a thickness of 1.1 mm, exhibited material properties including an elastic modulus of

200 GPa, density of 7850 kg/m³, yield strength of 300 MPa, and Poisson's ratio of 0.3. The core layer was composed of aluminium foam, characterized by a density of 300 kg/m³, an elastic modulus of 142 MPa, and a Poisson's ratio of 0.03. The experimental setup involved detonating an 8 kg cylindrical TNT charge at a standoff distance of 1.5 m above the panel. The peak deflection of the RC layer measured 19.45 cm, closely aligning with the experimental result of 18.70 cm, as depicted in Figure 2.17. The agreement between the numerical and experimental failure modes suggests that the numerical model can accurately simulate the behaviour of sandwich panels under blast loads.

Figure 2.19 illustrates the study's further exploration of the dynamic response of Precast Concrete Sandwich Panels (PCSPs) under blast loads, conducted through both simplified modelling and experimental testing. Various parameters were examined to assess their impact on blast resistance. Findings indicated that the thickness of the insulation layer had a minimal effect on the dynamic behaviour of PCSPs, while closer spacing of connectors improved blast resistance. Specifically, PCSPs with vertical connectors effectively utilized the compressive strength of concrete and rebar, resulting in minor bending failure. In contrast, PCSPs with crossing connectors exhibited significant punching damage in the central area. Additionally, a comparative analysis between RC slabs and PCSPs revealed that the latter demonstrated weaker blast resistance, highlighting the vulnerability of PCSPs in precast structures under explosive loads. The study suggests that the theoretical model offers a reliable means of predicting the dynamic response of PCSPs, though future research should consider the potential of novel connector materials to enhance anti-blast performance.

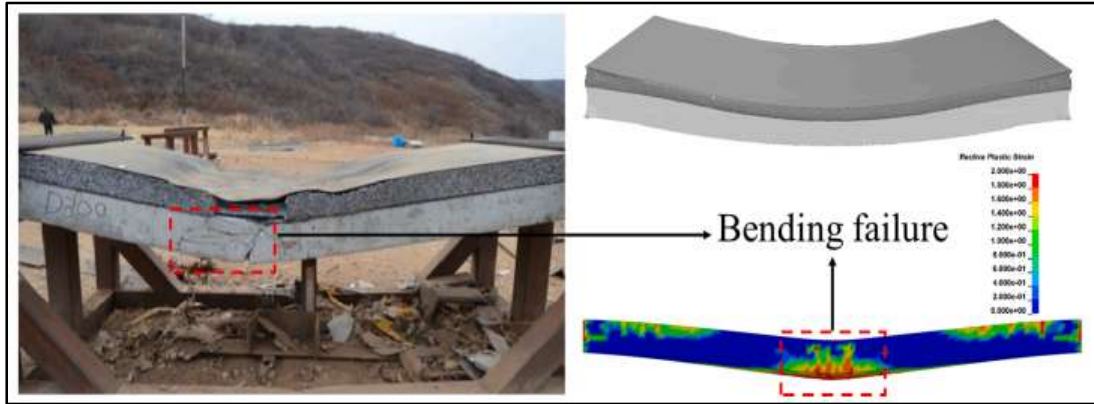


Figure 2.19: Comparison of experimental results and numerical simulation (Ye et al., 2021).

2.9 Effect of Explosive Charge Weight on Reinforced Concrete Panel Performance

Blast energy is defined based on the weight of the TNT charge used to generate the blast loading. Zhao et al. (2020) conducted a research study involving a numerical and theoretical analysis of the blast resistance of a fabricated reinforced concrete slab, utilizing dimensions of $180 \times 264 \times 20$ cm and concrete grades C20, C30, and C40. The research adjusted three parameters, the explosive charge, the slab thickness, and the grade of concrete. The damage status and crack distribution of the RC slab were examined both in numerical simulations and experimental tests, as shown in Figure 2.20. The results reveal that no cracks or compressive damage occurred on the top surface of the RC slab, with the numerical model accurately capturing the damage, as seen in Figure 2.20. Straight cracks were observed on the middle bottom surface of the slab in both the simulation and the experimental test, indicating that the FEM can effectively simulate the damage. The maximum displacements at the mid-span of the slab were 10.8 mm in the FEM and 10.1 mm in the experimental test, with a minor error of 6.9% between the two results (Zhao et al., 2020). This demonstrates

that the FEM provides a strong and accurate representation of the blast behaviour and damage mode of RC slabs, closely aligning with experimental observations.

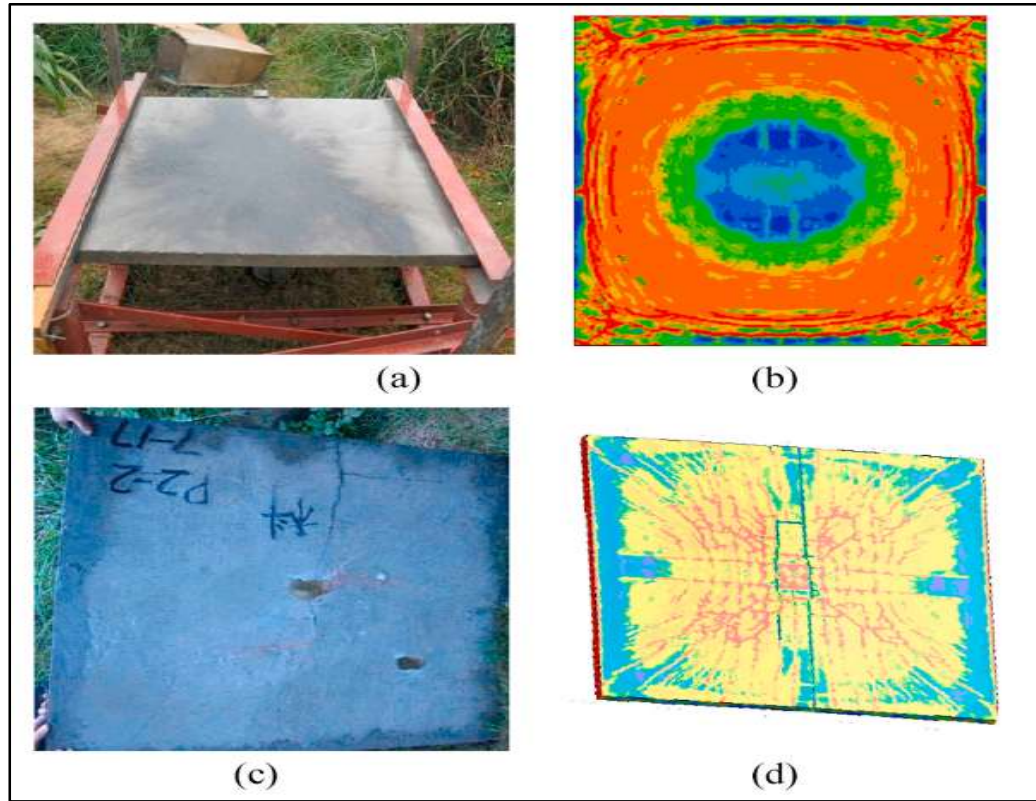


Figure 2.20: Damage modes of RC slab: (a) front surface of experiment, (b) front surface of numerical model, (c) bottom surface of experiment and (d) bottom surface of numerical model (Zhao et al., 2020).

Zhao et al. (2020), used four TNT charge which are 1.0kg, 2.0 kg, 3.0kg and 4.0kg. The damage occurred mode can be observed in Figure 2.20 whereas the crack and penetration damage on the bottom surface of the fabricated concrete slab. The damage on the fabricated concrete slab gradually increases due to the increasing of TNT charge. Hence, the greater the TNT charge, the greater damage on the slab. Based on Figure 2.21, the damage modes transition from bending deformation and bending failure to shear failure.

It is shown by Zhao et al. (2020), that displacement shows the trend of the harmonic wave with the time increasing. This can be seen in Figure 2.21 on displacement time history graph for different explosive charges. The first impact of blast wave is as compressive wave and then turn to be a tensile wave when it reaches to the front surface of the slab. This will make the slab vibrating much longer when the explosion occurs. It also can be summarised that higher the explosive charge, the longer the vibrating periods of fabricated concrete slab.

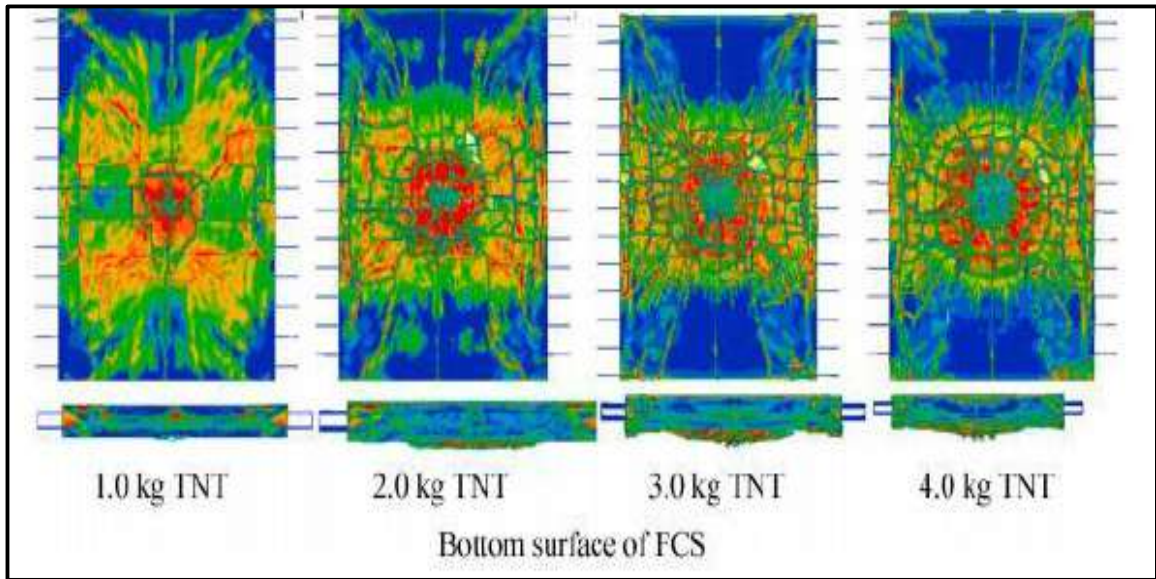


Figure 2.21: Failure mode of fabricated concrete slab (Zhao et al., 2020).

Figure 2.22 illustrates the displacement time history of fibre-reinforced composite slab (FCS) under various explosive charges, showing that the displacements follow a harmonic wave pattern as time progresses. The vibration periods of FCSs lengthen as the explosive charge increases, with peak displacements recorded respectively at 0.615 cm, 0.759 cm, and 0.952 cm for 2.0 kg, 2.5 kg, and 3.0 kg charges (Zhao et al., 2020).

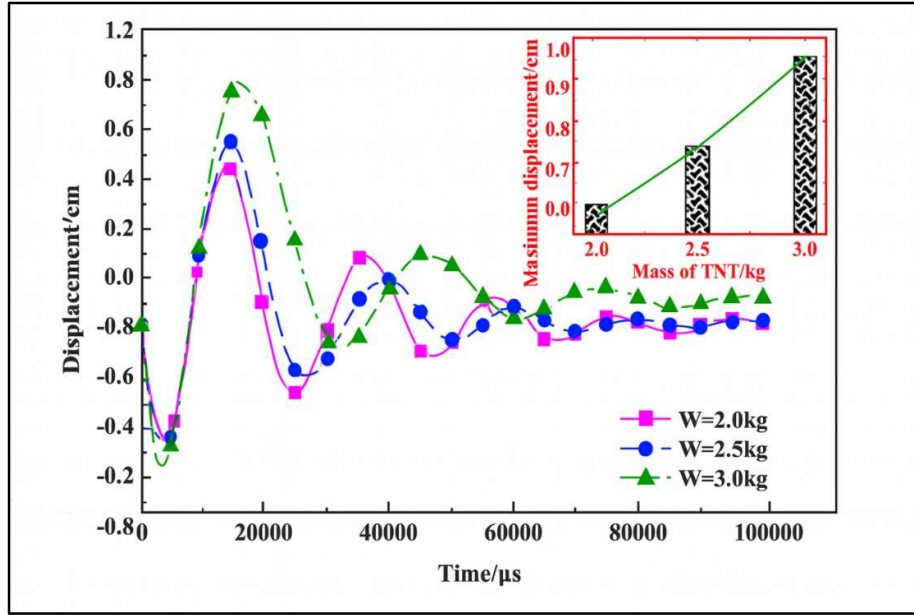


Figure 2.22: Displacement time history for different explosive charge on RC slab (Zhao et al., 2020).

Figure 2.23 illustrates, the performed another research on numerical simulation of reinforced concrete slab subjected to blast loading and structural damage assessment also using different weight of TNT charge. Wu et al. (2020) in the study used different weight of charge but at the same time manipulated the thickness of slab respectively to the weight of TNT charge. This finding will be discussed in Chapter 4, where similar trends and observations regarding the relationship between blast weight, slab thickness, and resulting damage are further analysed.

The paper provides a detailed analysis of the test setup and geometry of a concrete board under blast loading, as depicted in Figure 2.23 and detailed in Table 2.8. The tests maintained consistent board geometry and standoff distance, with variations limited to the number of explosive charges (kg) used. Additionally, the study categorizes structural damage into three levels: low damage, characterized by visible cracks; moderate damage, indicated by shallow

spallation; and high damage, involving significant collapse exceeding one-third of the slab thickness.

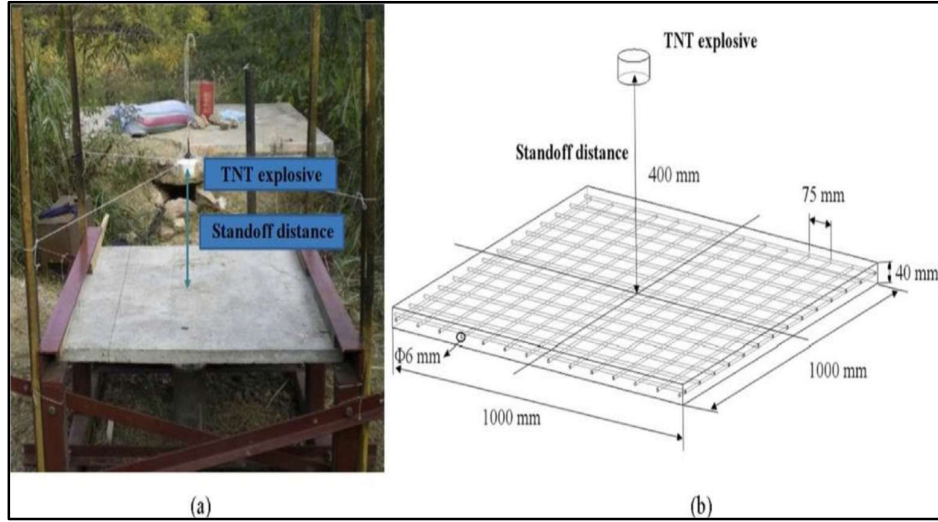


Figure 2.23: (a) The explosion experiments setting and (b) the geometry of the reinforced concrete board (Wu et al., 2020).

Table 2.7: Comparison between numerical results and test results Wu et al. (2020)

Test	Slab name	Dimension (mm)	Standoff distance (mm)	Explosive charge (kg)	Damage level
I	A	1000 × 1000 × 40	400	0.2	Low Damage
II	B	1000 × 1000 × 40	400	0.31	Moderate Damage
III	C	1000 × 1000 × 40	400	0.46	Moderate Damage
IV	D	1000 × 1000 × 40	400	0.55	High damage

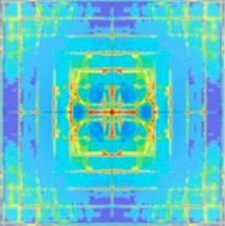
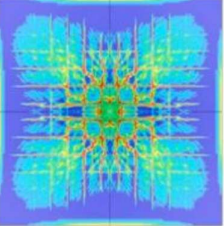
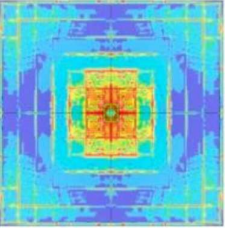
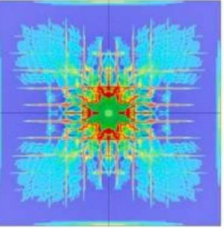
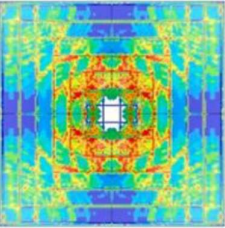
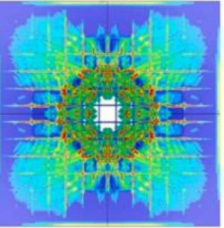
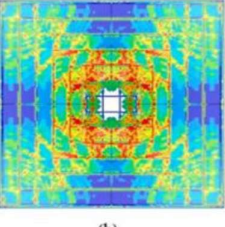
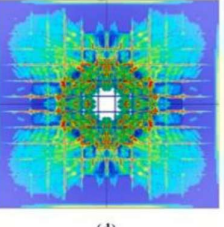
The comparison between the numerical and experimental damage contours of the reinforced concrete (RC) panel is presented in Table 2.8, where:

- a) represents the experimental results of the upper surface,
- b) represents the numerical results of the upper surface,
- c) represents the experimental results of the bottom surface, and
- d) represents the numerical results of the bottom surface.

Table 2.8 presents a detailed comparison of the damage areas observed in reinforced concrete slabs subjected to various TNT charges and standoff distances, both in experimental tests and numerical simulations.

In Test (I), involving a 0.2 kg TNT charge at a 0.4 m standoff distance, the slab showed minimal damage, with no significant damage on the top surface and only minor caving and cracks on the bottom. The numerical simulation accurately replicated this low level of damage, confirming its consistency with the experimental observations. In Test (II), with a 0.31 kg TNT charge, the slab experienced compressive crushing at the centre and the formation of radial and circumferential cracks on the upper surface. The rear surface showed a tensile spalling crater. The numerical simulation closely mirrored these damage patterns, demonstrating its reliability. In Test (III), a 0.46 kg TNT charge resulted in more extensive circumferential cracks due to reflecting tensile waves, along with a small damaged area at the centre of the upper surface and square spall damage on the bottom. The numerical results aligned well with the test findings, accurately capturing the observed damage. Finally, test (IV), using a 0.55 kg TNT charge, led to severe damage, including axial failure and the formation of a perforate hole at the centre of the slab. The numerical simulation was consistent with the experimental results, accurately reflecting the extent of the damage.

Table 2.8: The comparisons between the numerical and experimental results of the RC board damaged contour (Wu et al., 2020).

Test I				
	(a)	(b)	(c)	(d)
Test II				
	(a)	(b)	(c)	(d)
Test III				
	(a)	(b)	(c)	(d)
Test IV				
	(a)	(b)	(c)	(d)

2.10 Blast of concrete with different standoff distances

As illustrated in Figure 2.24, a setup where a reinforced concrete (RC) slab is mounted on a support structure, with a warhead positioned in front of the slab. This

arrangement appears to be designed for testing the impact or effects of a blast from the warhead on the RC slab, simulating structural response under explosive loading conditions. Characterizing load is important for establishing the severity of a blast and ultimately its effects which directly affect pressure intensity on structure. An increased standoff distance can also decrease the intensity of the blast wave, lowering even further damage to a structure. Conversely, a shorter standoff distance increases the intensity of the blast wave, resulting in greater damage to the structure.

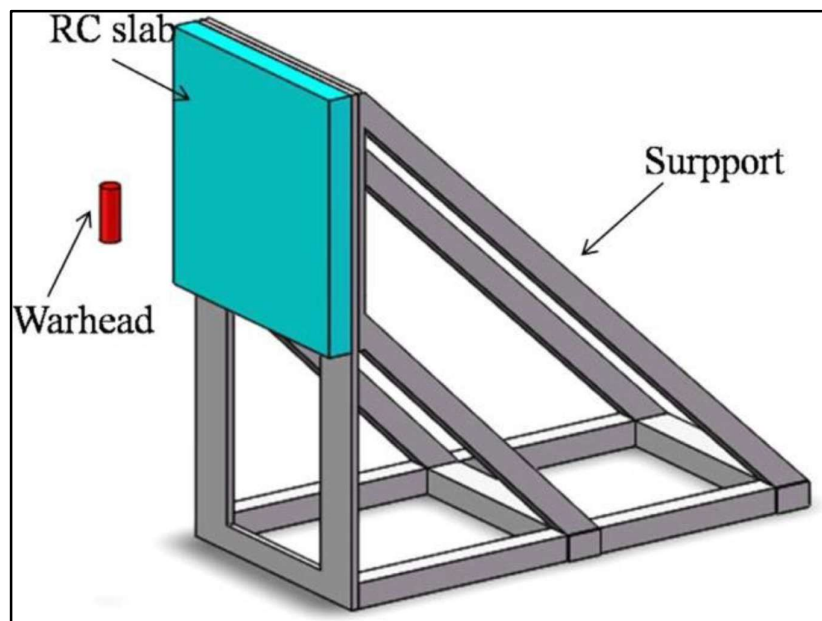


Figure 2.24: Schematic of the slab support and the geometry of the warhead (Li et al., 2020).

Li et al. (2020) conducted an experimental study and numerical analysis on an RC slab under a constant blast loading and concrete thickness in different standoff distances. The explosive used is a 76 mm warhead, with three standoff distances. The geometry of the concrete slab is $1\text{m} \times 1\text{m}$.

A total of three shots were conducted, with identical warheads used for all tests. The standoff distances, measured from the centre of the warhead to the slab, were set at 3.5 m, 3.0 m, and 1.6 m. The experimental program is summarized in Table 2.9.

Table 2.9: Summary of the experimental program of concrete slab under various TNT Standoff distance (Li et al., 2020).

Slab no.	Explosion	Standoff distance (m)	Scale distance (m/kg ³)
1	76 mm warhead	3.5	3.70
2	76 mm warhead	3.0	3.17
3	76 mm warhead	1.6	1.69

Figure 2.25 shows the comparison of damage status from numerical simulations and experiments. Figure 2.25 a, c, and e show numerical simulations of damage to slab 1 (a, b), slab 2 (c, d), and slab 3 (e, f) respectively. Figure 2.25 b, d, and f show blast test results depicting damage to slab 1, slab 2, and slab 3 respectively. As shown, extensive cracks and spall damage can be observed both in numerical simulation and blast tests. The simulation accurately replicates the penetration holes, crack patterns, and spall damage on reinforced concrete slabs due to blast load. The result demonstrates that the numerical model leads to credible predictions of RC slabs under combined blast and fragment loading.

Figure 2.25 shows the results verify that the closer the standoff distance, the higher the damage to the model or the test specimen. This also shows that standoff distance is greatly correlated to the blast energy received by the model and test specimens. An important thing to note from the paper itself is that the blast is not limited to the explosions by itself, rather it is a

combined loading from blast and the warhead. The author states that the fragment from the warhead significantly affected the damage of the RC slab.

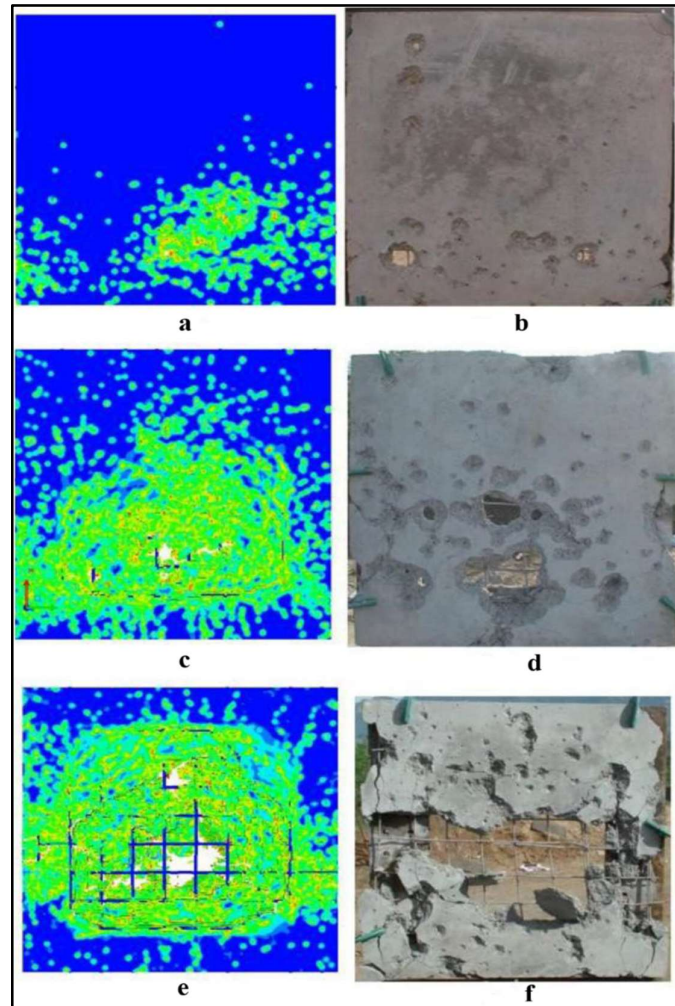


Figure 2.25: Comparison of the numerical and experimental results of the RC slab damage contour (Li et al., 2020).

2.11 Research gaps of literature review

The literature review reveals several key research gaps in the development of blast-resistant structural systems (see Table 2.10). Most existing studies have focused on conventional reinforced concrete (RC) panels under blast loads, using flat geometries and

standard materials without exploring advanced composites or sustainable alternatives. While some numerical models like Lin et al. (2014) show good predictive accuracy for RC panels, they largely exclude composite skins, polymer concretes, or curved bunker geometries. Studies like Syed et al. (2018) and Li et al. (2020) addressed the effects of blast distance and fragment interaction, but they did not investigate mitigation strategies using advanced materials. Although Abada et al. (2021) and Ye et al. (2021) introduced hybrid cladding and sandwich systems, these approaches added complexity and lacked validation on curved structures or polymer-based cores. Ghamry Metwally et al. (2017) evaluated a half-cylindrical shelter model but retained conventional concrete, overlooking the potential of integrating polymer concrete and sustainable fillers like tin slag. Overall, the reviewed studies lack comprehensive evaluation of innovative materials, such as carbon-fibre-reinforced polymer concrete or industrial by-products, in non-conventional geometries under blast conditions highlighting a clear need for integrated experimental and numerical investigations in this area.

Table 2.10: Summary of key studies on RC panel blast performance.

No	Study & Focus	Major Findings	Remaining Gap / Limitation
1	Lin et al. (2014) FE modelling of RC under ANFO blast	Numerical model (LS-DYNA + CONWEP) reproduced peak overpressure and mid-span deflection of RC panels with $\leq 7\%$ error	Flat RC panels only, no composite skins or curved bunker geometry; material stays conventional concrete.

Table 2.10: Continue

2	Syed et al. (2018) Near- vs far-field blast on RC panels	Near-field (2 m) blasts triggered punching failure, far-field (40 m) produced flexural response.	Focused on failure modes, not on mitigation; did not test alternative materials or sandwich layouts.
3	Zhao et al. (2020) TNT weight & slab thickness effects	Damage shifted from bending to shear/penetration as TNT charge rose from 1–4 kg; FEM results within 7 % of experiments	Looked at plain RC only; no CFRP strengthening or lightweight cores considered.
4	Li et al. (2020) RC slabs under combined blast + fragments	Closer stand-off (1.6 m to 3.5 m) drastically increased cracking & spall; numerical model captured holes and fragment damage	Still conventional RC; polymer concretes and sandwich skins not examined.
5	Abada et al. (2021) Sacrificial hybrid-tube cladding for RC panels	Hybrid cladding cut residual deformation and converted severe damage to minor cracks	Adds mass/complexity; efficacy on curved bunker walls or with polymer cores untested.
6	(Abada et al., 2021) Ye et al. (2021) Steel/foam/RC	Peak RC-layer deflection 19.45 cm (model 18.7 cm); connectors & foam core absorbed energy, but PCSPs still weaker than solid RC	Sandwich used metallic/foam core not high-strength polymer concrete.

Table 2.10: Continue

7	Ghamry Metwally et al. (2017) FE of hardened aircraft shelter	Half-cylindrical RC bunker model calibrated for blast loads; verified mesh & boundary conditions	Shelter kept conventional concrete; did not integrate sandwich composites or sustainable fillers like tin slag.
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2.12 Blast Parameters Gathered from Literature

The parameters employed in this research are guided by an extensive review of past studies on blast response of reinforced concrete (RC) structures and composite slabs (Table 2.11). The selected parameters TNT charge weight (1 – 25 kg), standoff distance (0.1 – 2.5 m), and slab thickness (200 – 500 mm) are based on prior experimental investigations by Ali et al. (2013), Krauthammer et al. (2004), Wu et al. (2020), Wang et al. (2018), Lu et al. (2012), and Kovar et al. (2014) who explored blast effects using TNT masses ranging from grams to over 25 kg and slab thicknesses up to 304 mm. These works informed the broader scope of this study to capture realistic and severe blast scenarios at bunker scale. To simulate the structural response, ABAQUS/Explicit was chosen over LS-DYNA due to its advanced concrete damage plasticity (CDP) model, which accurately captures cracking, crushing, and stiffness degradation under dynamic loads. The use of the CONWEP model allows for efficient application of blast pressure-time histories, as validated in studies by Zhao et al. (2018) and Nguyen et al. (2020). This literature-based framework ensures that both geometric parameters and modelling techniques reflect validated and realistic approaches for assessing blast resistance of CFRP-sandwiched polymer concrete panels.

Table 2.11: Summary of existing studies on blast response of RC panels.

Length (mm)	Width (mm)	Slab Thickness (mm)	Standoff Distance (mm)	TNT Weight (kg)	Materi als Used	Reference
600	600	50	40	1	CFRP	Ali et al. (2013)
1200	1200	50	40	3.5	CFRP	Ali et al. (2013)
4000	3600	304	1000	2.1	R.C	Krauthammer et al. (2004)
4000	3600	304	1000	6.3	R.C	Krauthammer et al. (2004)
4000	3600	304	1000	10.5	R.C	Krauthammer et al. (2004)
1300	1000	120	600	60	wood	Wu et al. (2020)
1300	1000	120	600	79	wood	Wu et al. (2020)
1000	1000	150	1500	4.08	UHSC	Wang et al. (2018)
1000	1000	150	1500	15.88	UHSC	Wang et al. (2018)
1000	1000	150	1500	4.08	RC	Lu et al. (2012)
6000	1500	300	100	25	RC	Kovar et al. (2014)

2.13 Summary

This study investigates the potential of polymer concrete (PC), advanced polymer composites (APCs), and tin slag as alternative materials for blast-resistant construction. PC, formed by binding aggregates with polymers, offers high strength influenced by polymer type, aggregate properties, and mix ratios. APCs, reinforced with fibres such as carbon or

glass, provide excellent strength-to-weight ratios and corrosion resistance, though their use is limited by cost and environmental concerns. Tin slag, a smelting by-product, is considered a low-cost aggregate replacement due to its abundance. The study also examines the mechanical behaviour of carbon fibres and key factors affecting the compressive and creep performance of PC, such as aggregate size and resin bonding. Blast resistance of reinforced panels is evaluated using experimental tests and LS-DYNA simulations to assess damage and structural performance. The chapter includes studies from Zhao et al. (2020) and Wu et al. (2020), which explore the effects of explosive charge, slab thickness, and concrete grade on damage patterns, showing that increased explosive charge leads to more severe damage and shifting failure modes.

Section 2.5 reviews the compressive behaviour of polymer concrete (PC), particularly focusing on studies by Shakil and Hassan (2020). Tests on tin slag polymer concrete reinforced with FRP demonstrated that smaller aggregate sizes, particularly in sample AU, led to higher compressive strength, peaking at 37.7 MPa. The stress–strain behaviour displayed three distinct phases: an initial elastic rise, a plateau near peak strength, and a post-peak decline. Improved resin-to-aggregate bonding, as in sample AC, enhanced strength further, reaching 58.21 MPa. Epoxy-based polymer concretes outperformed polyester-based variants in both compressive and flexural strength, with a maximum yield strength of 62 MPa at room temperature.

Section 2.6 concludes that numerical methods, particularly finite element models like the Plastic Kinematic Model in LS-DYNA, are effective in simulating the behaviour of reinforced concrete (RC) panels under blast loads. Studies by Lin et al. (2014) and Syed et al. (2018) demonstrate that these models accurately predict critical responses such as peak overpressure, deflection, arrival time, and failure modes. Despite minor discrepancies, the

simulations closely align with experimental results, capturing essential phenomena like stress distribution, material hardening, and energy dissipation. The extent of damage is influenced by factors such as geometry, charge weight, and standoff distance where near-field blasts cause severe local failures and far-field blasts result in milder effects. Overall, numerical modelling serves as a reliable and cost-effective tool for assessing blast impacts on RC structures.

In Section 2.7, the effects of different blast weights on reinforced concrete (RC) slabs are examined, particularly in terms of damage severity and structural response. Studies by Zhao et al. (2020) and Wu et al. (2020) show that increasing TNT charge weight significantly intensifies damage to RC slabs, shifting failure modes from bending to shear and collapse. Numerical simulations closely aligned with experimental data, revealing more severe cracking, penetration, and bottom-surface deterioration with higher blast loads. Displacement patterns exhibited harmonic behaviour, with longer vibration periods and greater amplitudes as charge weight increased. Even with increased slab thickness, Wu et al. (2020) observed substantial structural failure under near-field blasts, emphasizing that explosive weight is a critical factor in determining the severity of damage.

In Section 2.8, the effects of different blast weights and standoff distances on reinforced concrete (RC) slabs are analysed. Increasing the blast weight intensifies the damage to the structure, as seen in the transition from bending deformation to more severe shear failure and collapse. Conversely, varying the standoff distance significantly affects the intensity of the blast wave and, consequently, the level of damage to the RC slabs. A greater standoff distance reduces the pressure intensity of the blast, resulting in less damage, whereas a smaller standoff distance amplifies the blast wave's impact, leading to more severe structural damage.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Overview

In this chapter, the detailed modelling methodology of the sandwiched polymer concrete defence bunker is presented. The discussion begins with defining the geometry of the bunker, adopting a semi-circular cross-section inspired by the design of hardened aircraft shelters. Material properties are then specified, followed by the setup of interactions between the bunker components. The loading conditions, including blast loads, are applied next, along with the definition of boundary conditions to simulate realistic constraints. The model undergoes verification to ensure the accuracy of the methodology, which is crucial for obtaining reliable results. Finally, the analysis and results are discussed, providing insights into the bunkers structural performance under blast loads. Further details on the verification process are described in later sections.

A literature review was conducted on several relevant studies addressing the blast response of various structures. Based on these studies, parameters such as TNT charge, standoff distance, and core thickness needed for the current thesis were determined within the ranges established by existing research (Dharmasena et al., 2008; Foglar & Kovar, 2013; Muszynski & Purcell, 2003; Pichandi et al., 2013; Tai et al., 2011)

This chapter discusses the modelling methodology of sandwiched polymer concrete defence bunker by using ABAQUS/CAE 6.14. Taking the idea from Hardened Aircraft shelter Ghamry Metwally et al. (2017) and applied for the current bunker design, the shape of a semi-circular cross-section has been adopted. The verified model was established to

ensure that the methodology used in this research is valid and can be applied to a real model. Further details on the step-by-step procedure of this method will be discussed in Section 3.2.

3.2 General Finite Element Modelling Procedure

The flowchart in Figure 3.1 outlines the process of modelling and simulating blast loading on a sandwich polymer concrete bunker (SPCB) using ABAQUS/CAE 6.14 software. The first step involves gathering the geometry and material properties of the model from prior studies and analyses. Using ABAQUS/CAE 6.14, the various parts of the model are created with their respective material properties, sections, and section assignments. These parts are then assembled into a single model, and an analysis step module is used to define the analysis steps and specify the desired outputs.

The next steps involve creating interactions and defining interaction properties, particularly for assigning reference points for blast loading. An embedded region constraint is established within the concrete slab to embed the reinforcement bar. Boundary conditions are set on each side of the model to simulate supports system. Finally, the entire model is meshed before proceeding to create a job and run the simulation. A mesh convergence study was conducted to ensure that the element sizes in the finite element analysis were sufficiently small to achieve the desired level of accuracy. Local seeds were selected from the mesh manager with a method set to “by number” and a sizing of elements. The simulation collects data on the response of the model to blast loading, providing insights into its structural behaviours under such conditions. Sandwich Polymer Concrete Bunkers (SPCB) are expected to offer superior blast resistance, reduced deformations, and enhanced durability compared to conventional concrete bunkers, making them more effective in withstanding explosive loads and extending service life.

ABAQUS/CAE 6.14 was chosen for this study due to its built-in CONWEP function, which allows efficient and accurate simulation of air-blast loads. While LS-DYNA is widely used for high-energy, near-field blast analysis, ABAQUS is well-suited for modelling material behaviour like concrete damage plasticity and layered composites (Tabatabaei & Volz, 2012). Its capabilities align with the study's objective to assess SPCB performance under varying TNT loads and standoff distances, making it a suitable and deliberate choice.

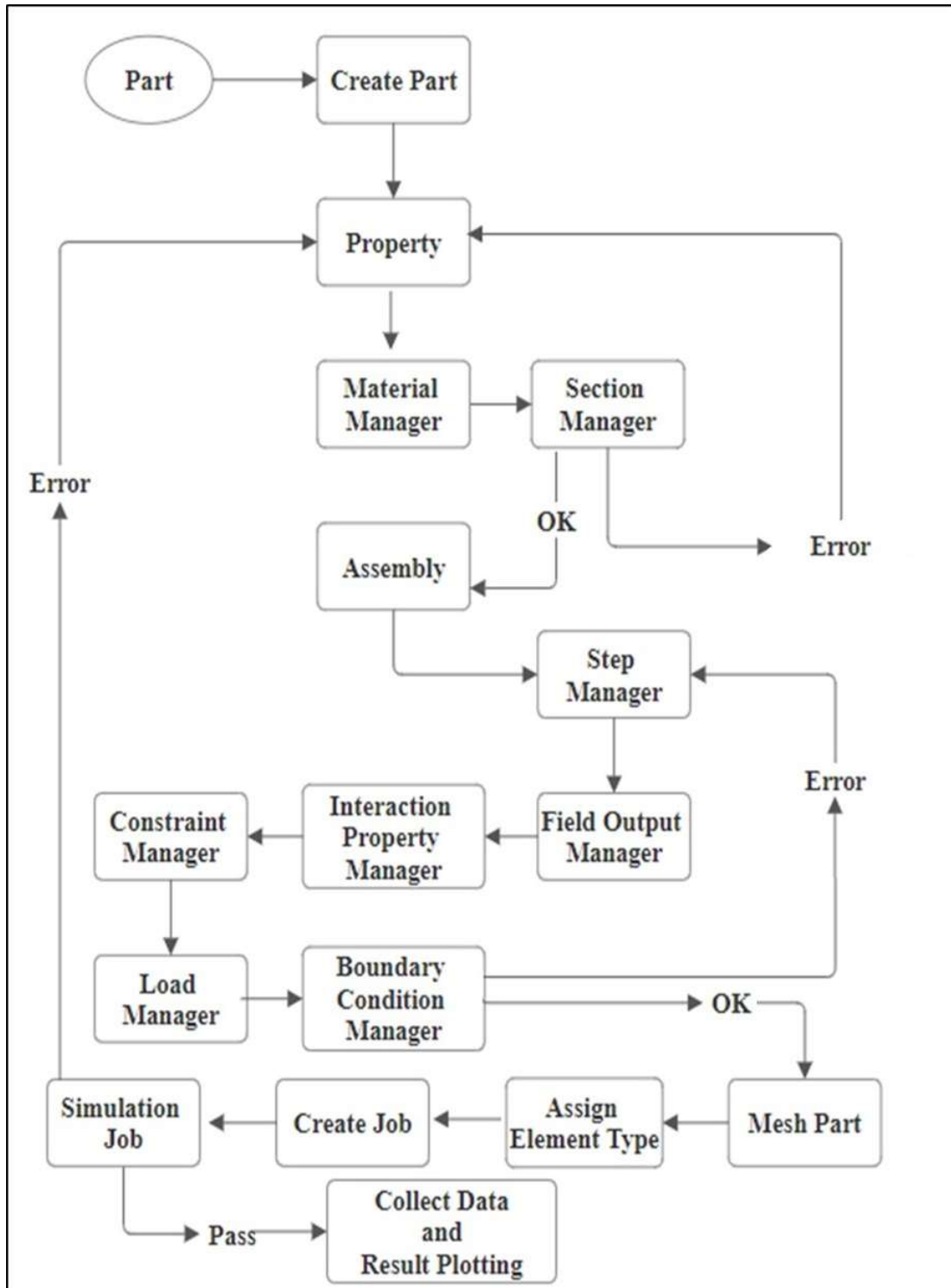


Figure 3.1: Flowchart in modelling by using ABAQUS/CAE 6.14.

Figure 3.2 illustrates the recreated model of the reinforced concrete panel under blast loading, created using ABAQUS/CAE 6.14, to verify the finite element modelling method. This verified model was then applied step by step for the current bunker design modelling technique.

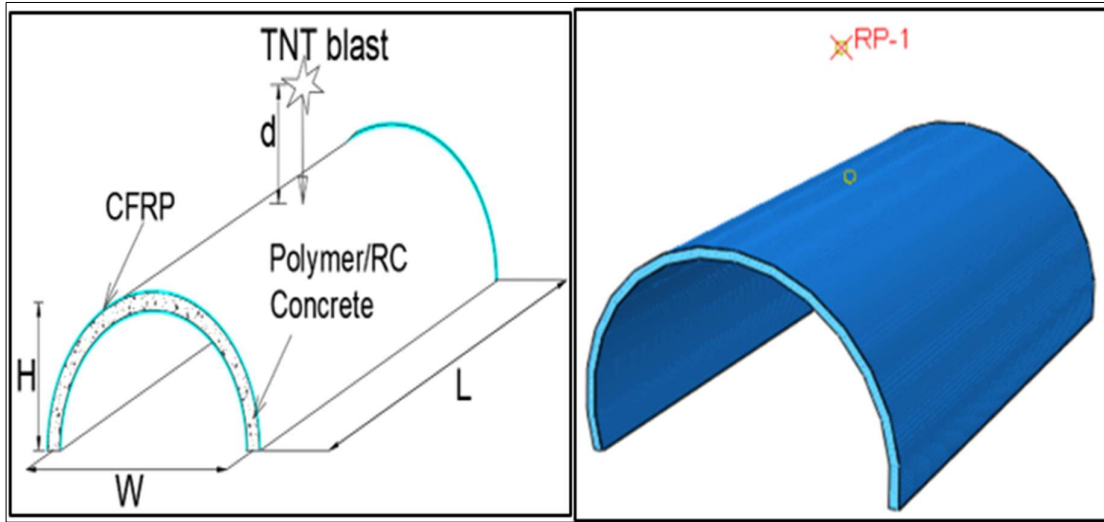


Figure 3.2: (a) Bunker sketch and (b) Bunker model by ABAQUS.

Upon verifying the modelling methodology, the studied bunker was modelled as a semi-circle cylindrical shape with dimensions of 3.5m (height) $\times$ 6.5m (width) $\times$ 10m (length), focusing particularly on the slab (core), which was treated as a separate component within the overall structure. The concrete core thickness was varied between 200mm, 250mm, 300mm, and 500mm to examine its influence on the bunker's response to blast loads such as 1kg, 5kg, 10kg, 25kg and distance 0.1m, 0.25m, 0.5m, 1m, 2m and 2.5m, with a 3 mm thick CFRP skin layer applied to both the top and bottom of the bunker. The core was made of tin slag polymer concrete with a compressive strength of 58.21 MPa (Shakil & Hassan, 2020) while the conventional concrete used G30 with a compressive strength of 30 MPa, specifically designed to withstand standard loading conditions. Reinforcement was

provided using 12 mm diameter bars arranged in two layers at the top and bottom, spaced at 150 mm intervals (T12@150 mm) with a 40 mm concrete cover, and both longitudinal and transverse reinforcements used T12 bars, as adapted from Yin et al. (2017). The structural response of the bunker to blast loads and its fixed support conditions were investigated, as depicted in Figure 3.2.

The behaviour of the sandwich structures was simulated using a 3D finite element model in ABAQUS 6.14 software. The details of the modelling methodology are given step by step in the following sections.

3.2.1 Part

Figure 3.3 illustrates a composite structure consisting of a tin slag polymer concrete core reinforced with carbon fibre-reinforced polymer (CFRP) skins, both on the top and bottom, along with additional reinforcement layers (longitudinal and transverse). This configuration enhances the overall structural integrity and performance, particularly in applications subjected to high stress, such as blast loading.

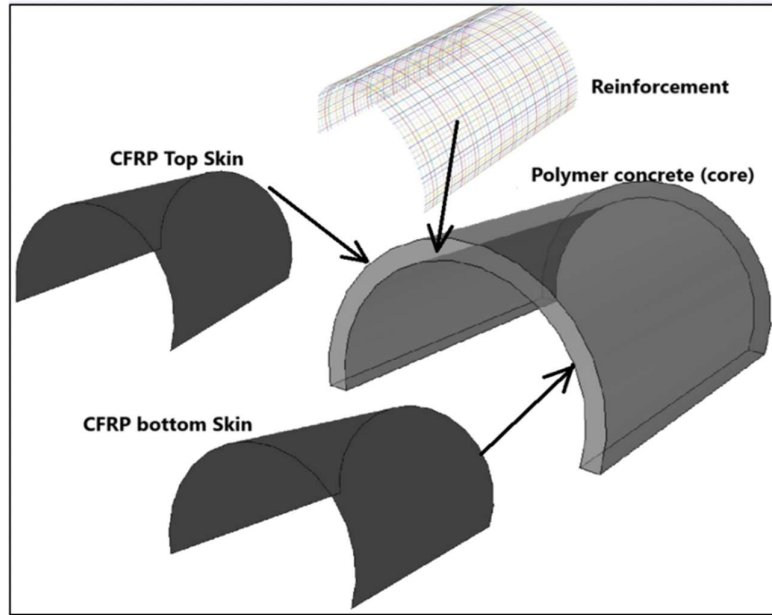


Figure 3.3: All parts of SPCB for ABAQUS modelling.

3.2.2 Property

This section focuses on the three key materials used in the construction of the sandwich bunker model:

1. Polymer concrete (Core)
2. CFRP (top and bottom skins)
3. Steel (reinforcement)

3.2.3 Polymer Concrete

Concrete is a mixed and brittle material that behaves differently under various loads, so accurate modelling is important for proper structural engineering analysis and design. The concrete damage plasticity model excels in capturing this complexity by incorporating damage evolution laws that effectively account for both tension and compression damage. Through this model, the study aims to provide a comprehensive understanding of the

materials response under different loading scenarios, enabling a more reliable prediction of the structural behaviour and, in turn, contributing to the advancement of concrete structural design and analysis methodologies.

The material specifications for the studied tin slag polymer concrete, as outlined in Shakil & Hassan (2020), include a density of 2001 kg/m^3 , Young's modulus of 36 GPa, and a Poisson's ratio of 0.2. These properties indicate that the polymer concrete possesses a strong structural framework, providing both flexibility and durability, making it suitable for applications requiring high resistance to compressive forces and dynamic loads, such as in the construction of blast-resistant bunkers.

Regarding the ABAQUS software, it provides three crack models for simulating damage in reinforced concrete elements: The smeared crack concrete model, brittle crack concrete model, and concrete damaged plasticity model. For this particular study, the concrete damaged plasticity model was chosen due to its capability to accurately represent the complete inelastic behaviour of concrete, encompassing both compression and tension damage characteristics.

The selection of the concrete-damaged plasticity model is crucial for developing a damage simulation model that can effectively analyse the behaviour of the sandwich polymer bunker under dynamic loading conditions. This choice allows researchers to capture the response of the bunker's materials to various loading scenarios, contributing significantly to a comprehensive understanding of its structural integrity and performance. The ABAQUS version 6.14 used in this study provides the necessary tools and capabilities to implement the concrete-damaged plasticity model effectively (ABAQUS 6.14, 2021).

Table 3.1 outlines key parameters for simulating the behaviour of SPCB bunkers under stress. It includes a dilation angle of 31° (indicating volumetric expansion during deformation), an eccentricity of 0.1 (defining the shape of the plastic potential function), and an $Fb0/Fc0$ ratio of 1.16 (comparing biaxial to uniaxial compressive strength). The K parameter (0.667) shapes the yield surface, while a viscosity parameter of 0.0001 accounts for time-dependent effects like creep (Yang et al., 2025). These values are crucial for accurately modelling the response of polymer concrete under high-stress conditions like explosions.

Table 3.1: Concrete damaged plasticity parameters (Yang et al., 2025).

Dilation Angle	Eccentricity	Fb0/Fc0	K	Viscosity Parameter
31	0.1	1.16	0.667	0.0001

The concrete damage plasticity (CDP) model is commonly employed when concrete experiences stress or strain levels that surpass its ability to deform elastically. Under such conditions, concrete undergoes significant inelastic behaviour, leading to cracking, crushing, and strain-softening. The material model of the CDP model is characterized by the post-peak stress-strain curve portion.

The polymer concrete component of the bunker model adopts the stress-strain relationship proposed by Tao et al. (2006) to describe concrete under uniaxial compression:

$$\sigma_c = \frac{E_o \varepsilon_c}{1 + \left(\frac{E_o \varepsilon_p}{\sigma_p} - 2 \right) \left(\frac{\varepsilon_c}{\varepsilon_p} \right) + \left(\frac{\varepsilon_c}{\varepsilon_p} \right)^2} \quad \text{Equation 3.1}$$

where σ_c represents the experimentally obtained compressive stress and ε_c denotes the experimental strain. Similarly, σ_p represents the experimentally determined maximum stress and ε_p experimental maximum stress strain. The elastic modulus of concrete, denoted as E_0 , is calculated using the formula $E_0 = 4730 \sqrt{f_c}$ Tao et al. (2006) is widely used to estimate the elastic modulus of concrete, in accordance with the guidelines established by the American Concrete Institute (ACI, 2002).

Converting stress and strain values Equations (3.2) and (3.3) to their true counterparts ensures compatibility and accuracy within the ABAQUS simulation. This allows for an accurate representation of the material's mechanical behaviour by accounting for changes in cross-sectional area and ensuring reliable analysis under various loading conditions where σ_{true} refers to the true stress, ε_{true} is the true strain and $\varepsilon_{inelastic}$ represents the inelastic strain. $\varepsilon_{inelastic}$ is the portion of the total strain in a material that remains after the removal of the applied load, representing permanent deformation. Unlike elastic strain, which is recoverable and disappears once the load is removed, inelastic strain is a measure of the irreversible changes in the materials shape or size due to plastic deformation or damage.

$$\sigma_{true} = \sigma_c (1 + \varepsilon_c) \quad \text{Equation 3.2}$$

$$\varepsilon_{true} = \ln(1 + \varepsilon_c) \quad \text{Equation 3.3}$$

The inelastic strain, $\varepsilon_{inelastic}$, is defined as

$$\varepsilon_{inelastic} = \varepsilon_{true} - \frac{\sigma_{true}}{E_0} \quad \text{Equation 3.4}$$

The compressive damage parameter, d_c , denotes the proportion of inelastic strain to total strain, signifying material damage under compression, while σ_p signifies the experimentally determined maximum stress.

$$d_c = 1 - \frac{\sigma_{true}}{\sigma_p} \quad \text{Equation 3.5}$$

Under uniaxial tension, the issue revolves around tensile cracking, with f_t representing the concrete uniaxial tensile strength. The parameter f_t signifies the maximum tensile stress that the concrete can withstand before fracturing under tension.

$$f_t = 1.4 \left(\frac{f_c - 8}{10} \right)^{\frac{2}{3}} \text{ MPa} \quad \text{Equation 3.6}$$

The tensile damage parameter, d_t , is the ratio of cracking strain to total strain, reflecting material damage under tensile loading.

$$d_t = 1 - \frac{\sigma_{true}}{\sigma_p} \quad \text{Equation 3.7}$$

3.2.4 Carbon Fibre-Reinforced Polymer (CFRP)

In this model, the CFRP material is assumed to exhibit elastic behaviour up to a certain stress level, after which it will no longer bear any additional stress. The maximum strain or yield strain considered for the CFRPs is 0.015 (Raza et al., 2020). The specifications of the carbon fibres used in the modelling are provided in Table 3.2.

The T350/EP-1006 composite is a unidirectional fibre-reinforced composite that often used in structural engineering because of its high strength and stiffness. Its design is made up of

carbon fibres, for high tensile strength and stiffness, in an epoxy resin matrix that helps the compressive loads on flexure from shearing. T350/EP-1006 is anisotropic material, properties will vary drastically with direction: As with all matrices, the fibres embedded in the longitudinal direction (parallel to the fibres) exhibit greater strength and stiffness compared to the transverse direction at 0 degrees, where the T355 matrix cures at a different rate compared to the through-thickness (toughness) direction. The concrete core is sandwiched on both the top and base each by 3 mm thick $[0/\pm 30]$ CFRP skin, expanding its solidarity against dynamic forces.

According to Table 3.2, the CFRP Hashin damage model offers valuable insights into the materials behaviour, emphasizing key strength values in different directions. The longitudinal tensile strength (X_t) is 1034.21 MPa, demonstrating the materials resistance to tension along the fibre direction, while the longitudinal compressive strength (X_c) is 689.48 MPa, indicating its capacity to withstand compression in the same direction. In contrast, the transverse tensile strength (Y_t) is 41.37 MPa, and the transverse compressive strength (Y_c) is 117.21 MPa, showing significantly lower resistance compared to the longitudinal properties. Additionally, both the longitudinal and transverse shear strengths (S_t and S_c) are 68.95 MPa, illustrating the materials shear resistance in these directions. These strength values are essential for comprehending the mechanical performance and damage response of CFRP under varying loading conditions.

Table 3.2: Properties of CFRP material parameters in ABAQUS.

Property	value	References
Density, ρ (Kg/m ³)	1600	Kim et al. (2017)
Longitudinal stiffness, E_1 (MPa)	138580	Soffi Manda et al. (2024) O'Higgins et al. (2008) Koloor et al. (2020) Raza et al. (2020)
Transverse stiffness, E_2 (MPa)	10070	
Poisson's ratio	0.34	
In-plane shear modulus, G_{12} (MPa)	5129	
Out-of-plane shear modulus, G_{13} (MPa)	2950	
Out-of-plane shear modulus, G_{23} (MPa)	5129	
Longitudinal tensile strength, X_t (MPa)	1034.21	Soffi Manda et al. (2024)
Longitudinal compressive strength, X_c (MPa)	689.48	
Transverse tensile strength, Y_t (MPa)	41.37	Soffi Manda et al. (2024) Liu et al. (2020)
Transverse compressive strength, Y_c (MPa)	117.21	Soffi Manda et al. (2024)
Longitudinal shear strength, S_t (MPa)	68.95	Soffi Manda et al. (2024) Lüders, (2020)
Transverse shear strength, S_c (MPa)	68.95	

3.2.5 Steel (Reinforcement)

The steel bars used in this investigation were 12 mm diameter rebars, uniformly spaced at 150 mm in both longitudinal and transverse directions, forming a cylindrical reinforcement layout as shown in Figure 3.3. The tensile properties of these steel rebar's were determined through tensile tests in accordance with MS EN 1993: Design of Steel Structure, showing a mass density of 7,850 MPa, a Young's modulus of 200,000 MPa, and a Poisson's ratio of 0.3 (Chen et al., 2006). This reinforcement configuration enhances the strength and stability

of the structural element, making it capable of effectively resisting loads in multiple directions.

3.2.6 Assembly and Contact

In Figure 3.4, the assembly in ABAQUS means combining more than one part to form a single model. In the case of a bunker this may be an assembly including three-layer CFRP on top and bottom surfaces, polymer concrete and horizontal/vertical reinforcement. The assembly should be created by importing the individual parts and then positioning and aligning them correctly. Finally, the assembly should be checked for any gaps or overlaps between the parts and adjusted as needed. Ensuring proper connection and effective load transfer between components makes the assembly process in ABAQUS a critical step in the simulation. The assembly can be employed by defining contact interactions among the different parts. The contact interactions of the bunker model are necessary for its correct response in simulating different loading under blast loads. They can be bonded or non-bonded interactions depending on the desired behaviour of materials. The model is arranged as a sandwich structure, starting with a top CFRP skin, transitioning to a polymer concrete core, and finishing with a bottom CFRP layer. This configuration encases the reinforcement rebar, allowing it to function as both a load-bearing element and enhancing the systems overall strength. The polymer concrete core effectively resists cracking and deformation, while the CFRP skins contribute significant tensile strength, ensuring stiffness throughout the structure. The modelling of the bonded contact between the CFRP skins and the polymer concrete core is a critical factor during an explosion, as it significantly influences the structural integrity and energy dissipation capacity of the panel. In ABAQUS, this bonded contact is typically defined using the tie constraint method, which assumes perfect bonding with no relative motion between the surfaces. The CFRP layer, although possessing high

strength, functions as more than just a sacrificial layer as it acts as external reinforcement, working in conjunction with the embedded rebar and polymer core to resist the blast loads and improve the overall structural performance.

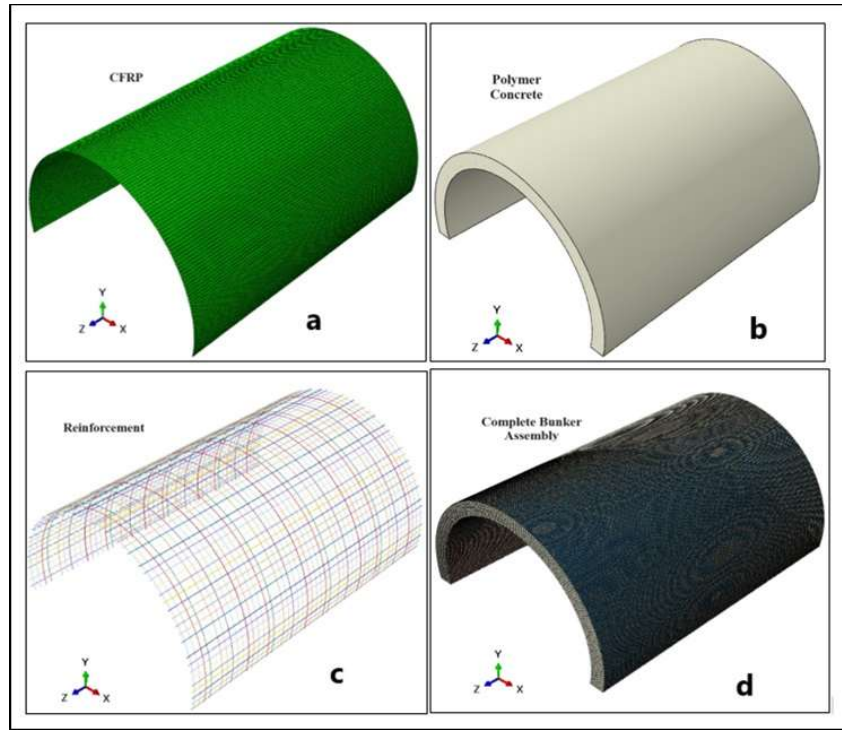


Figure 3.4: Complete assembly of the bunker.

3.2.7 Step Manager

In the step module, the type of analysis to be performed is defined; for this study, a dynamic analysis subjected to a time-varying load was selected to simulate the response of the bunker to blast loads. Within the step manager, the most critical aspect is to properly select the procedure, which in this case is a dynamic, explicit analysis. This method is well-suited for handling the complex, nonlinear behaviour associated with blast loading and rapid dynamic events. Additionally, the “nlgeom” option, which accounts for large deformations and nonlinear geometry effects, was turned on to improve the accuracy of the simulation. The

time for this analysis was set to 1.8 ms and the time incrementation, or the time step at which the solution is computed, was carefully defined. This blast period is sufficiently long for the wave to travel from the blast source to the structure, ensuring an accurate assessment of its impact (Mohammadzadeh et al., 2020).

The concrete damaged plasticity models, the parameters DAMAGET, DAMAGEC, and SDEG are used to represent different aspects of material damage. DAMAGET refers to the extent of damage when the material is under tensile stress, indicating how micro-cracks form and reduce the materials stiffness as tension is applied. DAMAGEC, on the other hand, reflects the damage that occurs under compressive loading, accounting for the crushing and micro-structural deterioration that reduces the concretes ability to withstand compression. SDEG, or stiffness degradation, measures the overall reduction in the materials stiffness due to damage, whether from tensile or compressive stress.

Another essential aspect of the step module in this research is the configuration of the field output manager. This section must be carefully set up as it controls the data captured during the simulation for post-processing and analysis. To ensure comprehensive results, the domain should include the entire model, with the output frequency set to evenly spaced time intervals, using an interval of 20 steps. The choice of output variables, such as Stress, Strain, DAMAGET, DAMAGEC, and SDEG, is critical and should align with the research objectives. These variables will provide the necessary insights into the structural response, damage progression, and overall performance of the polymer concrete sandwich bunker under blast loading. Proper configuration of the field output manager ensures that the necessary data will be collected for a thorough analysis and validation of the research findings.

3.2.8 Interaction and Boundary Condition

In this study, fixed boundary conditions were applied to the edges of the polymer concrete bunker to simulate a realistic scenario where the structure remains stationary under dynamic explosive loads. The load was modelled using the CONWEP method, accurately representing the pressure wave generated by TNT detonations, with time-varying characteristics to mimic the impact of the blast wave on the bunker. This approach allows for a precise assessment of the bunkers structural response, stress distribution, and effectiveness in withstanding different explosive charges. Within the interaction manager, an initial step and a dynamic explicit procedure were created, with the interaction type set as an incident wave to simulate blast impacts effectively. The interaction property settings involved configuring the CONWEP charge, where the air blast definition was selected, and conversions were applied: mass to kilograms (1,000), length to meters (0.001), time to seconds (1), and pressure to pascals (1E+006). Additionally, the constraint manager was used to ensure proper bonding, where the CFRP and the bunker were joined using a Tie constraint, and the rebar was embedded within the bunker using the embedded region setting.

3.2.9 Meshing

A mesh convergence study was conducted using solid elements for the concrete core and shell elements for the CFRP skins. Local seeds were applied using the “By Number” method, generating approximately 130 elements to ensure sufficient accuracy in capturing structural response. The concrete core and CFRP skins were modelled using the 8-node linear brick element with reduced integration (C3D8R), while the reinforcement was represented using 2-node 3D truss elements (T3D2). The mesh configurations for the sandwich polymer concrete bunker models varied by slab thickness.

Figure 3.5 illustrates the relationship between the element number and the maximum displacement (U2) in mm. The sharp drop in displacement values observed at low mesh numbers indicates poor accuracy in this regime. This convergence plot is used to identify a mesh density that is sufficiently high to ensure reliable results while remaining computationally efficient. As the element number increases, the displacement gradually stabilizes, reaching a steady state with minimal variation, hence, the needed accuracy.

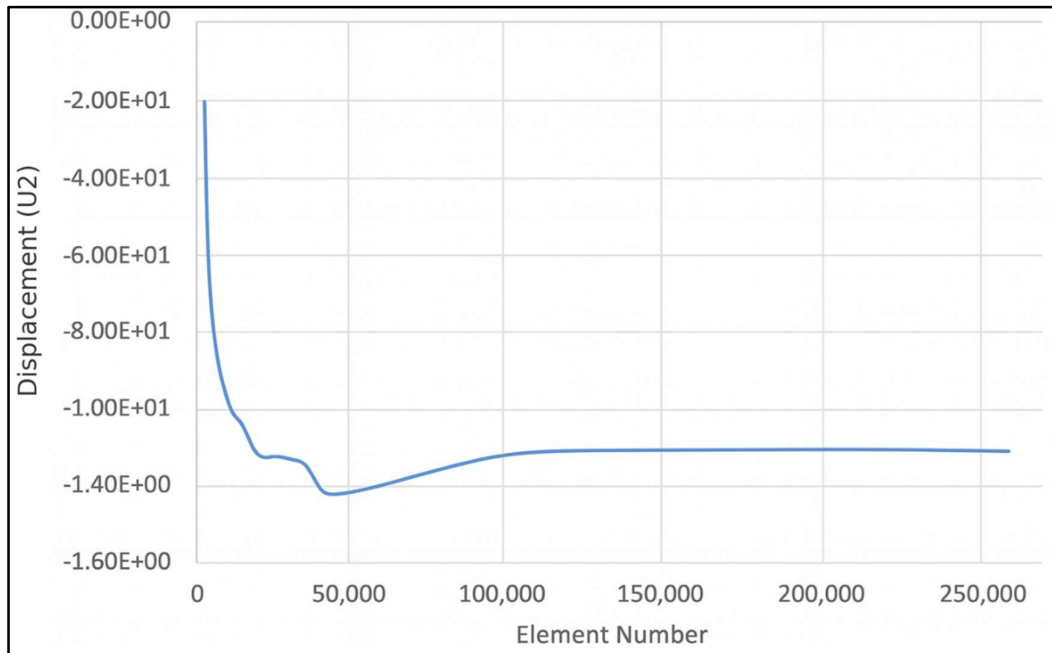


Figure 3.5: Converging maximum displacement at the centre of the sandwiched polymer concrete bunker (SPCB) with 200 mm thick core for increasing element number.

Table 3.3 presents details of four finite element analysis (FEA) models SPCB-200, SPCB-250, SPCB-300, and SPCB-500 where “SPCB” refers to the sandwiched polymer concrete bunker and the numerical values represent the core thickness in millimetres, highlighting the number of nodes and elements used in each model. The SPCB-200 model

consists of 195,846 nodes and 176,410 elements, while the SPCB-250 model has 218,551 nodes and 196,280 elements. Moving to more complex models, SPCB-300 includes 246,131 nodes and 220,800 elements, and SPCB-500 features the highest refinement with 275,150 nodes and 246,560 elements.

Table 3.3: Summary of the converged node and element numbers of bunkers with different core thicknesses.

Model code	Number of Nodes	Total of Elements
SPCB-200	195846	176410
SPCB-250	218551	196280
SPCB-300	246131	220800
SPCB-500	275150	246560

The model is fully meshed and ready to proceed to the final step. As shown in Figure 3.6, the completed model for the bunker thinness 200 mm displays the bunker with comprehensive meshing, utilizing a local seed for the reinforcement bar and seed edge on the SPCB.

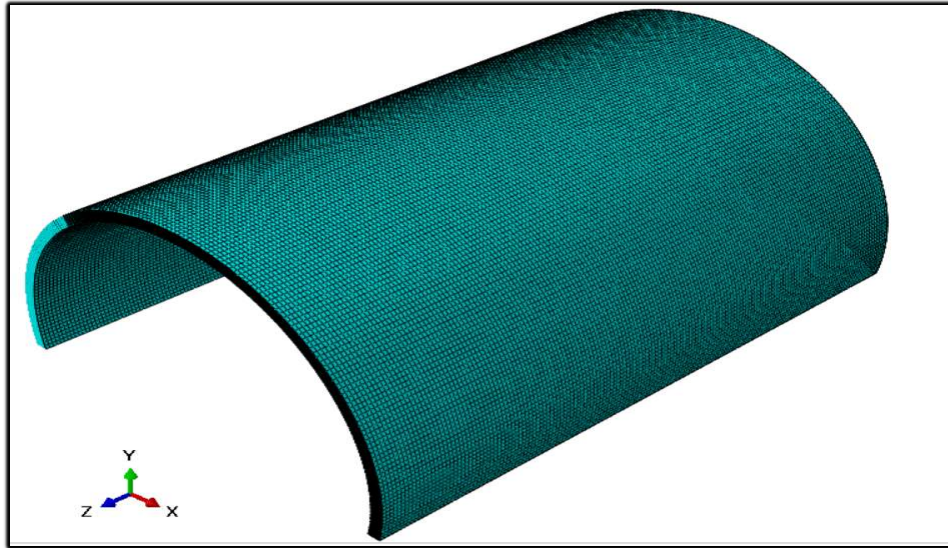


Figure 3.6: Complete meshing for the SPCB-200 bunker.

3.2.10 Job Module

In Figure 3.7, the module is used to execute the simulation, where the Job Manager function allows for creating and editing jobs, which should be appropriately named. Once all parameters are set, the Submit function initiates the analysis, while the Monitor function enables real-time error checking. Upon completion, the Results function displays the analysis outcomes in the Visualization module.

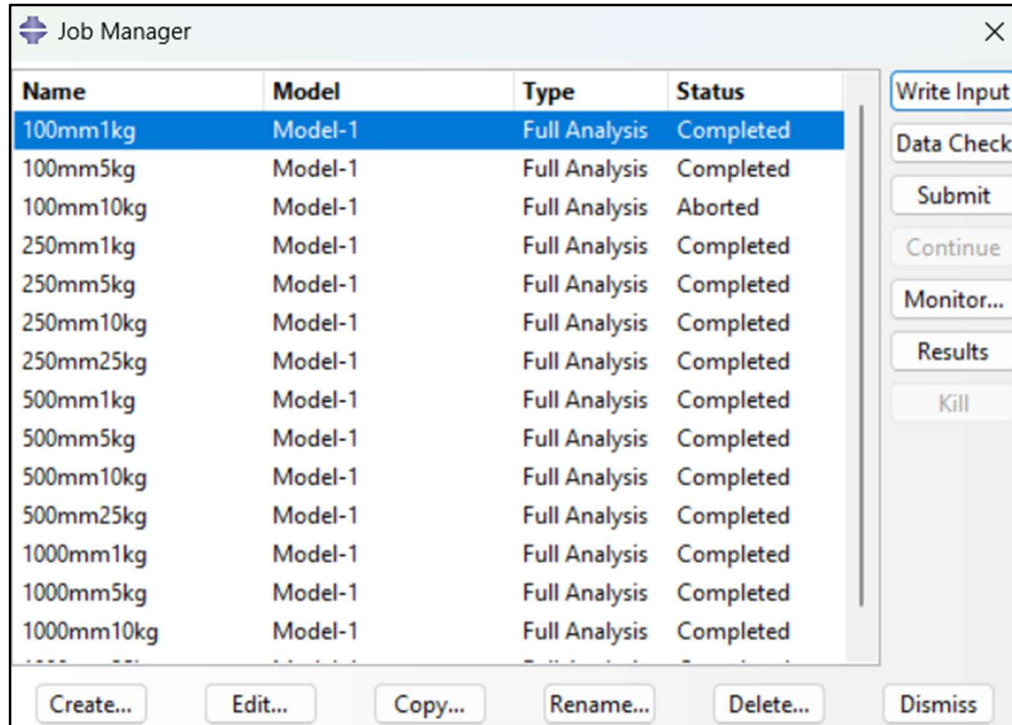


Figure 3.7: Job Manager.

3.2.11 Visualization and Result Plotting

Figure 3.8 shows the Visualization and Result Plot module is crucial for obtaining and analysing results. In this module, the Plot Contours on Deformed Shape function allows users to visualize contour plots on the deformed structure at specific time intervals, providing insights into stress distribution and deformation patterns. Additionally, the Create XY Data function is used to extract and plot numerical data from the simulation, with the ODB field output serving as the source. This process facilitates a detailed analysis and interpretation of the simulation outcomes, which will be presented in the next chapter.

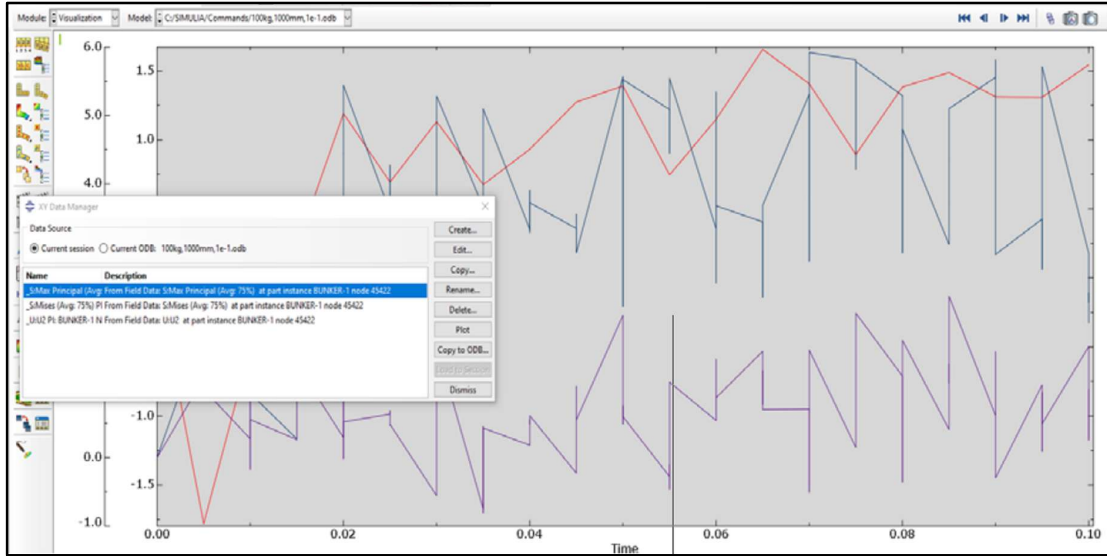


Figure 3.8: Visualization and Result Plot.

3.3 Verifications

The study by Shishegaran et al. (2020) was used to examine the response of reinforced concrete panels under blast loading conditions. In Figure 3.9, they investigated a reinforced concrete panel measuring $1400 \times 1000 \times 300$ mm, reinforced with D13 steel rebars, where “D13” denotes a rebar size with a diameter of 13 mm spaced at 100 mm intervals in two perpendicular directions. The concrete material properties included a density of 2350 kg/m^3 , a Young’s modulus of 30 GPa, a compressive strength (f_c) of 40 MPa, and a Poisson’s ratio of 0.15. The comparison will focus on the response of the reinforced concrete panel subjected to a 25 kg TNT blast load for 50 ms, with fixed support. The outcome of this comparison will be thoroughly presented in Chapter 4.

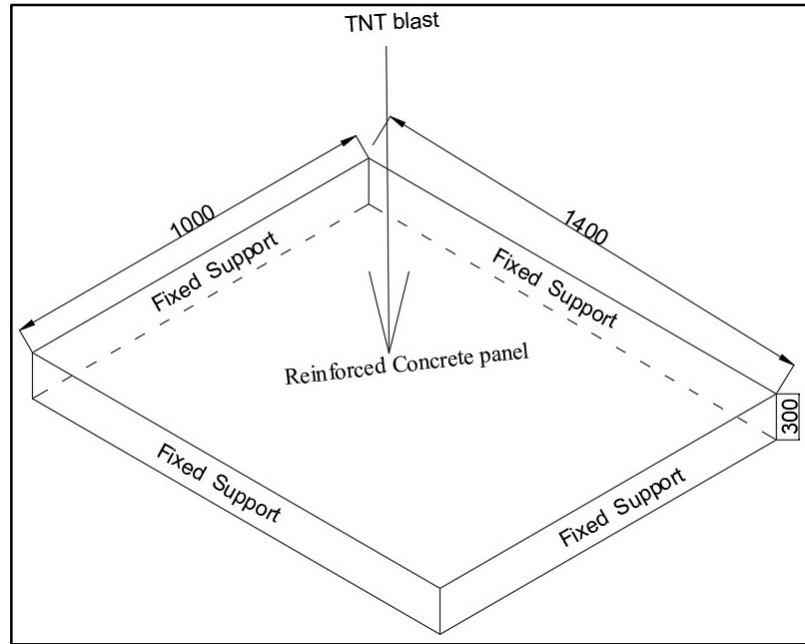


Figure 3.9: Blast on reinforced concrete panel (units: mm).

3.4 Regression Analysis

In the next step, a regression analysis was conducted using the Minitab software to independently predict the principal stress (σ_s) and the von Mises stress (σ_{Mises}) as functions of key input variables, including core thickness (t), TNT mass (m), and standoff distance (d).

In Figure 3.10, the flowchart outlines the step-by-step process for conducting a response surface methodology (RSM) analysis using Minitab. It begins with identifying key factors and responses, followed by setting up the design in Minitab, analysing the surface design, and generating a design table.

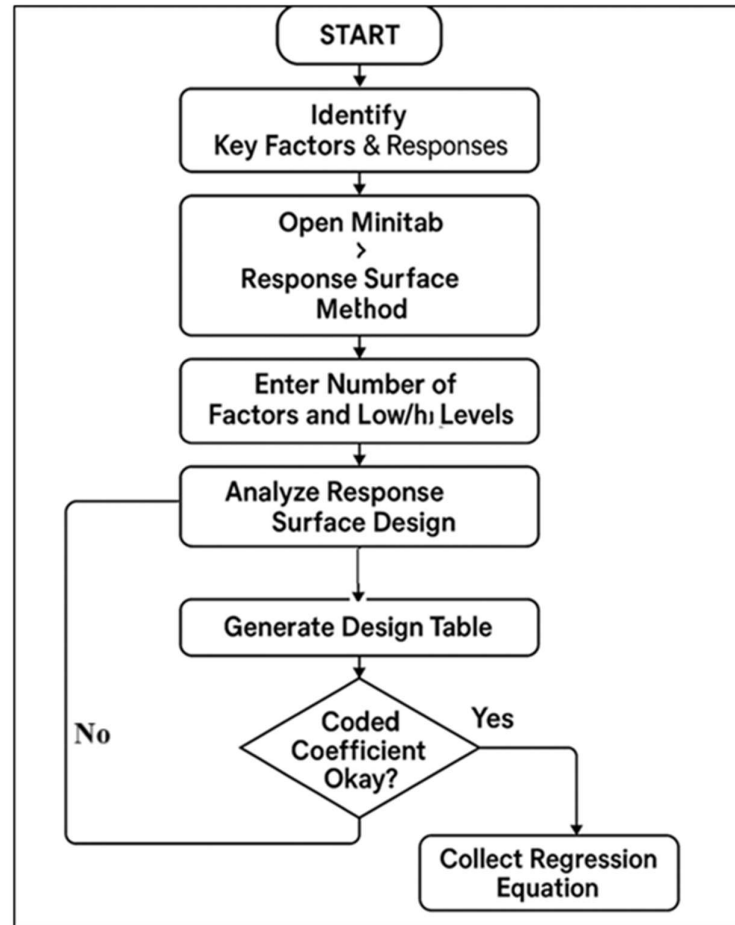


Figure 3.10: Response surface methodology (RSM) flowchart using Minitab.

In Minitab, performing a custom response surface analysis begins by selecting the Start section, followed by navigating to the DOE (Design of Experiments) subsection, and choosing Response Surface. This leads to the option to define custom response surface design, where specific factors and responses are set up for the analysis. In this design, the variables are defined as C1, C2, C3, and C4, representing thickness (t), mass (m), distance (d), and the output, which could be principal stress (σ_s) or von Mises stress (σ_{Mises}), respectively. In this setup, C1 to C3 (thickness, mass, and distance) are treated as continuous factors, meaning they can take any value within a specified range. C4, however, is treated as the output responses like principal stress or von Mises stress. The response surface

regression method was employed to compare the simulation data with the predicted data, resulting in a set of regression equations that statistically describe the relationship between these variables and the resulting stress in the structure.

The use of regression analysis in this study is justified as it allows for the development of predictive models that quantify the relationship between key blast parameters core thickness, TNT mass, and standoff distance and the resulting structural responses, such as principal stress (σ_s) and von Mises stress (σ_{Mises}). This approach provides a cost-effective and time-saving alternative to extensive simulations or experiments by generating mathematical equations that can predict stress outcomes under various blast conditions.

Two different types of concrete bunker configurations were analysed: the sandwiched polymer concrete bunker (SPCB) and the sandwiched concrete bunker (SCB). For SPCB, a full factorial design was created using four levels for each factor: core thickness of 0.2 m, 0.25 m, 0.3 m, and 0.5 m; TNT mass of 1 kg, 5 kg, 10 kg, and 25 kg; and stand-off distance of 0.1 m, 0.25 m, 0.5 m, and 1.0 m. This resulted in a total of $4 \times 4 \times 4 = 64$ unique combinations (cases). For SCB, the levels were core thickness of 0.2 m, 0.3 m, and 0.5 m; TNT mass of 1 kg, 10 kg, and 25 kg; and stand-off distances of 0.1 m, 1.0 m, 2.0 m, and 2.5 m, resulting in $3 \times 3 \times 4 = 36$ cases. All stress outputs were obtained from simulation results under various blast loading conditions.

To develop predictive models from the data, response surface regression was applied using a full quadratic model. This modelling approach includes main effects (t , m , d), interaction terms ($t \times m$, $t \times d$, $m \times d$), and quadratic terms (t^2 , m^2 , d^2) to capture potential non-linear and synergistic relationships between variables. The use of this regression approach is justified as it provides a mathematical framework to quantify the effect of each

blast parameter on the structural stress response. It also offers a cost-effective and time-efficient method to estimate stress outcomes under different scenarios without the need for exhaustive physical testing or simulations. Ultimately, the generated regression equations serve as valuable tools for predicting maximum principal and von Mises stresses in concrete bunkers subjected to various blast conditions, thus supporting improved design decision-making.

3.5 Summary

The methodology outlines a step-by-step approach for modelling and analysing sandwich polymer concrete bunkers (SPCB) under blast loads using ABAQUS. It begins with defining the bunker's geometry, followed by assigning material properties specifically the concrete-damaged plasticity model and the CFRP Hashin damage model to accurately simulate material responses under dynamic blast conditions.

Next, the assembly stage involves arranging the different components of the bunker into a cohesive model. Following assembly, the step manager is used to define the sequence of analysis steps, which includes setting up the loading conditions and the time increments for dynamic simulations. Following the step definition, the interaction stage is undertaken, where the relationships and contact conditions between different parts of the model are defined. This includes specifying whether contacts are tied, frictional, or sliding, and ensuring proper interaction behaviour during blast impact. These interactions are critical to achieving realistic mechanical behaviour under extreme loading. The blast load itself is also defined in this stage, typically as a pressure-time history applied over a designated surface area, corresponding to the stand-off distance and TNT mass parameters used in the experimental matrix. A proper definition of these contact interactions and blast loads is

essential for capturing the true response of the structure to explosive events and ensuring the reliability of the simulation outcomes.

Afterward, mesh generation is performed, where mesh convergence studies are essential to ensure that the model produces reliable and accurate results. The job setup follows, where the model is prepared for analysis in ABAQUS. Once the simulation is completed, verification against experimental data is conducted to validate the models accuracy.

Lastly, regression analysis is used to predict structural responses based on variables such as core thickness, TNT mass, and standoff distance. The chapter emphasizes that adhering to this step-by-step modelling sequence is crucial for ensuring precise results. Results for SPCB and SCB models will be analysed and discussed comprehensively in Chapter 4, providing insights into the results and discussion of the numerical analysis comparing the performance of sandwiched polymer concrete bunkers (SPCB) and sandwiched concrete bunkers (SCB) under various blast loading conditions. It begins with the verification of the finite element model to ensure accuracy, followed by an evaluation of the structural responses such as displacement, stress distribution, and damage patterns.

CHAPTER 4

RESULT AND DISCUSSION

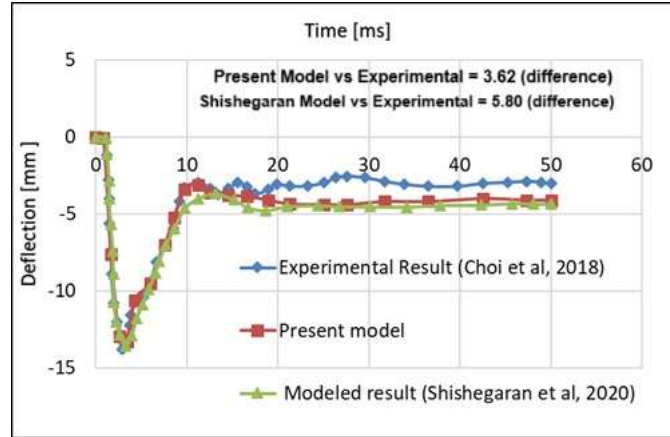
4.1 Overview

Chapter 4 presents the key results of the study, focusing on the maximum and minimum blast distances, the mass of TNT used, and the resulting damage to SPCB and SCB. These results are critical in understanding the bunkers response to varying explosive loads and distances. The detailed analysis provided in this chapter highlights the structural performance and the extent of damage experienced by the bunker under different blast conditions. Additional results and supplementary data, which support the findings but are not central to the primary conclusions, are provided in the appendix for further reference.

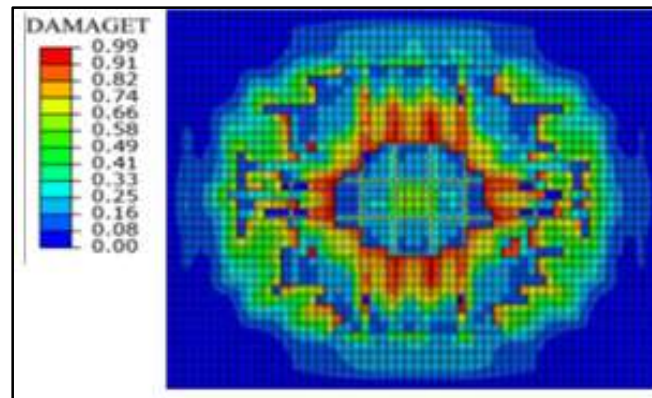
Blast response of polymer defence bunker can be affected by various factors. The responses of the SPCB and SCB were analysed under four levels of TNT weights 1 kg, 5 kg, 10 kg, and 25 kg at blast distances of 0.1 m, 0.25 m, 0.5 m, 1 m, 2 m, and 2.5 m, with bunker core thicknesses of 200 mm, 250 mm, 300 mm, and 500 mm. The duration of each blast was set at 1.8 ms.

4.2 Verification Result

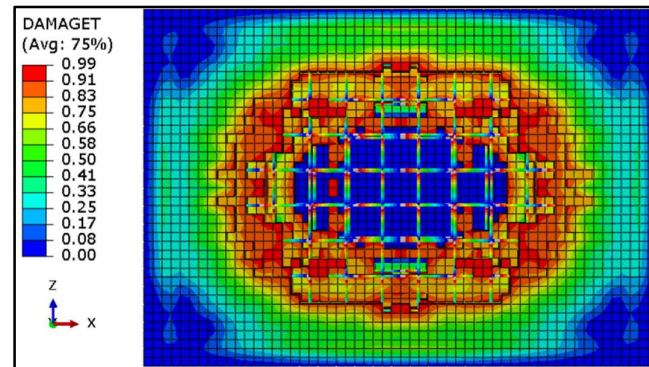
The model results from Shishegaran et al. (2020) were selected for verification as they provide a baseline for assessing the performance of reinforced concrete panels. Figure 4.1 shows the verification of the blast modelling technique, with deflection-time curves, demonstrating similarities to the current studies examination of structural response under comparable blast conditions and distance.



(a)



(b) i



(b) ii

Figure 4.1: Verification of blast modelling technique (a) Deflection-time curves (b) i.

Model result of Shishegaran (b) ii. present model.

Figure 4.1 illustrates that the current modelling methodology closely captures the relationship between the slabs normalised central deflection and time (ms), aligning well with both experimental results and modelling techniques reported by Choi et al. (2018) and Shishegaran et al. (2020). Figure 4.1(a) demonstrates a close correlation between the present model and the experimental data, highlighting its accuracy. While the Shishegaran model shows a 5.80% difference from the experimental results, the present model exhibits an even smaller discrepancy of only 3.62%, indicating improved precision. While Figure 4.1 (b) does not fully match, it still exhibits an approximately the same perforation hole when compared to Shishegaran et al. (2020). Overall, the model's performance, as shown in Figure 4.1 (a) and (b), suggests its effectiveness in accurately replicating real simulation data.

4.3 Blast displacement of conventional against polymer sandwich bunkers

Figure 4.2 shows the maximum vertical displacement at the centre of the bunker for different sandwich concrete bunker (SCB and SPCB) models subjected to TNT explosions at varying standoff distances.

The SCB-200-1 bunker, where “SCB” denotes a sandwiched concrete bunker, “200” refers to a slab thickness of 200 mm, and “1” represents a TNT charge of 1 kg, is exposed to a TNT explosion at a standoff distance of 0.1 m, resulting in a maximum vertical displacement of 30.6 mm. When the TNT source is located 1 m from the bunker's top, the maximum displacement significantly reduces to 0.21 mm. similar trends are observed for the SCB-250-1 bunker. At 0.1 m blast distance, the maximum displacement is 28.7 mm, decreasing to 0.16 mm at 1 m, with zero displacements recorded at 2 m and 2.5 m distances. The response of the bunkers to the blast does not appear to be significantly affected by the variation in thickness. However, the SCB-500-1 bunkers exhibit a noticeable reduction in maximum displacement compared to SCB-200-1 and SCB-250-1. At 0.1 m, the largest

displacement is only 22.0 mm, while at 1 m, it is a mere 0.158 mm, with no displacements at 2 m and 2.5 m.

The thicker bunker's ability to withstand the explosion is clearly demonstrated. As the TNT mass exposure increases, the displacements generally grow. For instance, in the case of the SCB-200-10 bunker, the SCB-200-10 bunker, where "SCB" denotes a sandwiched concrete bunker, "200" refers to a slab thickness of 200 mm, and "10" represents a TNT charge of 10 kg, is exposed to a TNT explosion at a standoff distance subjected to a blast distance of 0.1 m, the bunker cannot withstand the high TNT mass at close proximity. When the SCB models are placed 0.25 meters away and exposed to TNT masses of 10 kg and 25 kg, the simulations fail to run due to critical structural damage, indicating complete failure of the models under such extreme blast conditions.

At a blast distance of 1 meter, the SCB-200-10 bunker experiences a maximum vertical displacement of 8.66 mm. Similar trends are observed for other SCB models under 10 kg and 25 kg TNT charges. For example, the SCB-250-10 and SCB-500-10 bunkers record displacements of 7.29 mm and 5.44 mm, respectively, indicating that increased slab thickness reduces deformation. Under a 25 kg TNT charge at the same distance, the SCB-200-25 bunker shows a maximum displacement of 22.0 mm, while the SCB-250-25 and SCB-500-25 bunkers record 20.01 mm and 11.8 mm, respectively. These results clearly demonstrate that thicker cores provide better resistance to blast loads. However, when the TNT source is placed just 0.25 m or 0.1 m from the bunkers, the SCB models subjected to 10 kg and 25 kg TNT masses suffer critical structural failure, making the simulations unable to proceed.

Figure 4.2 presents a comparative analysis of the maximum vertical displacements experienced by various SPCB models subjected to TNT explosions at close standoff

distances. At an extremely close blast distance of 0.1 m with a 1 kg TNT charge, the maximum displacements for SPBC-200-1, SPBC-250-1, SPBC-300-1, and SPBC-500-1 are 6.13 mm, 5.14 mm, 3.74 mm, and 0.16 mm, respectively. These results indicate that increasing the thickness of the slab significantly reduces deformation, with the 500 mm thick model offering the highest blast resistance.

When the TNT mass is increased to 5 kg at the same 0.1 m distance, the maximum displacements rise dramatically to 36 mm, 24.9 mm, 18.2 mm, and 6.52 mm for SPBC-200-5, SPBC-250-5, SPBC-300-5, and SPBC-500-5, respectively. This sharp increase in deformation highlights the sensitivity of the models to explosive mass, particularly at close proximity. The data clearly show that while thicker cores improve resistance, even the SPBC-500-5 bunker suffers significant displacement, suggesting that extreme blast forces still impact high-thickness configurations.

Moreover, none of the SPCB models regardless of cores thickness could effectively withstand the explosive energy from 10 kg and 25 kg TNT charges at a 0.1 m distance, as structural integrity is compromised across all configurations. However, when the standoff distance increases slightly to 0.25 m, the models show improved performance. At this distance and under a 1 kg TNT charge, the SPBC-200-1, SPBC-250-1, SPBC-300-1, and SPBC-500-1 exhibit much lower displacements of 2.24 mm, 1.9 mm, 1.49 mm, and 0.56 mm, respectively. Similarly, under a 5 kg TNT charge, the maximum displacements are 12.1 mm, 10.7 mm, 7.86 mm, and 3.72 mm, respectively. These results reinforce the critical role of standoff distance in mitigating blast effects, as even with higher explosive charges, the increased distance significantly reduces structural response.

In contrast to the SCB models, which fail to produce any results at 0.25 m for 10 kg and 25 kg TNT due to severe structural failure and software termination, the SPCB models

continue to perform under the same conditions. For instance, SPBC-200-10, SPBC-250-10, SPBC-300-10, and SPBC-500-10 record maximum displacements of 54.6 mm, 37.3 mm, 27.55 mm, and 11.2 mm, respectively. The trend of decreasing maximum displacement with increasing slab thickness remains consistent. Under 25 kg TNT at 0.25 m, the SPBC-200-25 records the highest displacement at 152 mm, while SPBC-250-25, SPBC-300-25, and SPBC-500-25 show 114.5 mm, 81.59 mm, and 28.76 mm, respectively. Notably, even with a maximum displacement of 152 mm, the SPCB-200-25 simulation still completes successfully, underscoring the enhanced robustness of the SPCB design compared to the SCB counterparts.

The SCB models, particularly SCB-250-10 and SCB-250-25, fail to generate any simulation outcomes due to collapse under close-range and high-mass blast conditions, indicating a critical limitation in their structural resilience. In contrast, the SPCB configurations demonstrate a clear advantage, maintaining integrity and producing results under the same extreme loading scenarios. This critical evaluation highlights the superior performance of SPCB models in terms of both energy absorption and structural stability, particularly under high explosive loads and reduced standoff distances.

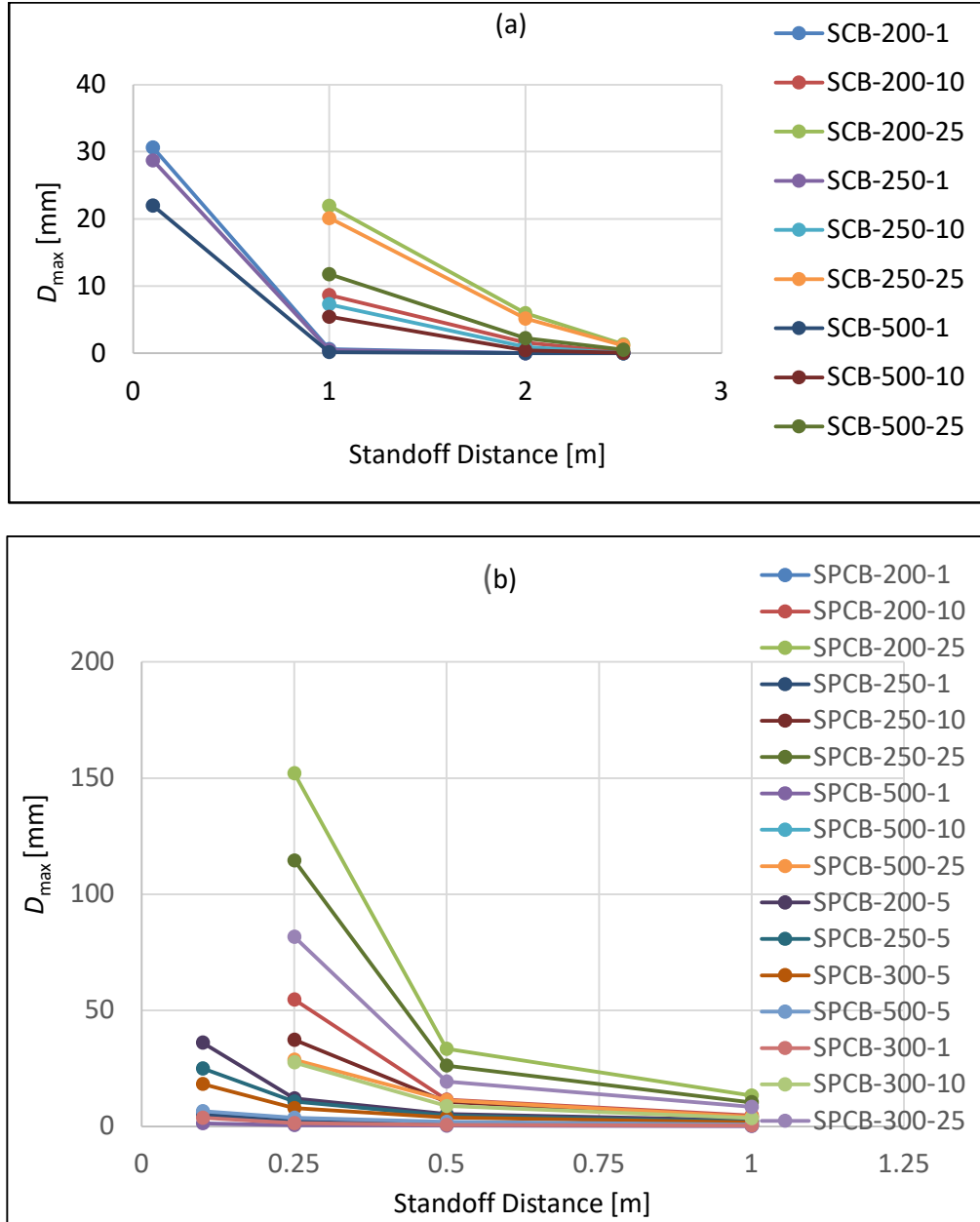


Figure 4.2: Maximum vertical displacement of (a) SCB and (b) SPCB models.

At a blast distance of 0.5 m, the maximum displacements observed for a TNT mass of 1 kg applied to the SPBC-200-1, SPBC-250-1, SPBC-300-1, and SPBC-500-1 bunkers are 1.1 mm, 0.85 mm, 0.64 mm, and 0.28 mm, respectively. However, when a 5 kg explosive is used at the same distance, the displacements increase significantly, with SPBC-200-5,

SPBC-250-5, SPBC-300-5, and SPBC-500-5 showing maximum displacements of 5.39 mm, 4.69 mm, 3.90 mm, and 1.95 mm, respectively. The maximum displacements further increase with a 10 kg TNT charge, reaching 11.5 mm, 10.5 mm, 8.74 mm, and 4.21 mm for SPBC-200-10, SPBC-250-10, SPBC-300-10, and SPBC-500-10, respectively. With a 25 kg TNT charge, the displacements for SPBC-200-25, SPBC-250-25, SPBC-300-25, and SPBC-500-25 are 33.4 mm, 26.4 mm, 19.2 mm, and 11.52 mm, respectively. These results highlight the substantial impact of increased TNT mass on the structural response of the bunkers at a constant blast distance. At a blast distance of 1 m, the maximum displacements observed for a TNT mass of 1 kg applied to the SPBC-200-1, SPBC-250-1, SPBC-300-1, and SPBC-500-1 bunkers are 0.62 mm, 0.48 mm, 0.37 mm, and 0.16 mm, respectively. When the TNT mass is increased to 5 kg at the same distance, there is a significant rise in displacements, with SPBC-200-5, SPBC-250-5, SPBC-300-5, and SPBC-500-5 experiencing maximum displacements of 2.63 mm, 2.09 mm, 1.65 mm, and 0.71 mm, respectively. For a 10 kg TNT charge, the maximum displacements are 4.7 mm, 3.91 mm, 3.63 mm, and 2.04 mm for SPBC-200-10, SPBC-250-10, SPBC-300-10, and SPBC-500-10, respectively. With a 25 kg TNT charge, the displacements further increase to 13.3 mm, 10.36 mm, 8.45 mm, and 4.16 mm for SPBC-200-25, SPBC-250-25, SPBC-300-25, and SPBC-500-25, respectively. These results illustrate the substantial effect of increased TNT mass on displacement outcomes at a fixed blast distance.

The presented result reveals that SPCB models consistently exhibit reduced displacement in response to varying TNT masses and distances when compared to their SCB counterparts. This substantial difference in performance not only highlights the enhanced structural integrity of SPCB but also emphasizes its capability to withstand explosive forces more effectively. The findings from Figure 4.3 collectively reinforce the notion that SPCB

represents a more robust and resilient solution, characterized by significantly lower displacement, making it a preferred choice in scenarios where blast resistance is paramount.

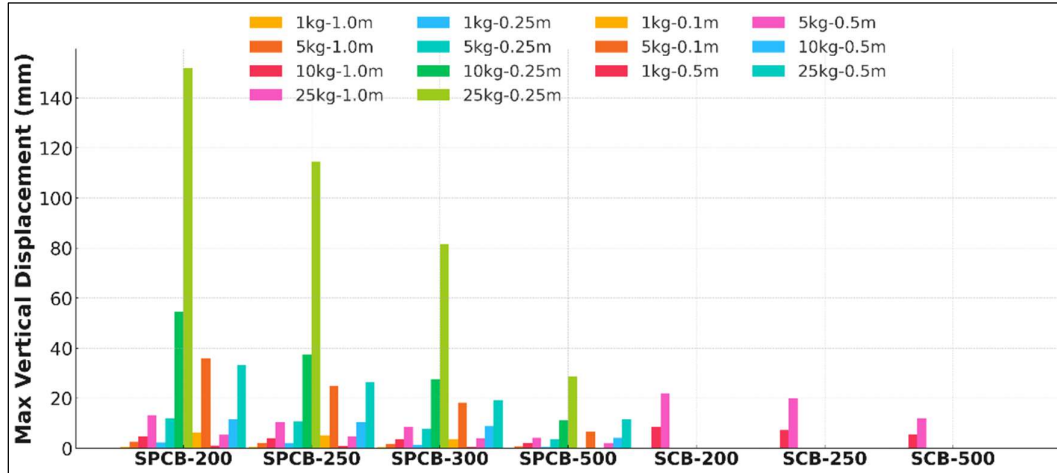


Figure 4.3: Maximum displacement of SCB and SPCB models.

Overall, the study emphasizes the significant influence of TNT mass and stand-off distance on bunker explosion resistance. At a distance of 0.1 m, SCB-200-1, SCB-250-1, and SCB-500-1 had displacements of 30.6 mm, 28.7 mm, and 22.0 mm, respectively. Similarly positioned near a 1 kg TNT load, SPCB-200-1, SPCB-250-1, SPCB-300-1, and SPCB-500-1 showed peak displacements of 6.13 mm, 5.14 mm, 3.74 mm, and 0.16 mm, respectively. The results emphasize the importance of both TNT mass and distance for constructing blast-resistant structures. SPCB-200-1 is 80% more potent than SCB-200-1, SPCB-250-1 is 82% more potent than SCB-250-1, and SPCB-500-1 is 99% more potent than SCB-500-1 based on the percentage difference. The higher potency of SPCB specimens is due to the polymer concrete's superior ability to absorb and dissipate blast energy, delay crack formation, and reduce stress transmission, resulting in significantly lower displacement under identical explosive conditions. Laqsum et al. (2025), demonstrated that the incorporation of polymer modifiers in concrete, particularly epoxy-based binders, led to

a remarkable increase in impact resistance by as much as 80% highlighting its improved energy absorption and reduced vulnerability to dynamic loads. Additionally, a review by Bahmani & Mostafaei (2025), affirmed that polymer concrete possesses superior fracture toughness and stress-wave mitigation capabilities, which contribute to its effective performance in high-strain-rate environments such as explosions and impacts.

4.4 Principal stress distribution of SCB against SPCB

Figure 4.4 illustrates the distribution of principal stress (S11) in the bunkers, as simulated in Abaqus, under a 1 kg TNT explosion at a stand-off distance of 0.1 meter, where S11 represents the primary stress component acting in the material (Dong et al., 2025). The SCB-200-1 bunker shows elevated stress levels compared to other thicknesses, resulting in element deletions, perforation, and a diminished capacity to fully withstand the blast load. Conversely, the higher-strength polymer concrete in SPCB-200-1 effectively prevents this damage, demonstrating its enhanced blast resistance. Thicker variants such as SCB-250-1 and SCB-500-1, positioned 0.1 meter away, exhibit no visible damage, indicating robust blast resistance. Furthermore, polymer concrete bunkers, including SPCB-200-1, SPCB-250-1, and SPCB-500-1, show no signs of cracking or damage at this proximity, underscoring their superior ability to endure the blast due to the exceptional strength of polymer concrete.

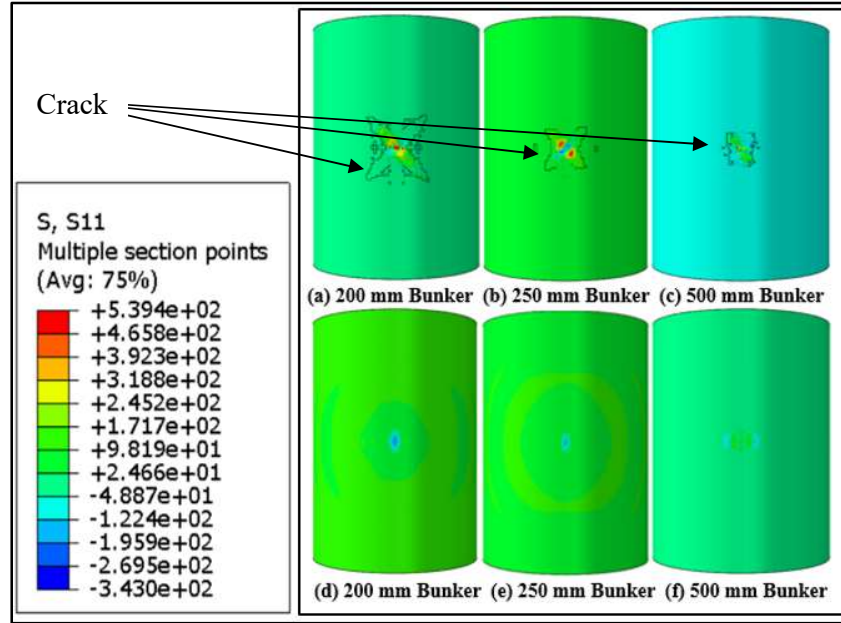


Figure 4.4: Principal stress distribution at distance 0.1 meter with 1 kg of TNT, (a) SCB-200-1, (b) SCB-250-1, (c) SCB-500-1 and (d) SPCB-200-1, (e) SPCB-250-1, (f) SPCB-500-1.

Figure 4.5 illustrates the principal stress distribution of bunkers subjected to a 5 kg TNT explosion at a distance of 0.1 meter. The SCB-200-5 bunker shows extensive cracking in a rectangular shape with multiple instances of element deletions and perforations in the centre of bunker. In contrast, the higher-strength polymer concrete in SPCB-200-5 effectively prevents such damage, demonstrating enhanced blast resistance with no visible cracking. Thicker variants, such as SCB-250-5, show reduced cracking compared to SCB-200-5 but exhibit some additional cracks outside the rectangular area and more element deletions, potentially due to the high blast load and damage to the CFRP skins. The SCB-500-5 bunker, positioned 0.1 meter away, displays no element deletions but has a visible rectangular crack line, which is less extensive than those in SCB-200-5 and SCB-250-5. Additionally, polymer concrete bunkers, including SPCB-200-5, SPCB-250-5, and SPCB-

500-5, exhibit no signs of cracking or damage at this proximity, underscoring their superior ability to endure the blast due to the exceptional strength of polymer concrete.

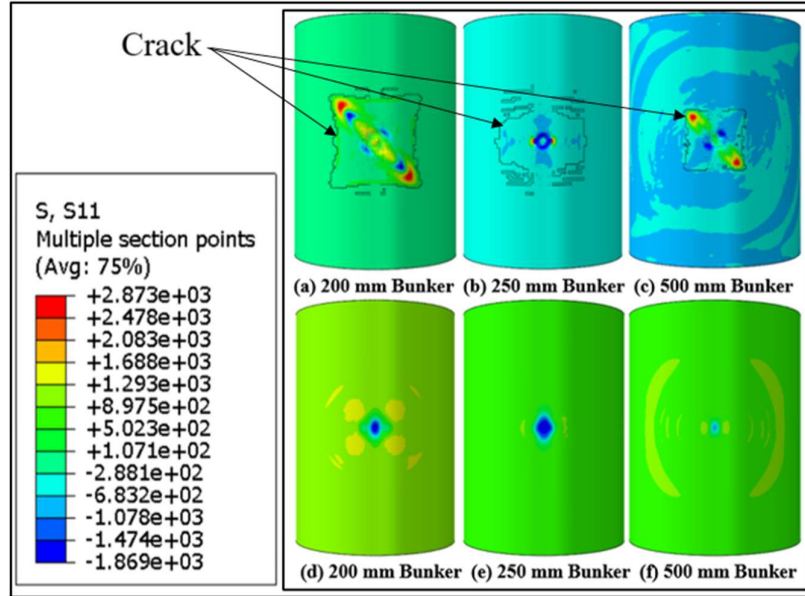


Figure 4.5: Principal stress distribution at distance 0.1 meter with 5 kg of TNT, (a) SCB-200-5, (b) SCB-250-5, (c) SCB-500-5 and (d) SPCB-200-5, (e) SPCB-250-5, (f) SPCB-500-5.

The principal stress distribution of bunkers subjected to 10 kg and 25 kg TNT explosions at a distance of 0.1 meter reveals significant findings. For SCB bunkers of all thicknesses, the stress levels are extremely high, leading to severe damage that renders the structures incapable of withstanding the blast. The extent of damage is so substantial that further analysis cannot be conducted on these bunkers. Similarly, SPCB bunkers of all thicknesses also experience massive damage under these conditions, highlighting the overwhelming force of the explosions. The polymer concrete, despite its superior properties, fails to maintain structural integrity when subjected to such high explosive loads at close

proximity. This underscores the need for further research and development of materials and design strategies to enhance the blast resistance of bunkers against extreme explosive threats.

Figure 4.6 plots the principal stress distribution of bunkers subjected to a 1 kg TNT explosion at a distance of 1 meter. The SCB-200-1 exhibits elevated stress levels compared to bunkers of other thicknesses, such that it experiences element deletions, causing perforation and reducing its capacity to fully withstand the blast load. In contrast, the higher-strength polymer concrete in SPCB-200-1 prevents this damage, highlighting its enhanced blast resistance. Thicker variants, SCB-250-1 and SCB-500-1, positioned 1 m away, demonstrate no visible damage, indicating good blast resistance. Polymer concrete bunkers, specifically SPCB-200-1, SPCB-250-1, and SPCB-500-1, show no signs of cracking or damage at a 1 m distance from a 1 kg TNT explosion, thus underscoring their ability to endure the blast due to the superior strength of polymer concrete.

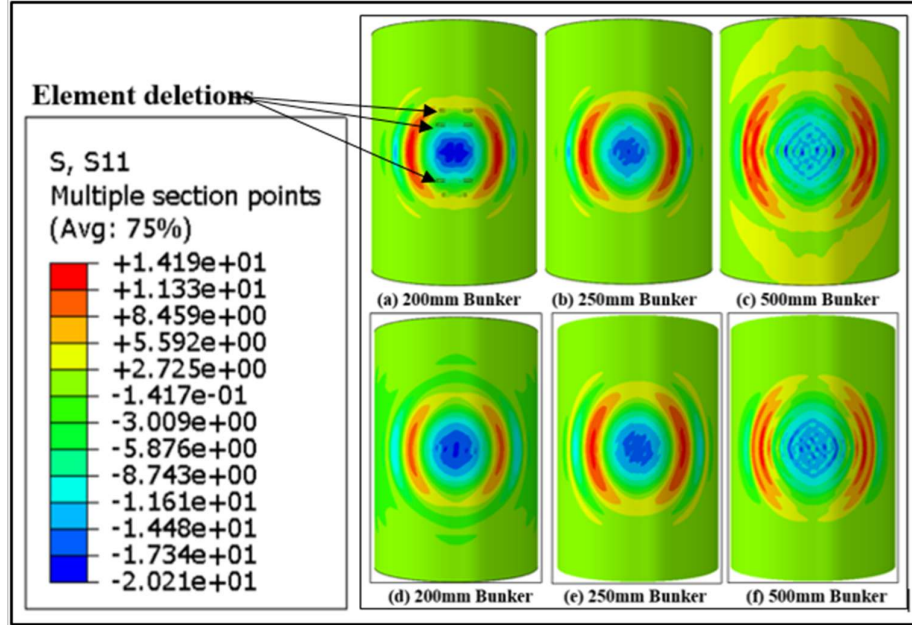


Figure 4.6: Principal stress distribution at distance 1 meter with 1 kg of TNT, (a) SCB-200-1, (b) SCB-250-1, (c) SCB-500-1 and (d) SPCB-200-1, (e) SPCB-250-1, (f) SPCB-500-1.

Figure 4.7 illustrates the principal stress distribution of bunkers subjected to a 5 kg TNT explosion at a distance of 1 meter. The SCB-200-5 bunker shows extensive cracking with numerous instances of element deletions and perforations. Conversely, the higher-strength polymer concrete in SPCB-200-5 effectively prevents such damage, demonstrating its enhanced blast resistance with no visible cracking. Thicker variants, such as SCB-250-5, exhibit reduced cracking compared to SCB-200-5, though there are still notable cracks in the center of the bunker and some element deletions, possibly due to the high blast load and damage to the CFRP skins. The SCB-500-5 bunker, positioned 1 meter away, shows element deletions and a circular crack line, which is less extensive than those in SCB-200-5 and SCB-250-5. Furthermore, polymer concrete bunkers, including SPCB-200-5, SPCB-250-5, and

SPCB-500-5, show no signs of cracking or damage at this proximity, underscoring their superior ability to endure the blast due to the exceptional strength of polymer concrete.

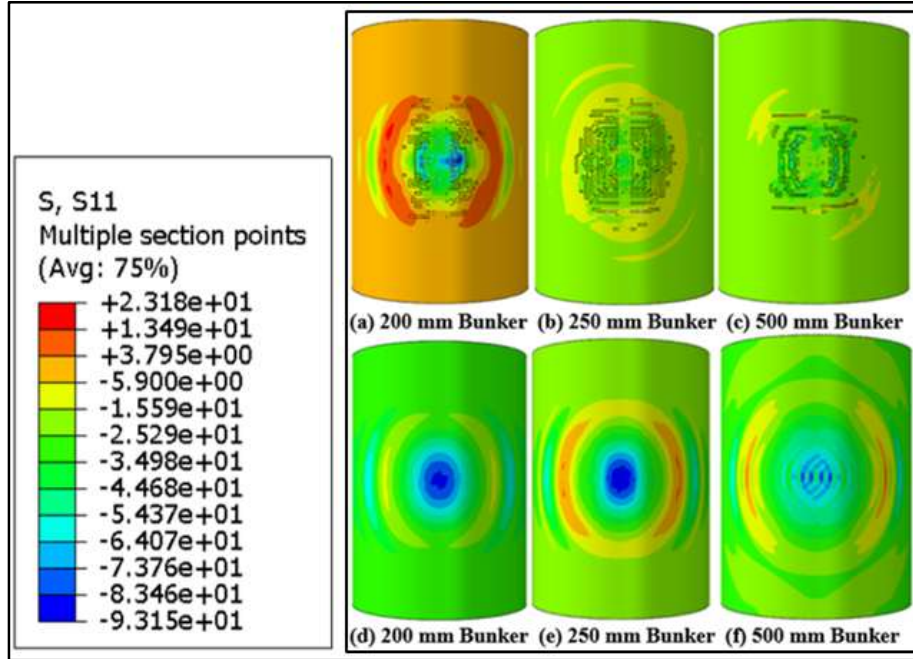


Figure 4.7: Principal stress distribution at distance 1 meter with 5 kg of TNT, (a) SCB-200-5, (b) SCB-250-5, (c) SCB-500-5 and (d) SPCB-200-5, (e) SPCB-250-5, (f) SPCB-500-5.

Figure 4.8 illustrates the principal stress distribution of bunkers subjected to a 10 kg TNT explosion at a distance of 1 meter. The SCB-200-10 bunker shows extensive cracking and multiple instances of element deletions and perforations. In contrast, the higher-strength polymer concrete in SPCB-200-10 effectively prevents such damage, demonstrating its enhanced blast resistance with no visible cracking. The 10 kg TNT explosion, significantly more powerful than a 1 kg TNT explosion, generates a much larger blast wave, resulting in higher pressures, impulses, and strains on the structures. Despite the high levels of energy transferred by the blast wave, polymer concrete bunkers, including SPCB-200-10, SPCB-

250-10, and SPCB-500-10, show no signs of cracking or damage at this proximity, underscoring their superior ability to endure the blast due to the exceptional strength of polymer concrete. Conversely, the SCB-200-10 bunker faces 15.2 m² of perforation, the SCB-250-10 bunker faces 11.1 m² of perforation, and the SCB-500-10 bunker faces 7.5 m² of perforation. These results highlight the insufficiency of standard concrete bunkers to withstand the high levels of energy from the blast wave, whereas polymer concrete bunkers exhibit superior blast resistance.

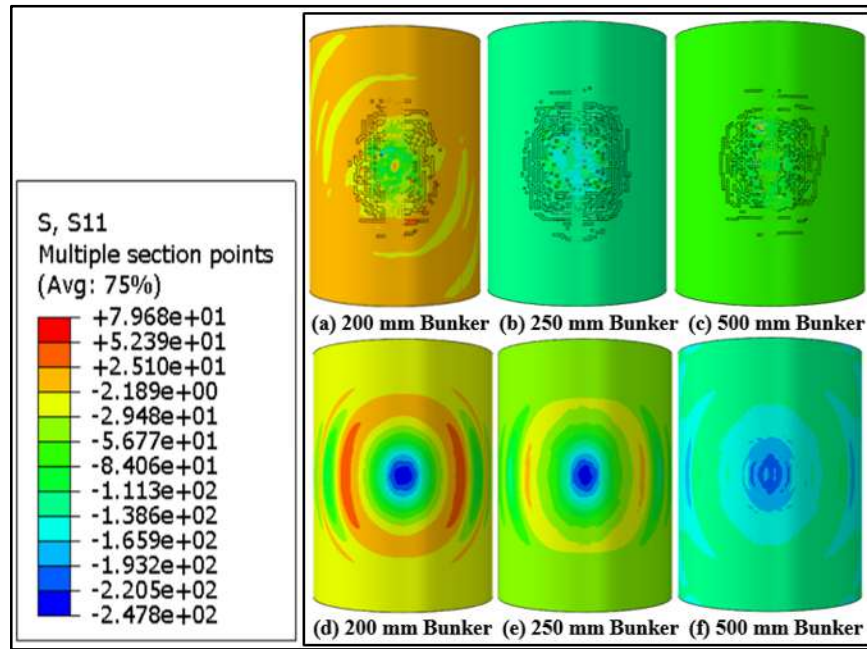


Figure 4.8: Principal stress distribution at distance 1 meter with 10 kg of TNT, (a) SCB-200-10, (b) SCB-250-10, (c) SCB-500-10 and (d) SPCB-200-10, (e) SPCB-250-10, (f) SPCB-500-10.

To seek more significant impact, Figure 4.9 presents the principal stress distribution of bunkers subjected to a 25 kg TNT explosion at a 1 m distance. The SCB-200-25 exhibits the greatest stress levels compared to other thicknesses in comparison, and it encounters element removals covering 18.1 m². Using the ellipse method, the damage area 18.1 m², by

fitting an ellipse over the boundary of failed elements (element removal) and applying the formula $A = \pi ab$, where A represents the estimated damage area in square metres (m²), is calculated. The constant π , approximately equal to 3.1416, is the mathematical ratio of a circle's circumference to its diameter and is used here due to the elliptical shape assumption. The term a refers to the semi-major axis, which is the longest radius from the centre of the damaged area, while b denotes the semi-minor axis, the shortest radius from the same centre. This method provides a simplified yet effective approach to approximating irregular blast damage by geometrically enclosing it within an ellipse. The maximum principal stress distribution recorded in the SCB-200-25 bunker is 486 MPa, while, in comparison, the SCB-200-1 bunker experiences a significantly lower maximum principal stress of 91.8 MPa. Conversely, the higher-strength polymer concrete in SPCB-200-25 prevents element deletions, highlighting its enhanced blast resistance. Thicker SCB-250-25 and SCB-500-25 variants, positioned 1 m away, sustain noticeable damage (16.8 m² and 13.05 m², respectively), indicating that the blast load surpasses the structures capacity. This underscores the significantly higher potency of a 25 kg TNT explosion, producing a blast wave with greater pressure, impulse, and strain on the buildings compared to a 1 kg TNT explosion. Polymer concrete bunkers with SPCB-200-25, SPCB-250-25, and SPCB-500-25 exhibit no cracking or damage at a 1 m distance from a 25 kg TNT explosion, emphasizing their capacity to withstand the blast due to the superior strength of polymer concrete, which is considered a safer material compared to normal concrete.

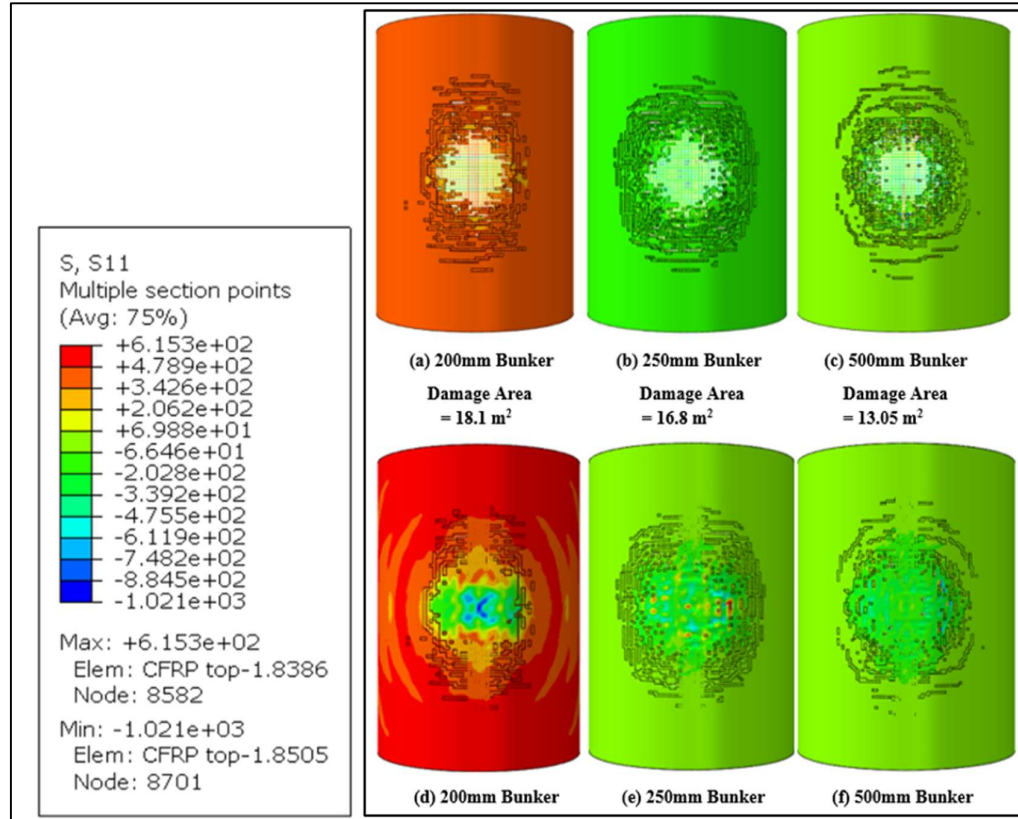


Figure 4.9: Principal stress distribution at distance 1 meter with 25 kg of TNT, (a) SCB-200-25, (b) SCB-250-25, (c) SCB-500-25 and (d) SPCB-200-25, (e) SPCB-250-25, (f) SPCB-500-25.

In summary, while SPCB-200-1 demonstrates superior resistance to TNT explosions, the stress distribution analysis reveals that SCB-200-1 is significantly more vulnerable. The effectiveness of polymer concrete is further evidenced by the absence of damage in thicker SCB specimens such as SCB-250-1 and SCB-500-1, as well as the complete lack of cracking in all SPCB variants. Notably, the enhanced blast resistance of SPCB-200-25, compared to the high stress levels and evident damage observed in SCB-200-25, reinforces the structural safety and reliability of polymer concrete under extreme loading conditions.

4.5 Damage pattern on SPCB

Figure 4.10 provides a detailed visualization of the tensile damage (DamageT) observed in sandwich polymer bunkers when exposed to a 1 kg TNT blast at a distance of 0.1 meter, viewed from the top. Among the thicknesses represented are 200 mm, 250 mm, 300 mm, and 500 mm.

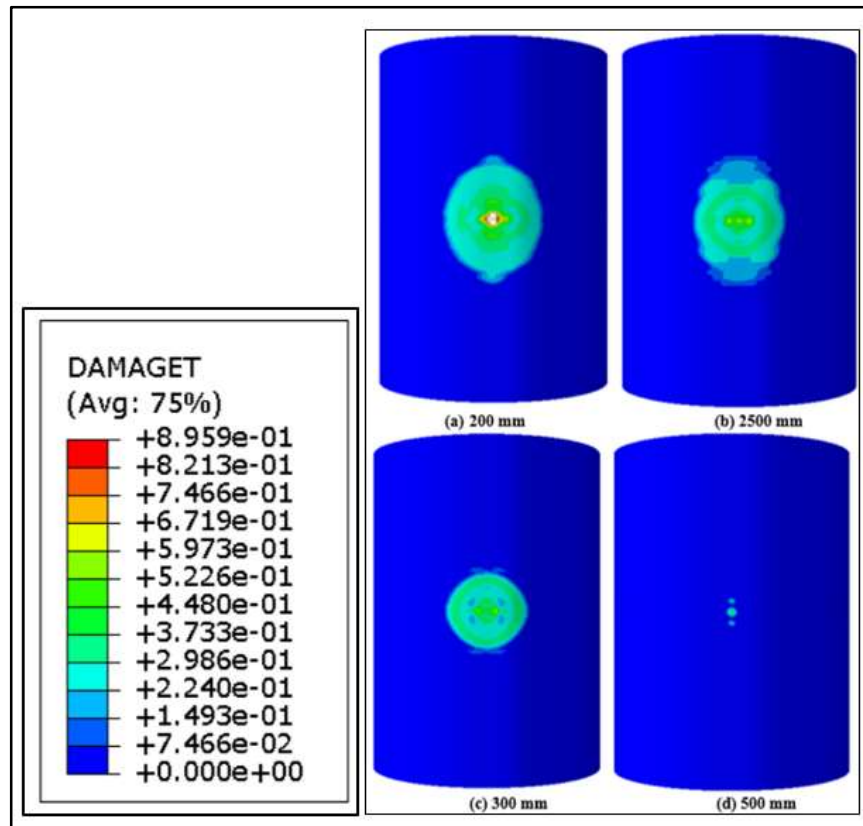


Figure 4.10: Tensile damage (DamageT) of SPCB under 1 kg TNT at 0.1 m blast distance.

Figure 4.10 reveals that the majority of the structures did not experience significant material damage changes as a result of the blast, with the exception of Figure 4.10(a), which sustained minor damage due to its thin core thickness and close proximity to the explosion. This limited damage is primarily due to the relatively low blast pressure produced by a 1 kg

TNT explosion at close range. As a result, all thicknesses of the sandwich polymer concrete bunkers displayed a high level of resilience, successfully resisting the blast without any substantial damage. This finding highlights the effectiveness of polymer concrete in preserving structural integrity under low-intensity blast conditions.

Figure 4.11 provides a detailed visualization of the tensile damage (DamageT) experienced by sandwich polymer concrete bunkers (SPCB) when subjected to a 5 kg TNT blast at a distance of 0.1 meters, viewed from the top. Appendix A, Figures 1-4 offer detailed visual supplements to enhance understanding of the topics discussed in this section. Among the various core thicknesses investigated, 200 mm, 250 mm, 300 mm, and 500 mm the sandwich polymer concrete bunker (SPCB) with the 200 mm thickness exhibited the most extensive tensile damage, as illustrated in Figure 4.11(a), with a total breakage area of 3.2 m². In comparison, the SPCB with a 250 mm thickness, shown in Figure 4.11(b), exhibited slightly less damage at 3.01 m², demonstrating improved resistance. The 300 mm thick SPCB, depicted in Figure 4.11(c), sustained 1.98 m² of tensile damage, indicating further enhancement in blast resistance. Notably, the SPCB with a 500 mm thickness showed significant resilience, experiencing minimal damage despite the high-intensity blast, underscoring its superior structural integrity under such extreme conditions.

The tensile damage (DamageT) of SPCB under 10 kg and 25 kg TNT explosions at a distance of 0.1 meter reveals significant findings. For SCB bunkers of all thicknesses, the stress levels are extremely high, leading to severe damage that renders the structures incapable of withstanding the blast. The extent of damage is so substantial that further analysis cannot be conducted on these bunkers. The polymer concrete, despite its superior properties, fails to maintain structural integrity when subjected to such high explosive loads at close proximity. This underscores the need for further research and development of

materials and design strategies to enhance the blast resistance of bunkers against extreme explosive threats.

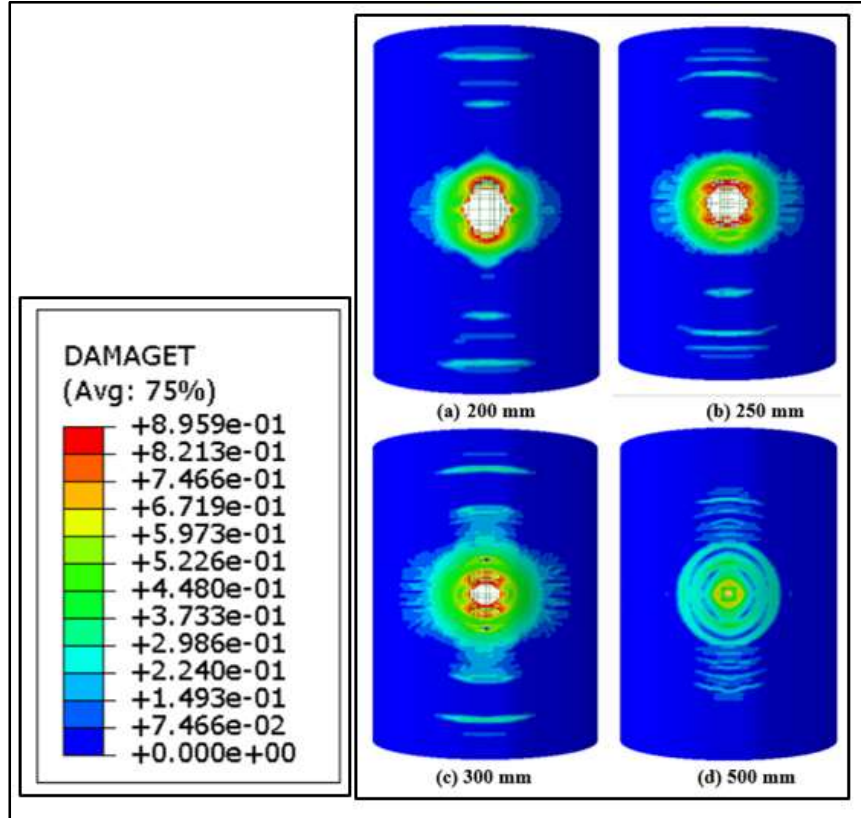


Figure 4.11: Tensile damage (DamageT) of SPCB under 5 kg TNT at 0.1 m blast distance.

The effects of a 1 kg TNT blast at a standoff distance of 0.25 m were examined for four different SPCB slab thicknesses: 200 mm, 250 mm, 300 mm, and 500 mm. Among these, the 200 mm thick SPCB exhibited the most severe damage, while the extent of damage progressively decreased with increasing slab thickness. This inverse relationship between slab thickness and damage intensity is illustrated in Appendix A, Figures 5-8.

The SPCB-200-5 bunker experienced a significant hole measuring 0.98 m² due to its thin core, whereas the SPCB-250-5 bunker sustained minimal damage, with only 0.22 m²

affected. In contrast, the SPCB-300-5 and SPCB-500-5 bunkers, positioned 0.25 meters away from a 5 kg TNT explosion, exhibited no visible damage, as shown in Appendix A, Figures 9-12, demonstrating exceptional blast resistance. This absence of damage underscores the superior strength and resilience of polymer concrete, proving its effectiveness in maintaining structural integrity under moderate-intensity blast conditions and affirming its suitability for applications requiring high durability against explosive threats.

The results presented in Figure 4.12 reveals that the SPCB-200-10 bunker, with its relatively thin slab, sustained a hole measuring 2.9 m², indicating significant damage. The SPCB-250-10 bunker also experienced damage, albeit to a lesser extent, with 2.52 m² affected. The SPCB-300-10 bunker showed some damage as well, with a hole size of 2.02 m². In contrast, the SPCB-500-10 bunker, positioned 0.25 meters away from a 10 kg TNT explosion, sustained only 0.81 m² of damage, demonstrating remarkable blast resistance. Despite the increased explosive force, the thicker slabs, particularly in the SPCB-500-10, effectively minimized damage, highlighting the superior protective capabilities of these polymer concrete structures under high-intensity blast conditions.

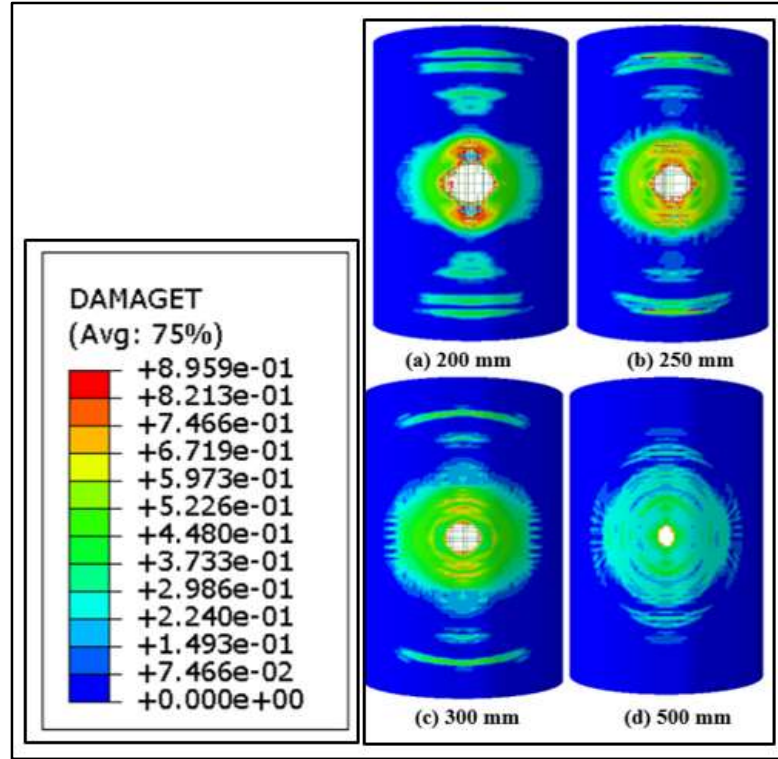


Figure 4.12: Tensile damage (DamageT) of SPCB under 10 kg TNT at 0.25 m blast distance.

Figure 4.13 depicts the tensile damage (DamageT) observed in SPCB subjected to the explosive force of a 25 kg TNT blast at a 0.25 m distance, presenting a Z-axis cross-section perspective. Among the represented thicknesses (200 mm, 250 mm, 300 mm, and 500 mm), Figure 4.13(a) highlights the substantial effect on the 200 mm thickness, showcasing a significant top surface damaged area of 27.99 m² and bottom surface damage of 13.24 m² compared to Figure 4.13(b), (c), and (d). Contrary to the lower TNT weight scenario depicted in Figure 4.13, the higher TNT weight observable damage across all bunkers. Specifically, bunker (b) SPCB-250-25 showcased a top surface damage area with cracking at 21.63 m² and 9.08 m² at the bottom surface. Bunker (c) SPCB-300-25 exhibited a higher top surface damage area at 13.55 m² with 6.96 m² at the bottom surface, while

bunker (d) SPCB-500-25 experienced less damage, with a top surface damage area of 3.88 m² and 3.78 m² at the bottom surface due to the increased TNT weight. Notably, despite the heightened destructive force, the SPCB-200-25 bunker demonstrated maximum damage with cracks, while the SPCB-500-25 bunker exhibited the least effect, aligning with expectations owing to its greater thickness and capacity for heightened resistance against explosive impact.

The tensile damage (DamageT) observed in the SPCB subjected to a 1 kg TNT blast at a distance of 0.5 m indicates that the SPCB-200-1 experienced a more substantial impact compared to the others, as detailed in Appendix A, Figures 13-16. Despite this, all the bunkers maintained structural integrity with no visible damage or cracking under the lower TNT weight. The SPCB-500-1 mm model showed minimal to negligible impact, demonstrating its superior resilience against the blast due to its greater thickness, effectively withstanding the explosive force with little to no discernible effect.

The tensile damage (DamageT) analysis of sandwich polymer concrete bunkers (SPCB) subjected to a 5 kg TNT explosion at a standoff distance of 0.5 meters, observed from the top view, reveals no visible signs of damage or cracking across all slab thicknesses investigated. This finding indicates that the SPCB configurations, regardless of thickness, effectively resisted the blast impact under the specified loading condition. As a result, the sandwich polymer bunkers effectively withstand the blast without compromising their overall stability, demonstrating their robustness under these specific conditions as detailed in Appendix A, Figures 17-20.

The tensile damage (DamageT) analysis of sandwich polymer concrete bunkers (SPCB) subjected to a 10 kg TNT explosion at a standoff distance of 0.5 meters, observed from the top view, indicates no visible damage or cracking across all slab thicknesses.

However, the stress levels generated under this loading condition are significantly higher compared to those observed under 1 kg and 5 kg TNT blasts. As illustrated in Appendix A, Figures 21-24, the maximum stress is concentrated at the centre of the bottom surface of the bunker. This finding underscores the increased internal stress despite the absence of surface damage, thereby demonstrating the structural robustness and blast resistance of SPCBs under higher explosive loads.

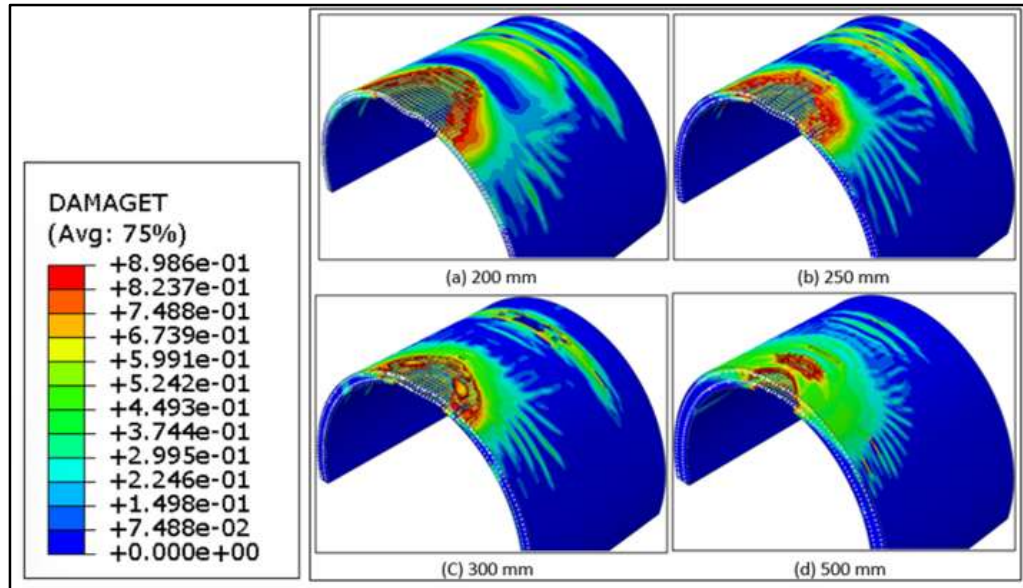


Figure 4.13: Tensile damage (DamageT) of SPCB under 25 kg TNT at 0.25 m blast distance in the Z-axis cross-section.

The tensile damage (DamageT) observed in SPCB when exposed to the impact of a 25 kg TNT blast at a distance of 0.5 m. Among the represented thicknesses (200 mm, 250 mm, 300 mm, and 500 mm), Figure 4.14 (a) SPCB-200-25 highlights the notable impact on the 200 mm thickness, displaying a considerable top surface damaged area of 7.58 m² and bottom surface damage of 3.49 m² when compared to Figure 4.14 (b) SPCB-250-25, (c) SPCB-300-25, and (d) SPCB-500-25.

Figure 4.14 illustrates the tensile damage (DamageT) observed in sandwich polymer bunkers when exposed to the impact of a 25 kg TNT blast at a distance of 0.5 m, presenting blast distance in *X*- and *Z*-axes cross-section perspective, specifically in Figure 4.14 (a). Among the represented thicknesses (200 mm, 250 mm, 300 mm, and 500 mm), Figures 4.14 and 4.15 (a) highlights the notable impact on the 200 mm thickness, displaying a considerable top surface damaged area of 7.58 m² and bottom surface damage of 3.49 m² when compared to Figures 4.15 (b), (c), and (d).

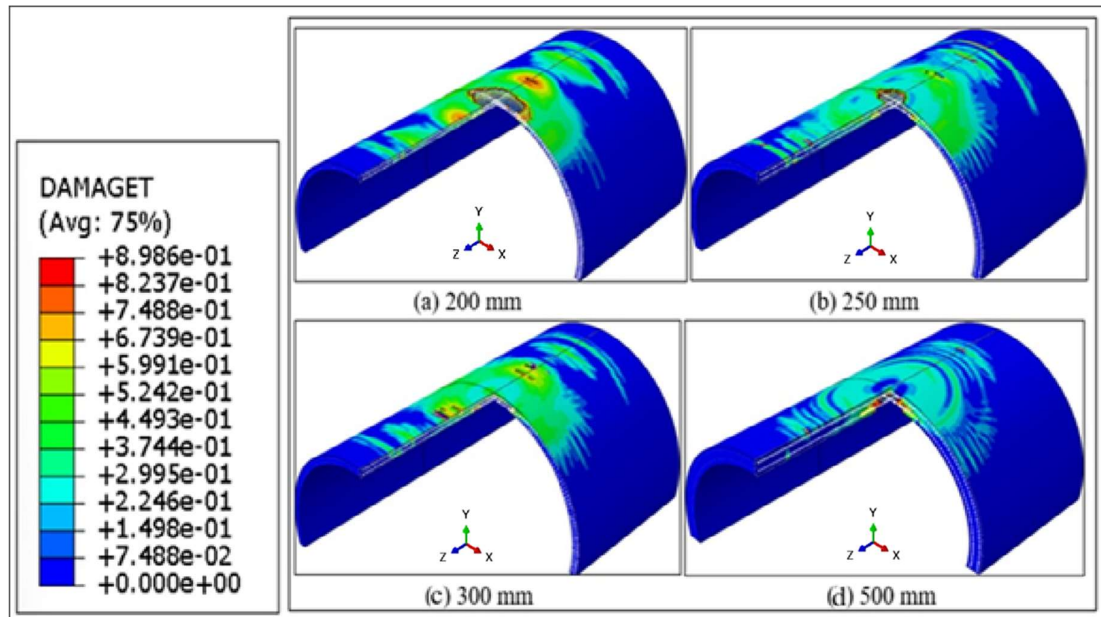


Figure 4.14: Tensile damage (DamageT) of sandwich polymer bunkers under 25 kg TNT at 0.5 m blast distance in *X*- and *Z*-axes cross-section.

Inspecting the damage condition, Figure 4.15, bunker (b) SPCB-250-25 shows a top surface damage area with cracking at 2.33 m² and 2.19 m² at the bottom surface. Bunker (c) SPCB-300-25 experiences no damage on the top surface but displays a few places of material removals with minor cracking, with the bottom surface encountering 3.90 m² of damage. Similarly, bunker (d) SPCB-500-25 showcases no damage on the top surface but presents

minimal material deletion and slight cracking, with 1.43 m² of damage on the bottom surface due to the increased TNT weight. To summarise, the SPCB-200-25 mm (model SPCB-200-25) mm thickness demonstrates maximum damage with cracks, while the SPCB-500-25 mm (model SPCB-500-25) thickness exhibits the least effect, aligning with expectations based on its substantial thickness and capability to withstand higher explosive forces. These images provide clearer views of the structural integrity and damage progression of reinforced concrete slabs under various blast conditions.

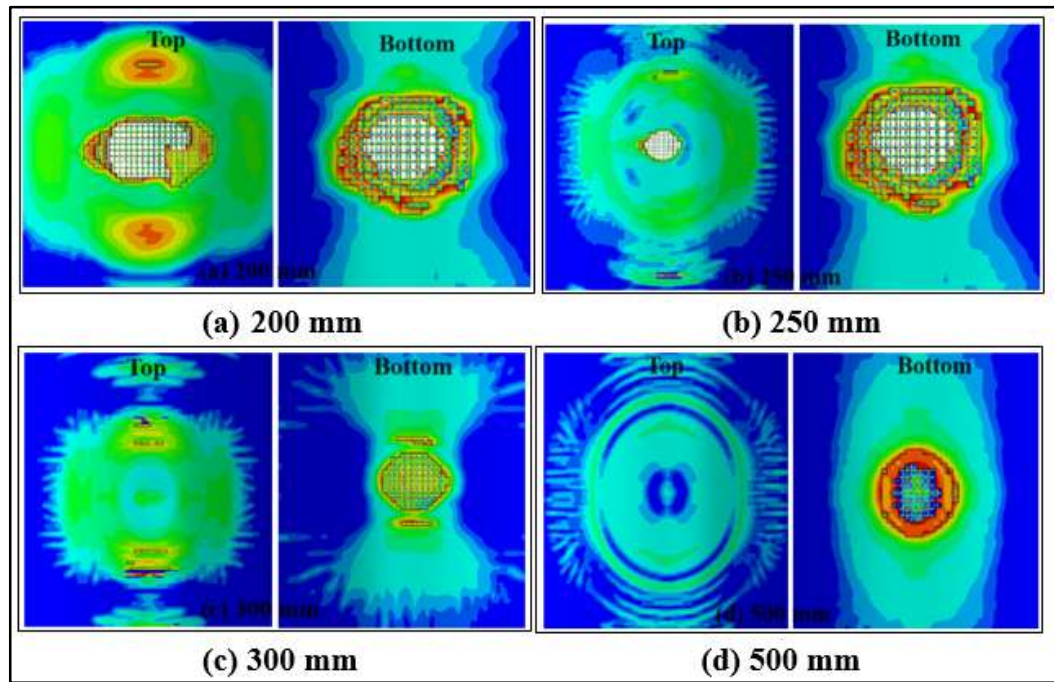


Figure 4.15: Tensile damage (DamageT) of SPCB under 25 kg TNT at 0.5 m blast distance.

The tensile damage (DamageT) observed in sandwich polymer bunkers subjected to a 1 kg TNT blast at a distance of 1 m, across the depicted thicknesses (200 mm, 250 mm, 300 mm, and 500 mm), reveals that the 200 mm thickness, as well as the figures shown in Appendix A, Figures 25-28, do not exhibit any observable effects or damage. The findings

from reveal that all represented bunkers maintain their structural integrity without experiencing any visible damage or cracking. This lack of damage can be attributed to the considerably lower TNT weight coupled with the increased distance, suggesting that the blast effect diminishes significantly as the distance from the explosion increases, confirming the bunkers resilience against the lower explosive forces due to the substantial distance factor.

The tensile damage (DamageT) observed in sandwich polymer bunkers subjected to a 5 kg TNT blast at a distance of 1 meter, as shown from a top-view perspective in Appendix 29-32, reveals that the 200 mm thickness experiences higher stress concentrations at the center of the bunker compared to other thicknesses. In contrast, the thicker variations do not exhibit any observable effects or damage, with gradually lower stress levels than the 200 mm thickness. This indicates that while the 200 mm thickness faces more stress, the thicker variations are more effective at dissipating the blast load, thereby reducing overall stress and preventing damage.

The tensile damage (DamageT) observed in sandwich polymer bunkers subjected to a 10 kg TNT blast at a distance of 1 meter, as shown from a top-view perspective in Appendix A, Figures 33-36, indicates that the 200 mm thickness experiences the maximum stress at the center of the bunker, reaching 49.7 MPa. In contrast, the thicker variations do not exhibit any observable effects or damage, with stress levels gradually decreasing compared to the 200 mm thickness. Notably, the 500 mm bunker proves to be the safest, showing minimal impact. This suggests that while the 200 mm thickness faces higher stress concentrations, the thicker variations are more effective at dissipating the blast load, thereby reducing overall stress and preventing damage.

The tensile damage (DamageT) recorded in SPCB following exposure to a 25 kg TNT blast at a distance of 1 m, focusing specifically on Figure 4.16 (a) SPCB-200-25 while comparing it with Figure 4.16 (SPCB-250-25, SPCB-300-25, and SPCB-500-25). Notably, the SPCB-200-1 mm thickness showcased a noteworthy response, with the top surface demonstrating no damage and no crack, yet registering a bottom surface damage area of 3.25 m², inclusive of 4.86 m² of hole and cracks.

Figure 4.16 exhibits the tensile damage (DamageT) recorded in sandwich polymer bunkers following exposure to a 25 kg TNT blast at a distance of 1 m, focusing specifically on Figure 4.16 and 4.17 (a) while comparing it with Figures 4.16 and 4.17 (b,c,d). Notably, the 200 mm thickness showcased a noteworthy response, with the top surface demonstrating no damage and no crack, yet registering a bottom surface damage area of 3.25 m², inclusive of 4.86 m² of whole and cracks with materials deletion, compared to the other representations.

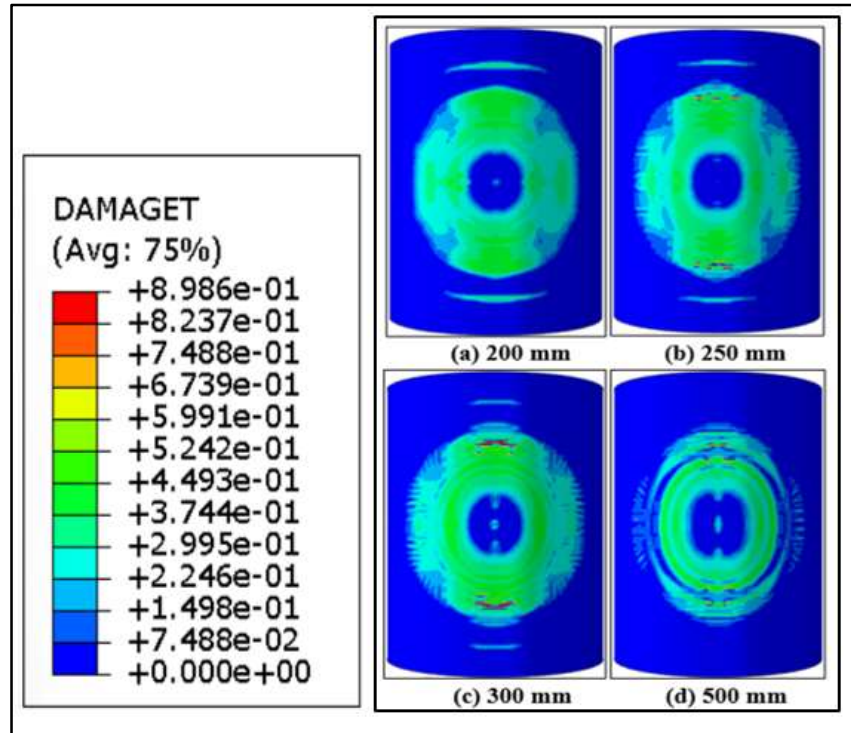


Figure 4.16: Tensile damage (Damage_T) of sandwich polymer bunkers under 25 kg TNT at 1 m blast distance on top view.

From the bottom perspective in Figures 4.17, Bunker (b) SPCB-250-25 displays no damage on the top surface but features 3.11 m² of the bottom surface exposed reinforcement and 3.65 m² of perforation hole. Bunker (c) SPCB-300-25 exhibits no damage on the top surface, including no materials deletion, while the bottom surface shows 2.11 m² of exposed reinforcement along with 3.54 m² of materials deletion. Bunker (d) SPCB-500-25 presents no damage on the top surface with no materials deletion, yet encounters 0.1 m² of damage in the exposed reinforcement area and 2.22 m² of crack area due to the higher TNT weight. Again, the SPCB-200-25 mm thickness sustains maximum damage with cracks, while the SPCB-500-25 mm thickness shows minimal effect, consistent with expectations stemming from the greater thickness, which enhances its resilience against higher explosive forces.

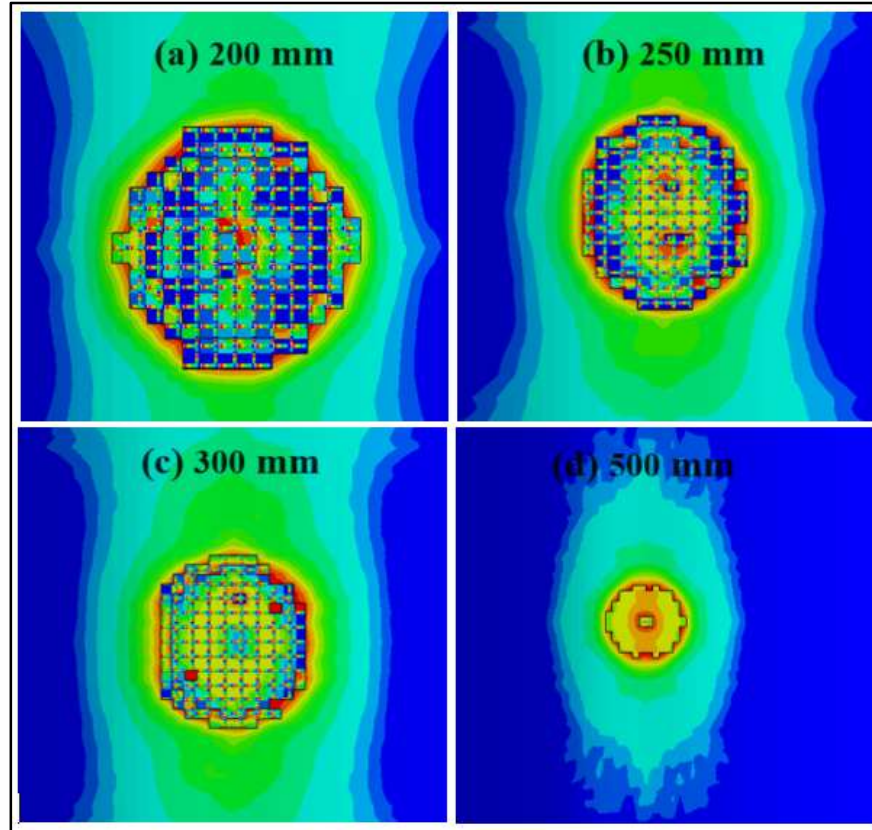


Figure 4.17: Tensile damage (DamageT) of SPCB under 25 kg TNT at 1 m blast distance (bottom view).

Figure 4.18 illustrates peak overpressure versus standoff distance for TNT charges (1 kg, 5 kg, 10 kg, and 25 kg) showing that overpressure increases significantly at shorter distances and with higher charge weights. Calculated using empirical blast wave equations, the results highlight a nonlinear relationship where even small changes in distance or TNT mass drastically affect pressure. This visualisation supports the analysis in Section 4.5 by demonstrating how increased charge and proximity amplify structural damage. The graph reinforces the need for effective blast-resistant design, especially for structures exposed to high-energy explosive threats.

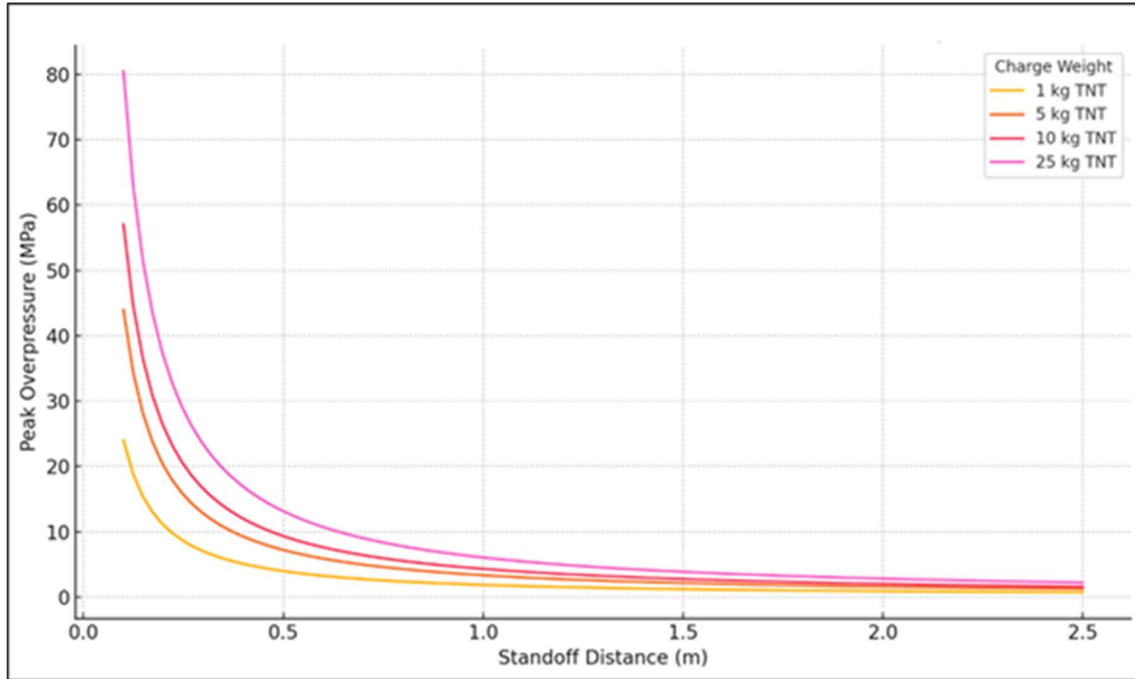


Figure 4.18: Peak overpressure versus standoff distance with tensile damage (DamageT).

4.6 Damage areas comparison of SCB against SPCB

The section 4.6 presents a detailed discussion of the extensive damage and perforations observed in various cases, primarily due to the focus on exploring closer distance blast scenarios. In these scenarios, the SCB bunkers could not produce results at close distances with high TNT mass due to excessive damage. This section presents a comparative analysis of sandwich polymer concrete bunkers (SPCB) and conventional sandwich concrete bunkers (SCB) subjected to blast loads at varying standoff distances of 0.1 m, 1 m, 2 m, and 2.5 m. Across all these distances, SPCB bunkers within the non-perforated range consistently maintained their structural integrity. As illustrated in Figure 4.19, the SCB-200-1 model exposed to a 0.1-meter standoff distance exhibited a perforation area of 1.14 m² on the top surface. Under identical conditions, the SCB with a 250 mm slab thickness demonstrated a slightly reduced perforation area of 1.05 m², while the 500 mm

thick SCB showed a further reduction in damage, with a perforation area of only 0.9 m². In contrast, the SPCB with a 200 mm thickness subjected to the same blast conditions sustained only a minor perforation of 0.28 m², with the remainder of the structure remaining intact. Furthermore, SPCB bunkers with greater core thicknesses specifically 250 mm, 300 mm, and 500 mm exhibited outstanding blast resistance, with no visible damage observed at all evaluated standoff distances. These findings highlight the superior performance of SPCB systems in mitigating blast-induced damage.

When subjected to a standard 1 kg TNT charge at a standoff distance of 1 meter, both the sandwich polymer concrete bunkers (SPCB) and the conventional sandwich concrete bunkers (SCB) demonstrated no visible signs of damage or perforation. This finding indicates that at this particular blast intensity and distance, both bunker types are capable of maintaining their structural integrity. The absence of damage can be attributed to the relatively low explosive mass in combination with the increased standoff distance, which significantly reduces the intensity of the blast wave upon impact.

The relationship between explosive mass and proximity plays a critical role in determining the extent of damage inflicted on a structure. As illustrated in Figure 4.19, an increase in explosive mass results in more intense energy release during detonation, producing higher peak overpressure and impulse. Conversely, decreasing the standoff distance between the explosion and the target intensifies the blast wave impact on the structure due to reduced dissipation, leading to greater risks of cracking, deformation, or perforation. Therefore, a smaller TNT mass detonated farther from the target delivers significantly lower energy to the structure's surface, thereby reducing the potential for structural failure. This interplay highlights the necessity of jointly considering explosive yield and standoff distance in evaluating the blast resistance of protective structures such as

SCBs and SPCBs. These findings are supported by Chiquito et al. (2023), who demonstrated that smaller scaled distances correlate with more extensive slab damage, underscoring the effect of both charge weight and proximity on structural integrity under blast loading.

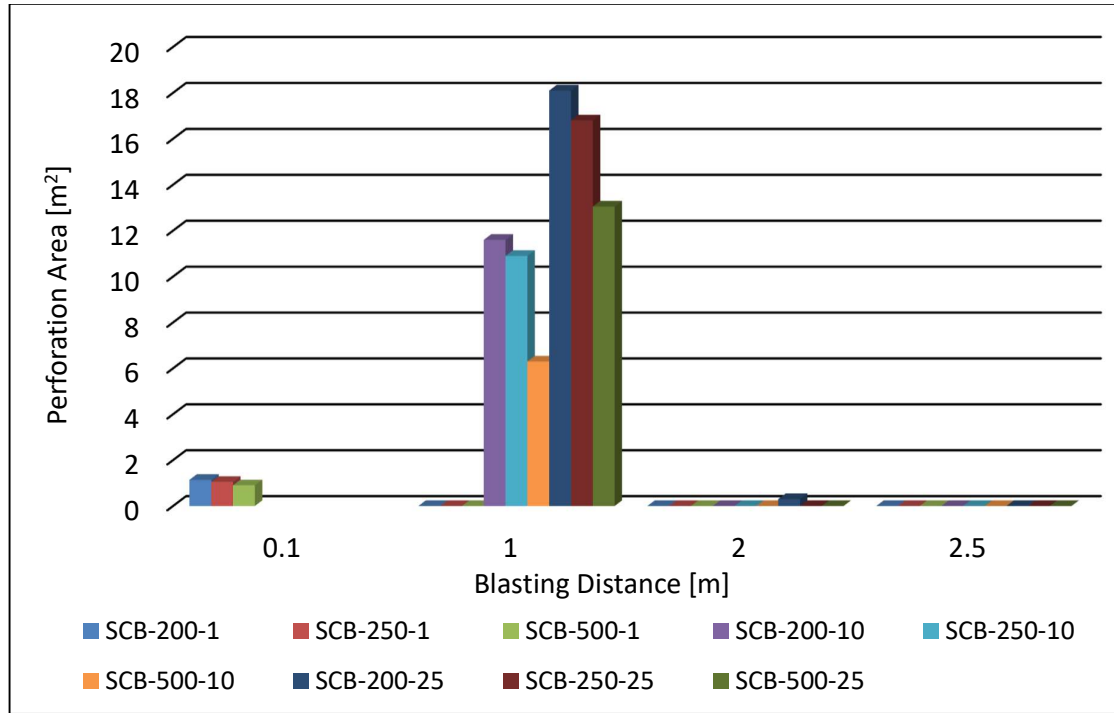


Figure 4.19: Perforation area comparison of SCB models.

Furthermore, the SCB bunker with a 200 mm thickness, exposed to a substantial 10 kg TNT mass at a 1 m distance, exhibits a notable 11.6 m² perforation hole on its top surface. Conversely, SCB-250-10 at the same distance displays a slightly reduced impact, resulting in a 10.9 m² perforation hole. SCB-500-10 at the same distance, on the other hand, shows a slightly reduced impact, resulting in a 6.30 m² perforation hole. In contrast, SPCB bunkers with 200, 250, and 500 mm thicknesses, under the extreme conditions of a 10 kg TNT mass and a 1 m distance, unveil a remarkable ability to withstand the forces without incurring any damage or hole formation. SCB-200-25 detonated at a 1 m distance exhibits a significant impact resulting in a sizable 18.1 m² perforation hole on its top surface. SCB-250-25 at a 1

m distance demonstrates slightly reduced damage, presenting a 16.8 m² damage hole on the top surface. Furthermore, SCB-500-25, under identical explosive conditions, displays a reduced impact with a 13.05 m² damage hole on the top surface. The observation that all SPCB remained undamaged under 25 kg and 10 kg TNT charges at a 1-meter standoff distance, and that only the thinnest SPCB (200 mm) exhibited damage under 1 kg TNT at a very close 0.1 m distance, can be explained by the combined influence of explosive energy dissipation and the structural properties of the SPCB system.

As illustrated in Figure 4.19, both the SCB and the SPCB exhibit notable blast resistance under various scenarios involving 1 kg and 10 kg TNT charges at a standoff distance of 1 meter. While only the SCB models are shown in the figure due to the absence of damage in the SPCB models, the results consistently indicate that neither bunker type experienced visible structural damage or perforation under these conditions. This absence of damage across all studied core thicknesses can be attributed to the relatively low explosive mass and the sufficient standoff distance, which together significantly reduce the peak overpressure and impulse imparted to the bunker surfaces. The findings highlight that the combination of lower TNT charge and increased blast distance plays a crucial role in maintaining the structural integrity of both SCB and SPCB bunkers. Notably, SCB bunkers exposed to 10 kg TNT and the 2 m blast distance showcase only minor surface cracks without any discernible damage or hole formation. Conversely, the SPCB bunkers, regardless of the TNT mass and the 2 m blast distance, consistently exhibit no visible damage or hole formation, highlighting their robustness and ability to withstand these conditions effectively. However, SCB-200-25 at a 2 m blast distance displays a minor 0.3 m² perforation on its top surface, indicating a slight breach in its integrity. In contrast, the SCB bunkers with 250 mm and 500 mm thicknesses under the same testing conditions show crack lines on their top

surfaces without substantial damage or hole formation. Meanwhile, the SPCB bunkers across various thicknesses and the extreme 25 kg TNT charge at the 2 m distance consistently disclose no observable damage or hole formation, highlighting their superior resistance and structural robustness compared to the SCB counterparts in these testing conditions.

At a substantial 2.5 m blast distance, both SCB and SPCB bunkers demonstrate remarkable resilience, showing no visible damage or hole formation. Specifically, in the case of SCB bunkers, under the extreme conditions of 10 and 25 kg TNT charges, those with 200 mm, 250 mm, and 500 mm thicknesses exhibit minor crack lines on their top surfaces, indicative of surface stress, but do not incur substantial damage or hole formation. Conversely, the SPCB bunkers all consistently exhibit no visible signs of damage or hole formation, showcasing their superior structural integrity and capacity to withstand these testing conditions effectively. These findings underscore the critical influence of both TNT mass and standoff distance in determining the blast resilience of protective structures. Specifically, an increase in explosive mass results in higher peak overpressure and impulse, thereby elevating the potential for structural damage. Conversely, a greater standoff distance allows more energy dissipation before the blast wave reaches the target, significantly reducing its destructive effect. The interplay between these two parameters directly impacts the severity of blast-induced damage. Notably, the SPCB configurations consistently demonstrate superior resistance compared to their SCB counterparts, owing to the enhanced energy absorption and stress distribution capabilities of the polymer concrete core and CFRP skin.

Here, the comparison elucidates the differences in damage between SCB and SPCB across diverse scenarios. Specifically, deformations in SPCB models consistently prove lower than those in SCB models across all cases. For instance, under a 25 kg TNT blast at a

standoff distance of 2.5 meters, the 200 mm thick conventional sandwich concrete bunker (SCB-200-25) exhibited a perforation area of 1.402 m². In contrast, the corresponding sandwich polymer concrete bunker (SPCB-200-25) sustained only minor damage, with a significantly smaller perforation area of 0.28 m². Between the two models, damage varies by 80.03%, with significant differences observed in perforation sizes. The observed variations underscore the effectiveness of polymer concrete with CFRP skin in enhancing specimen stiffness, thereby reducing deformations and resulting in smaller damage areas. Particularly, SPCB models with thin cores (200 mm) demonstrate the most substantial reduction in damage, indicating the success of polymer concrete with CFRP skin in mitigating major damage for thin core bunkers.

It is worthwhile to realize that other than 200 mm thickness, SPCBs show no visible perforation or severe damage. The results confirm that SPCB bunkers exhibit much greater strength and safety in comparison to SCB bunkers, emphasizing their better capacity to resist blasts.

This study outlines the comparison of damage between sandwich concrete bunkers (SCB) and sandwich polymer concrete bunkers (SPCB) across various scenarios. Notably, deformations in SPCB models consistently exhibit reduced magnitude of deformation responses compared to SCB models across all three scenarios.

4.7 Regressed prediction

Upon compiling the data obtained from all models analysed, a set of regression equations is formulated to describe the maximum principal stress, σ_s , in terms of the input variables of the core thickness (t), TNT mass (m), and standoff distance (d), which can be statistically expressed as:

$$\sigma_s = -159 - 1100d + 44.70m + 2.947t + 806 d^2 - 26.85 dm - 0.448 m^2 - 0.00422 t^2 \quad \text{Equation 4.1}$$

Equation (4.1) incorporates various factors denoted by d , m , and t representing specific parameters under examination. The p -values corresponding to d , d^2 , m , and dm are all found to be < 0.00 , signifying their substantial significance as contributors to the stress equation. Moreover, the m^2 term, although resulting in a p -value of 0.026, is statistically significant, further supporting its influence on the principal stress. Similarly, while the t term yields a p -value of 0.0933, indicating slightly less significance, it is also considered statistically significant within this context.

The black line in Figure 4.20 (a) and (b) represents the line of perfect agreement between the predicted and simulated maximum von Mises stress values. It indicates where predictions would exactly match the simulation results. Data points close to this line show that the regression model accurately predicts stress values, confirming the model's reliability in estimating the blast response of SPCB structures.

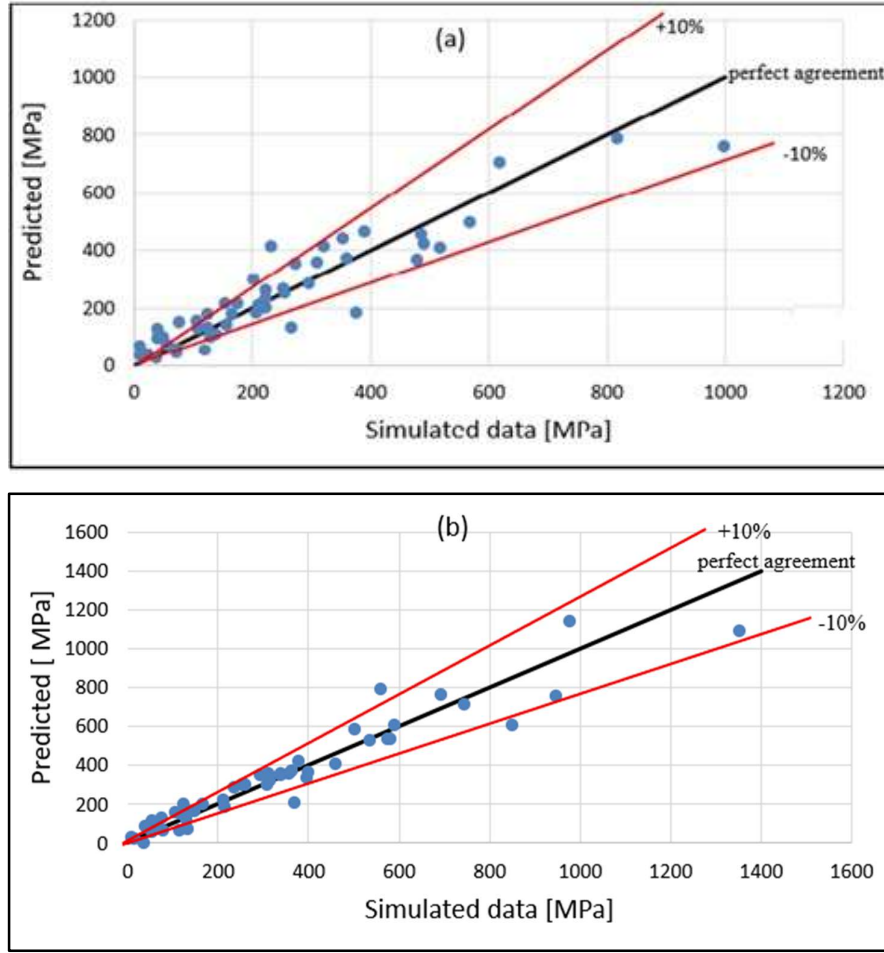


Figure 4.20: Comparison of predicted maximum (a) σ_s and (b) σ_{Mises} vs simulation data.

Furthermore, the mathematical generalization for the von Mises stress (σ_{Mises}) is given by the equation:

$$\sigma_{Mises} = 179 - 1460d + 78.38m + 1.34t + 898d^2 - 37.01dm + 0.669dt - 0.602m^2 - 0.0479mt - 0.00243t^2 \quad \text{Equation 4.2}$$

Equation (4.2) encapsulates multiple variables denoted by d , m , and t , representing distinct parameters considered in the analysis. The p -values corresponding to d , d^2 , dt , m , mt ,

and t are all found to be < 0.00 , indicating their substantial significance as contributors to the von Mises stress equation. Furthermore, although the m^2 term yields a p -value of 0.01, and the t^2 term results in a p -value of 0.109, these factors are deemed statistically significant. Similarly, the mt term, with a p -value of 0.044, also holds statistical significance within this context. Figure 4.20 incorporates $\pm 10\%$ error bands around the line of perfect agreement to assess the predictive accuracy of the regression model. The majority of data points lie within these bounds, indicating that the predicted maximum von Mises stress values deviate by less than 10% from the corresponding simulated results. This close alignment confirms the reliability and robustness of the regression model in accurately predicting the structural response of the bunker system under blast loading conditions.

Figures 4.20 (a) and (b) present the predictability of Equations (4.1) and (4.2) in comparison to simulated data, revealing substantial statistical metrics. Equation (4.1) yields an R^2 value of 87.40%, an adjusted R^2 value of 85.52%, and a predictive R^2 value of 81.49%, depicting robust predictability for σ_s . Similarly, Equation (4.2) demonstrates an R^2 value of 91.30%, an adjusted R^2 value of 89.78%, and a predictive R^2 value of 86.29%, signifying strong predictive capabilities for σ_{Mises} . The results show that regression models explain response variable variability using input variables (d, m , and t). Regression equation findings may guide future application design and optimization. It is vital to note that data dependability and accuracy determine forecast accuracy. The regression equations should be validated by experimental observations in future research to provide a more robust and reliable implementation of these models in actual contexts.

The maximum principal and von Mises stresses were extracted at 1.8 ms during the simulation, as this specific time step corresponds to the peak structural response under blast loading. Selecting this time frame ensured the accurate capture of the maximum stress

distribution induced by the explosive impact, thereby providing a reliable representation of the critical stress state within the structure. Maximum principal and von Mises stresses were predicted to evaluate the structural performance of bunkers under blast loads. Principal stress is critical for identifying potential cracking in concrete and CFRP, which are weak in tension, while von Mises stress helps assess yielding or plastic deformation in ductile materials such as steel and even PC. Together, these stress measures provide a comprehensive understanding of both brittle and ductile failure mechanisms, enabling the design of more resilient and blast-resistant bunker structures. Overprediction of stress values is generally considered safe in engineering, as it leads to conservative designs that reduce the risk of structural failure. It provides a safety margin by assuming worst-case scenarios. However, excessive overprediction can result in higher costs, inefficient designs, and unnecessary material use. Therefore, while safe, overprediction should be kept within an acceptable range to ensure both safety and design efficiency.

4.8 Summary

The comparison between conventional sandwich concrete bunkers (SCB) and sandwich polymer concrete bunkers (SPCB) reveals that SPCB bunkers offer significantly better blast resistance. Under proximity explosions with a 1 kg TNT mass, SPCB bunkers demonstrate lower displacements than SCB bunkers. As the TNT mass increases and the distance decreases, SCB bunkers experience a dramatic rise in displacement, while SPCB bunkers maintain more controlled displacement, particularly in thicker models. Even under high TNT masses at a 0.5 m distance, SPCB bunkers show relatively low displacement levels, underscoring their superior blast resistance. Additionally, the study of principal stress distribution indicates that SPCB models effectively resist damage, showing no visible cracking or element deletions, even under extreme conditions. In contrast, SCB models

suffer significant stress-related damage, especially under higher blast loads. This highlights the enhanced safety and structural integrity of SPCB bunkers, particularly in high-stress scenarios such as a 25 kg TNT explosion, where SPCB-200-25 remains undamaged, while SCB-200-25 experiences substantial damage.

The comparison between sandwich concrete bunkers (SCB) and sandwich polymer concrete bunkers (SPCB) demonstrates significant differences in their resilience under explosive scenarios. SPCB models consistently show lower deformations and smaller perforation areas than SCB models. For instance, a 200 mm SCB bunker exposed to a 1 kg TNT explosion at a 0.1-meter stand-off distance exhibits a 1.14 m² perforation, while the SPCB counterpart shows only 0.28 m², representing a 75.44% reduction in damage. This superior performance of SPCB is attributed to the polymer concrete with CFRP skin, which enhances stiffness, reduces deformation, and mitigates damage, particularly in thinner core bunkers. Even under extreme conditions, such as a 25 kg TNT explosion at close range, SPCB bunkers show no visible damage, whereas SCB bunkers suffer 18.1 m² damage. The findings underscore the superior strength and blast resistance of SPCB bunkers, emphasizing the advantages of polymer concrete in improving structural integrity and safety.

Further analysis led to the development of regression equations for predicting principal stress (σ_s) and von Mises stress (σ_{Mises}) based on core thickness (t), TNT mass (m), and standoff distance (d). The equations reveal that variables such as d , d^2 , m , and dm are highly significant, while m^2 and t also contribute, albeit to a lesser extent. These models demonstrate strong predictive capabilities, with R^2 values of 87.40% for σ_s and 91.30% for σ_{Mises} . However, the accuracy of these predictions depends on reliable data, and future research should validate these models experimentally to ensure their real-world applicability.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study investigates blast responses of sandwich polymer concrete bunkers (SPCBs), with carbon fibre-reinforced polymer (CFRP) skins and a core of reinforced tin slag polymer concrete, using ABAQUS/CAE numerical simulation approach. It compares the blast performance of SPCBs with conventional reinforced concrete bunkers (SCBs) under various TNT loads, standoff distances, and core thicknesses.

Firstly, the study successfully simulated the blast responses of SPCBs using ABAQUS/CAE 6.14 and the CONWEP function. The simulation results confirmed that increasing the TNT charge (from 1 kg to 25 kg) and decreasing the standoff distance (from 2.5 m to 0.1 m) led to increased deflection, von Mises stress, and damage. Notably, SPCBs with 200 mm and 500 mm core thicknesses withstood heavy blast loads without failure, indicating the effectiveness of CFRP-skinned tin slag polymer concrete in resisting blasts.

Secondly, when comparing the performance of SPCBs with SCBs, significant differences were observed. A 200 mm thick SPCB experienced only 0.28 m² of perforation, in contrast to 1.14 m² in the corresponding SCB, amounting to a 75.44% reduction in damage. Furthermore, under a 25 kg TNT load at a 1-meter standoff, a 500 mm thick SCB sustained 34.8% perforation damage, while the 500 mm SPCB showed no damage at all. This clearly demonstrates that SPCBs exhibit superior blast resistance, with lower principal and von Mises stresses and less deformation than SCBs under identical blast conditions.

New generalized prediction equations for maximum principal stress and von Mises stress were successfully formulated using the response surface method. These equations, based on core thickness, TNT mass, and standoff distance, demonstrated strong predictability (R^2 values of 87.40% and 91.30%) and provided valuable insights into stress behaviour under various blast conditions, with recommendations for further experimental validation.

The study successfully achieved all research objectives. SPCBs and SCBs were accurately modelled using ABAQUS/CAE, enabling realistic blast simulations. SPCBs, especially with thicknesses ≥ 250 mm, showed superior blast resistance compared to SCBs, even under extreme conditions. Regression models developed using the response surface method (RSM) accurately predicted maximum stress responses, with most results within $\pm 10\%$ of simulated values. Overall, the study confirms SPCBs enhanced performance and the reliability of the predictive models for assessing structural behaviour under blast loads.

5.2 Recommendations

To extend the present work and advance the development of blast-resistant bunkers, the following research directions are proposed:

- i. Examine the effectiveness of thicker or multilayer CFRP laminates in mitigating blast effects (Kam et al., 2014; Kueh et al., 2011; Soufeiani et al., 2017).
- ii. Investigate concrete mixes incorporating steel fibre, polypropylene fibre, or textile composites to improve ductility and energy absorption (Nikmatin et al., 2015; 2017; Kueh, 2012; 2013; 2014; 2023).
- iii. Evaluate steel-fibre-reinforced concrete, ultra-high-performance concrete (UHPC), reactive powder concrete (RPC), and hybrid FRP (HFRP) systems for superior blast resistance (Marini et al., 2024).

- iv. Explore geo-polymer and ultra-high-performance polymer concretes (compressive strength ≥ 100 MPa) for their potential to enhance strength and durability under extreme loads (Marini et al., 2024).
- v. Assess sacrificial layers, geotextile-based barriers, polymeric coatings, and energy-absorbing foam inserts as supplemental shock-mitigation measures.
- vi. Extend modelling beyond ABAQUS by employing explicit dynamic solvers, non-linear finite-element formulations, and multi-scale approaches to capture complex material interactions with higher fidelity.
- vii. Apply machine-learning and AI techniques to optimise material selection, predict failure modes, and uncover latent patterns in large blast-response datasets, thereby improving modelling efficiency and accuracy (Tang et al., 2022; Kueh, A. B. H. 2021).
- viii. Conduct full-scale or scaled blast tests to validate the regression models and simulation outcomes reported herein, ensuring reliability for real-world implementation.
- ix. Adopt integrated design strategies that consider bunker geometry, foundation enhancement, and multi-layered protection systems to achieve comprehensive blast resilience.

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APPENDICES

Appendix A: DamageT contour plot

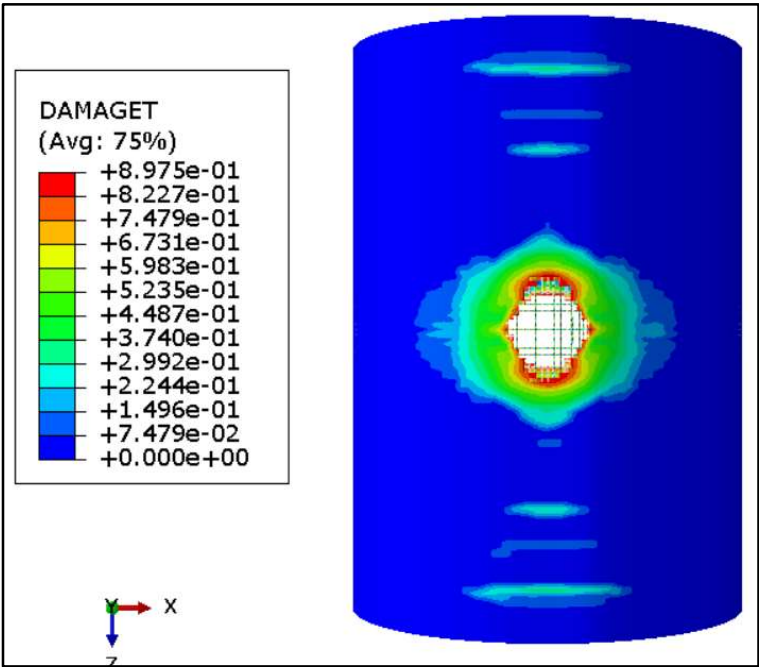


Figure 1: SCPB-200-5-0.1

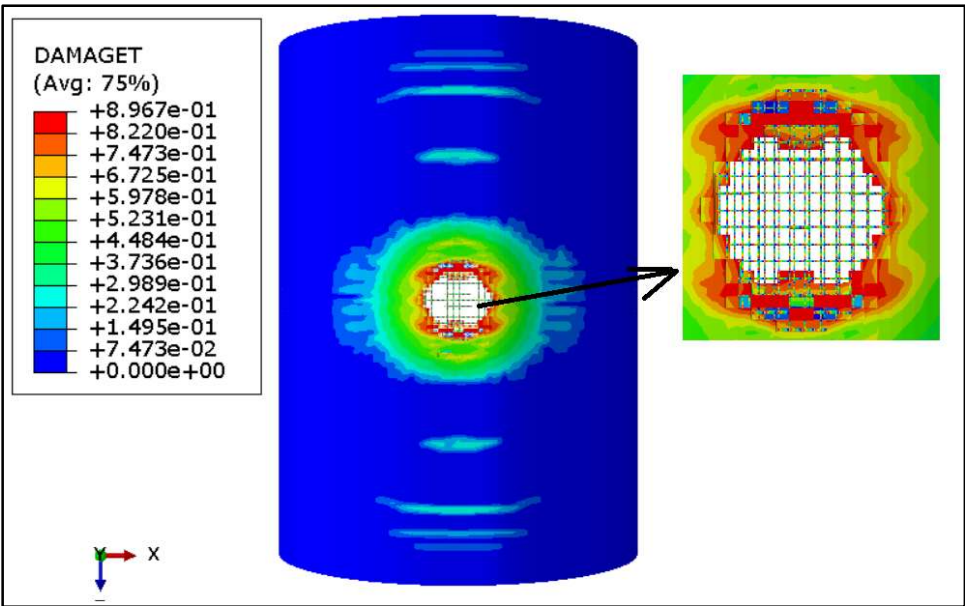


Figure 2: SCPB-250-5-0.1

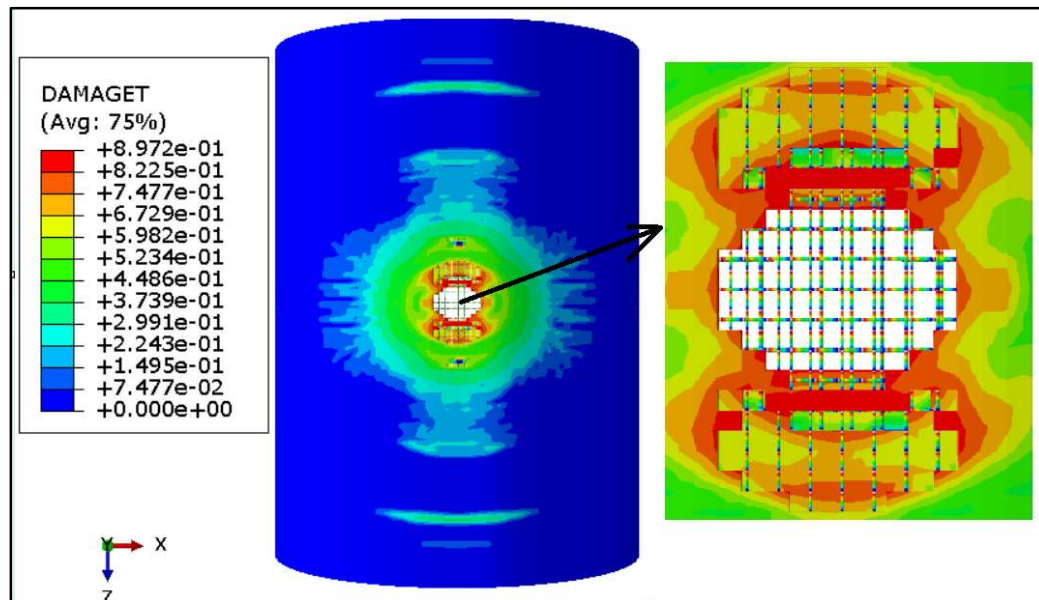


Figure 3: SCPB-300-5-0.1

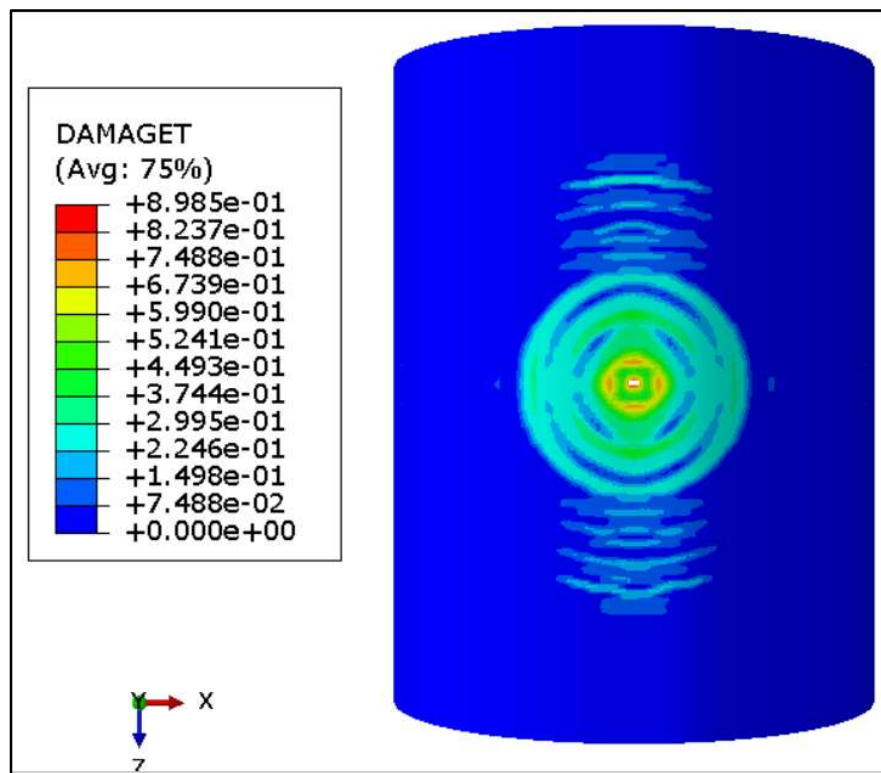


Figure 4: SCPB-500-5-0.1

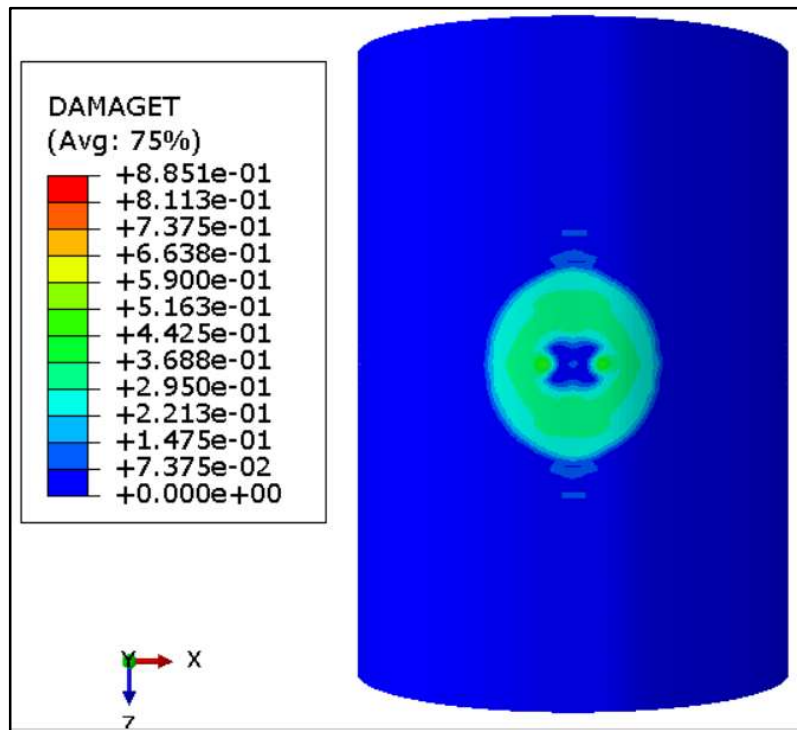


Figure 5: SCPB-200-1-0.25

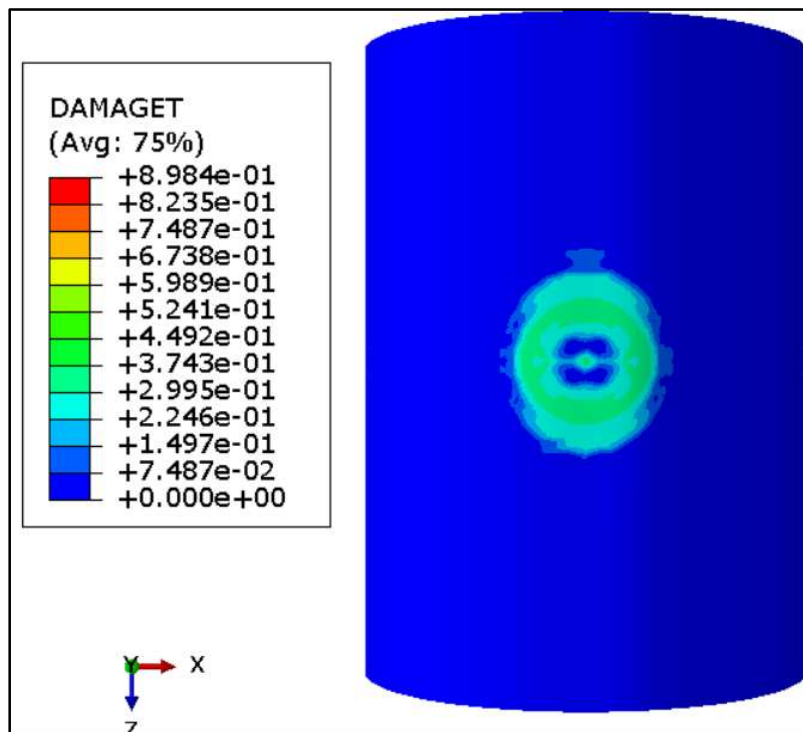


Figure 6: SCPB-250-1-0.25

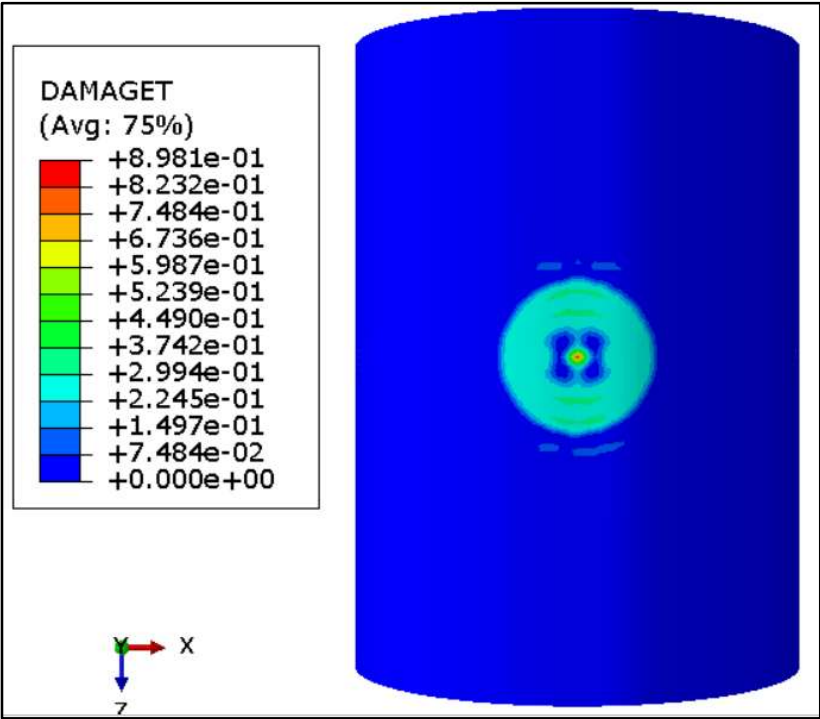


Figure 7: SCPB-300-1-0.25

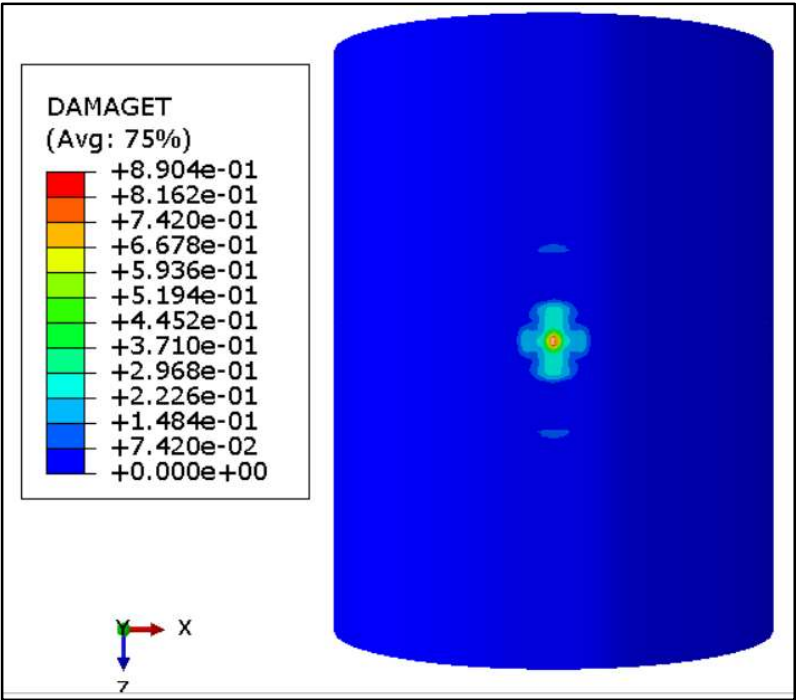


Figure 8: SCPB-500-1-0.25

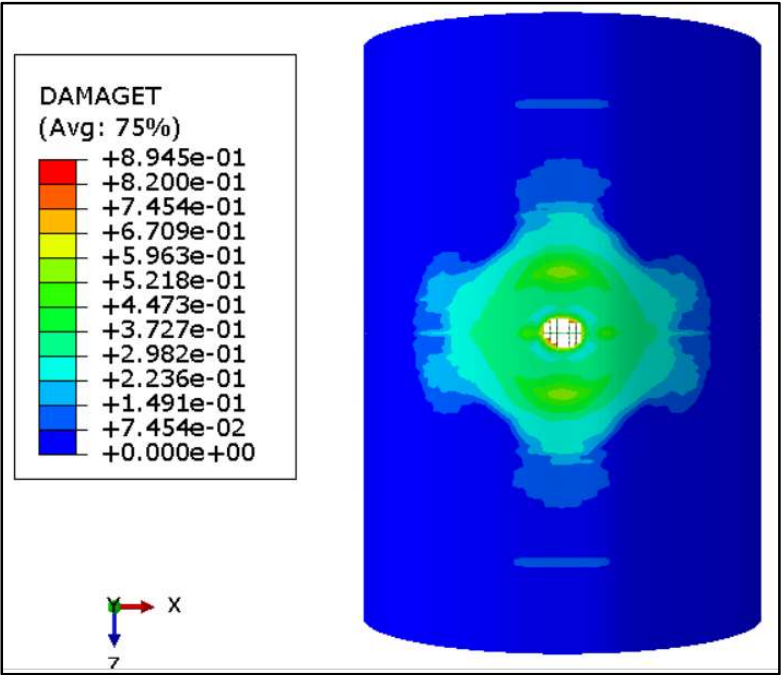


Figure 9: SCPB-200-5-0.25

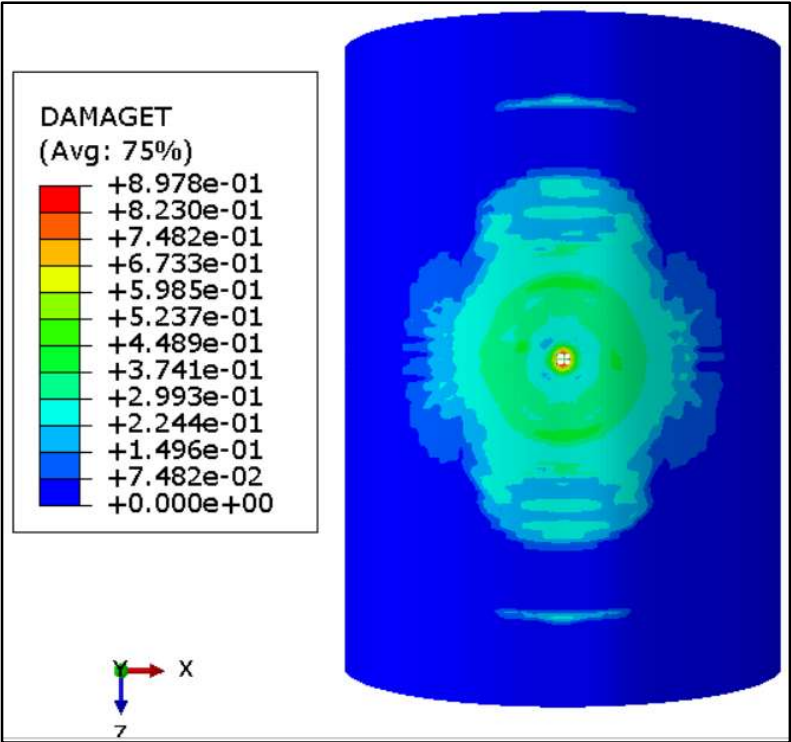


Figure 10: SCPB-250-5-0.25

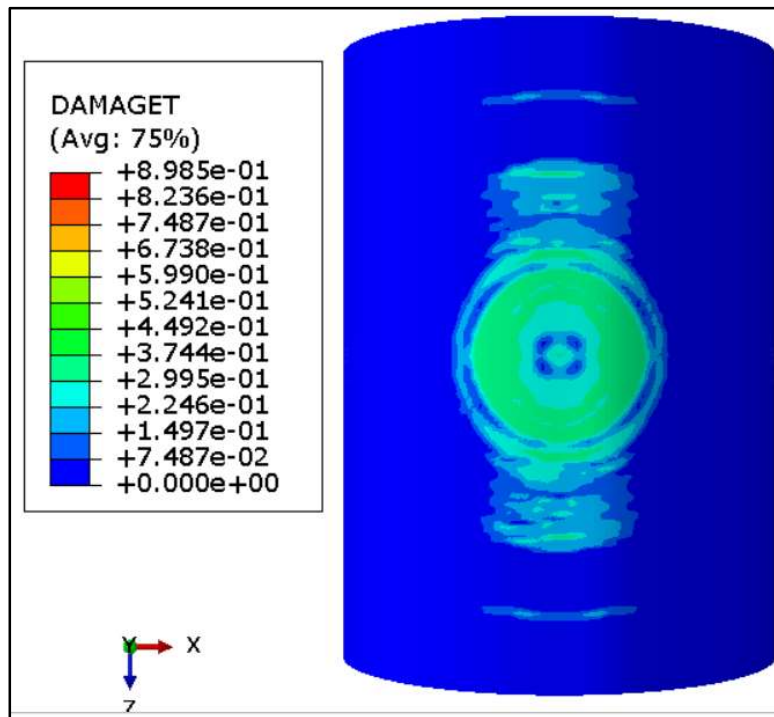


Figure 11: SCPB-300-5-0.25

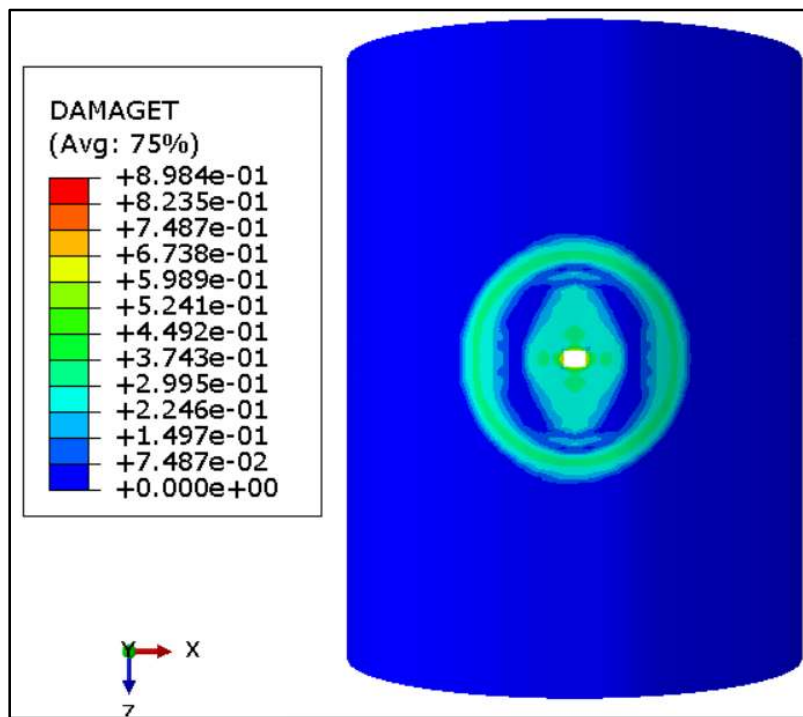


Figure 12: SCPB-500-5-0.25

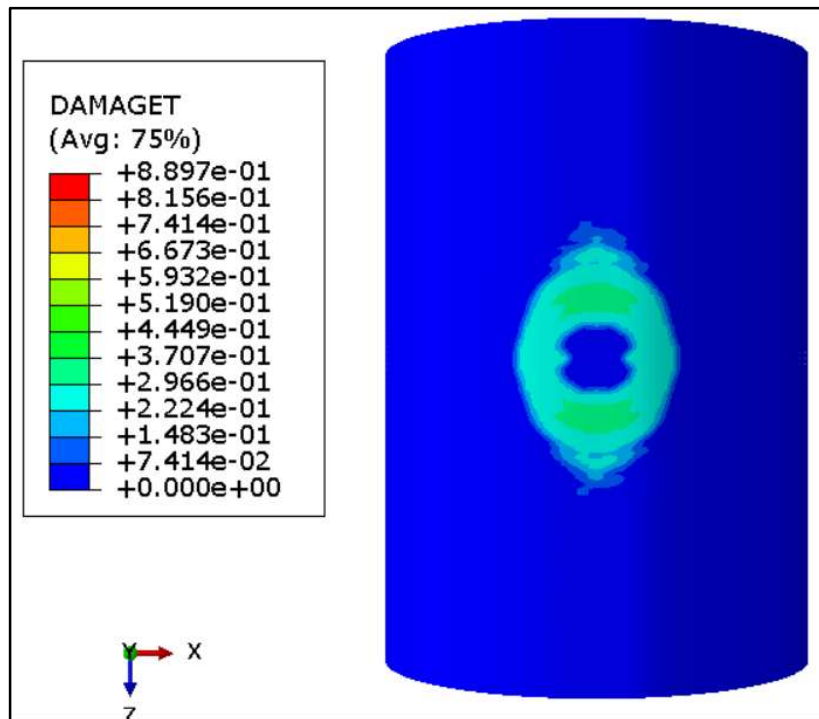


Figure 13: SCPB-200-1-0.5

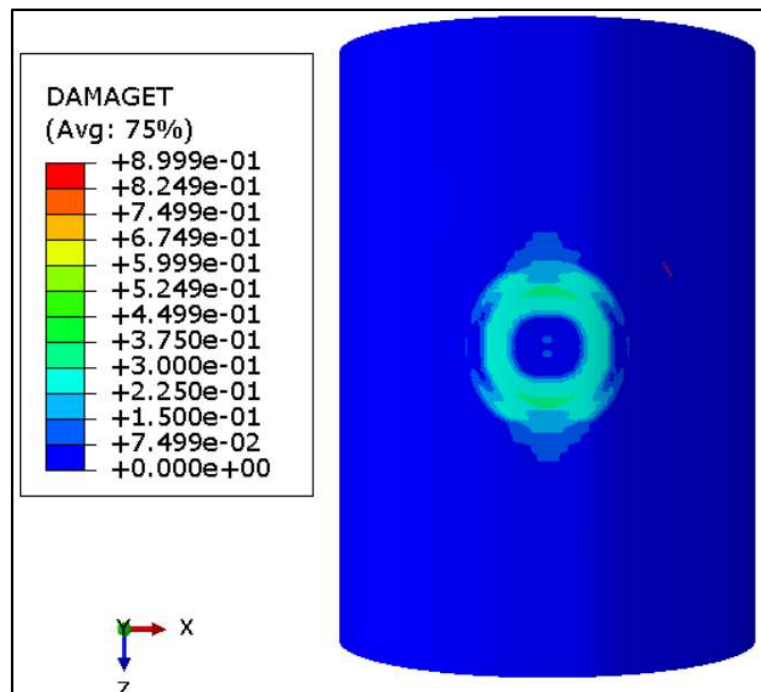


Figure 14: SCPB-250-1-0.5

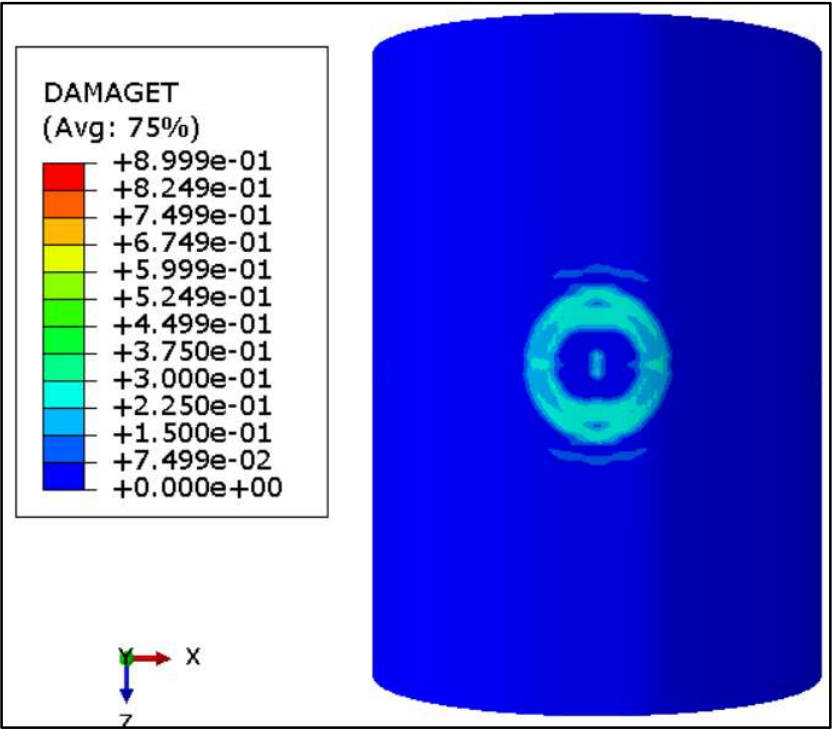


Figure 15: SCPB-300-1-0.5

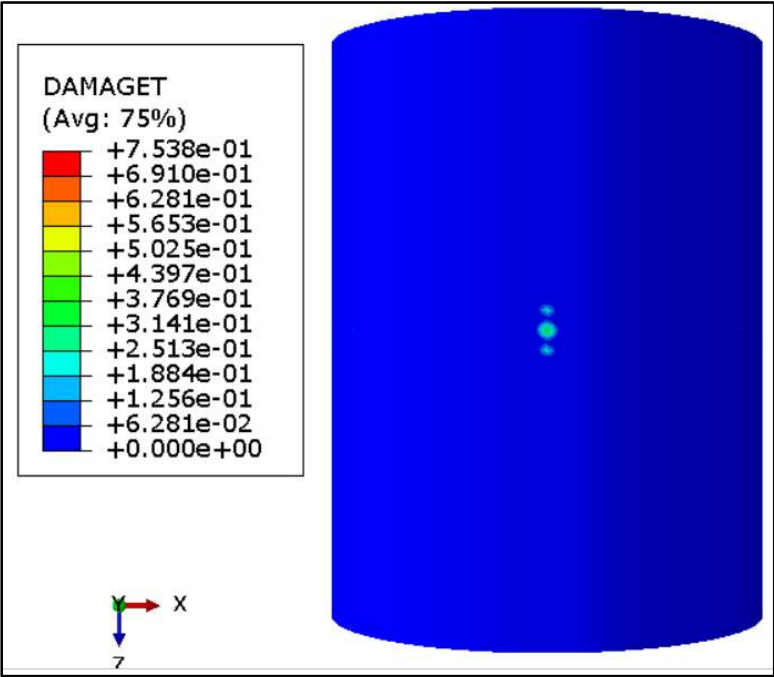


Figure 16: SCPB-500-1-0.5

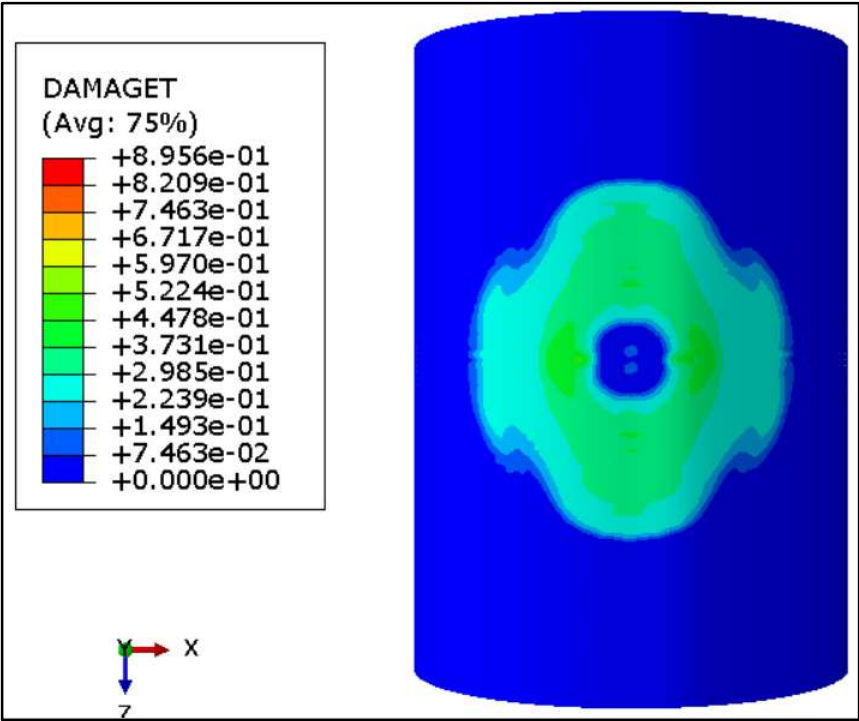


Figure 17: SCPB-200-5-0.5

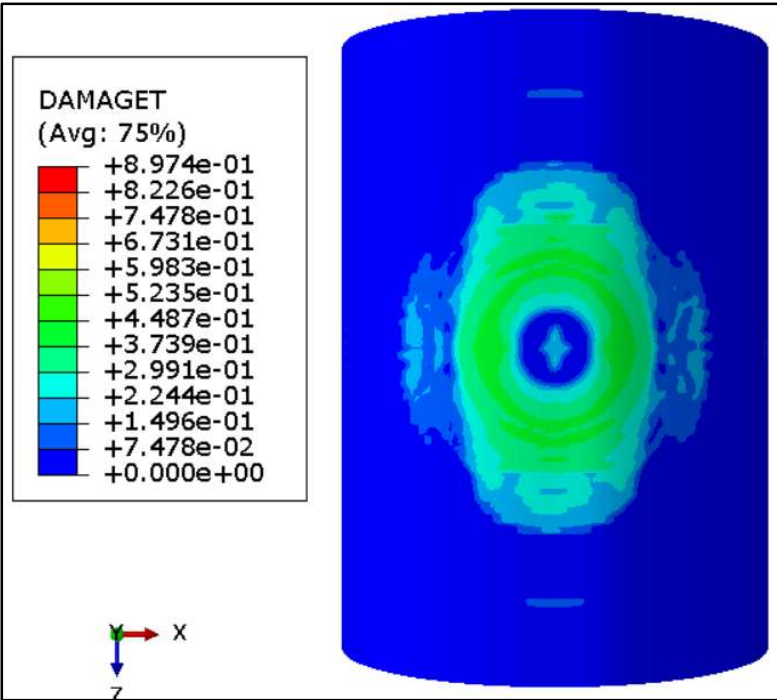


Figure 18: SCPB-250-5-0.5

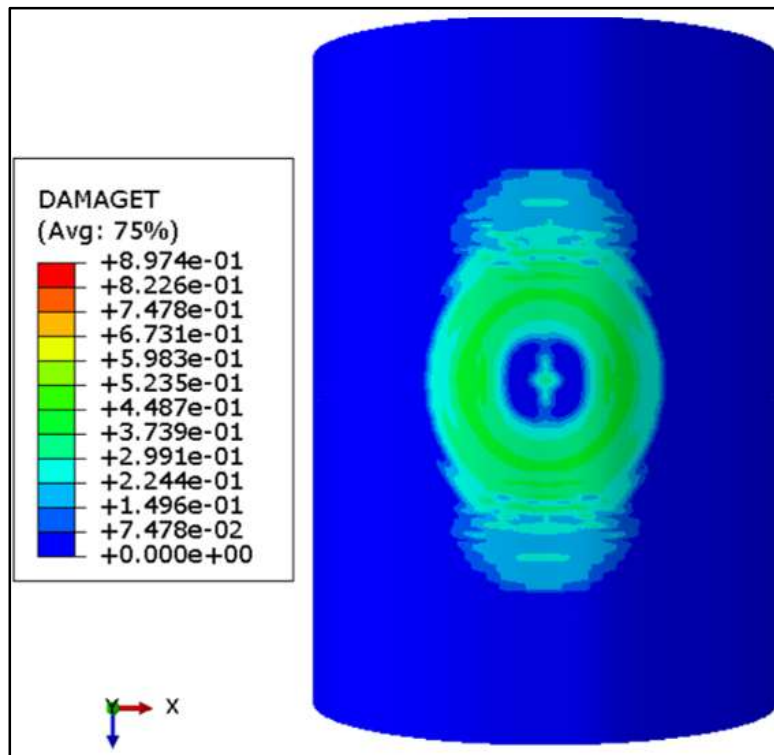


Figure 19: SCPB-300-5-0.5

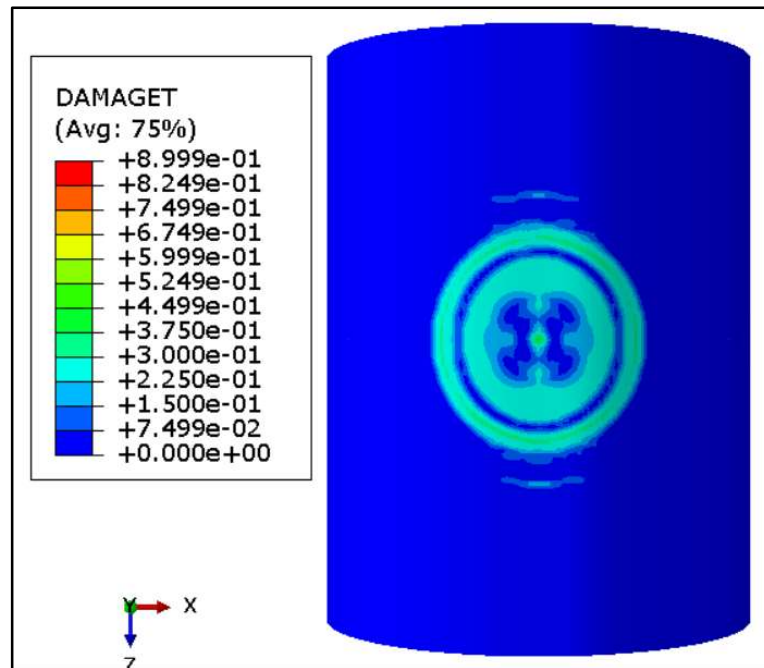


Figure 20: SCPB-500-5-0.5

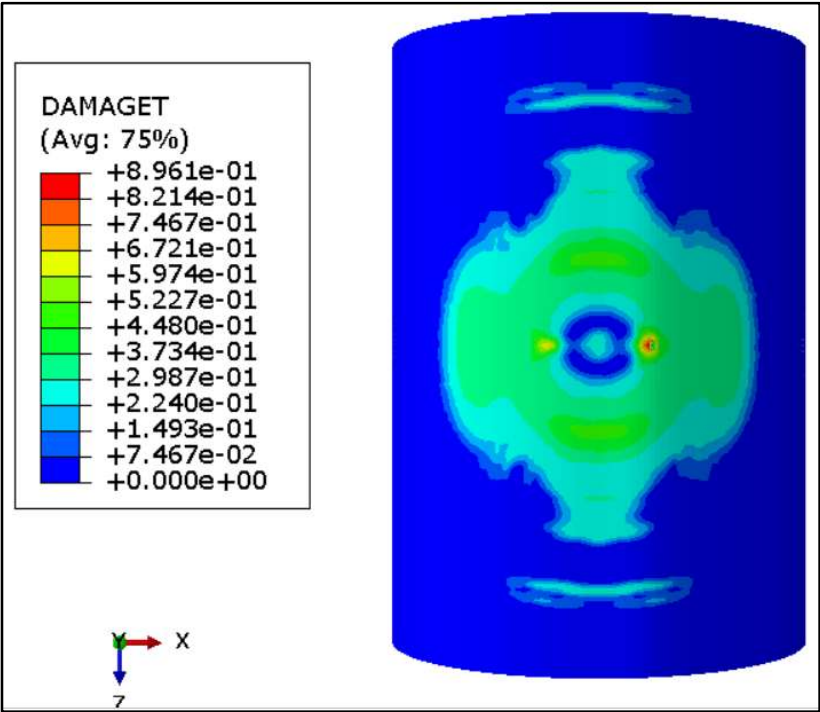


Figure 21: SCPB-200-10-0.5

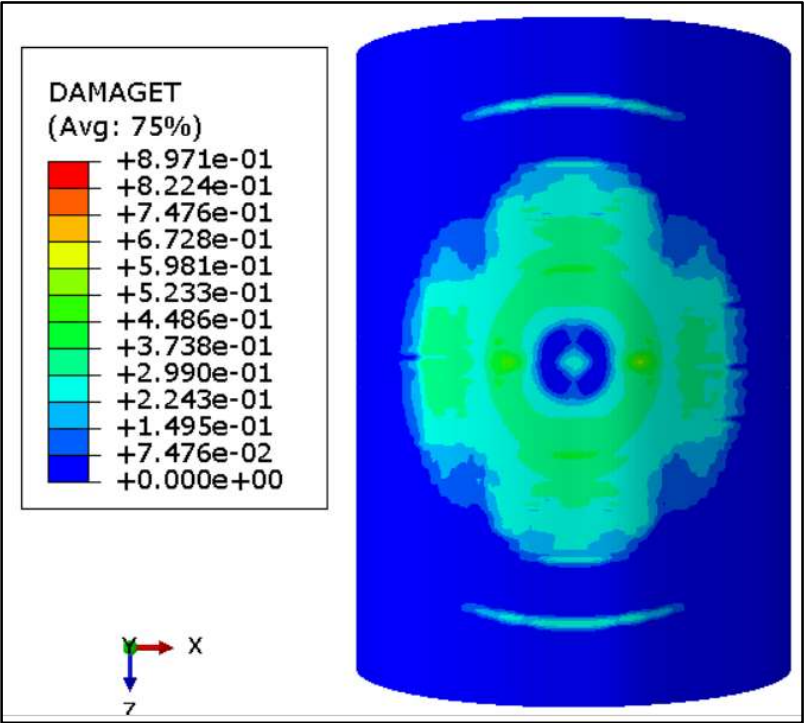


Figure 22: SCPB-250-10-0.5

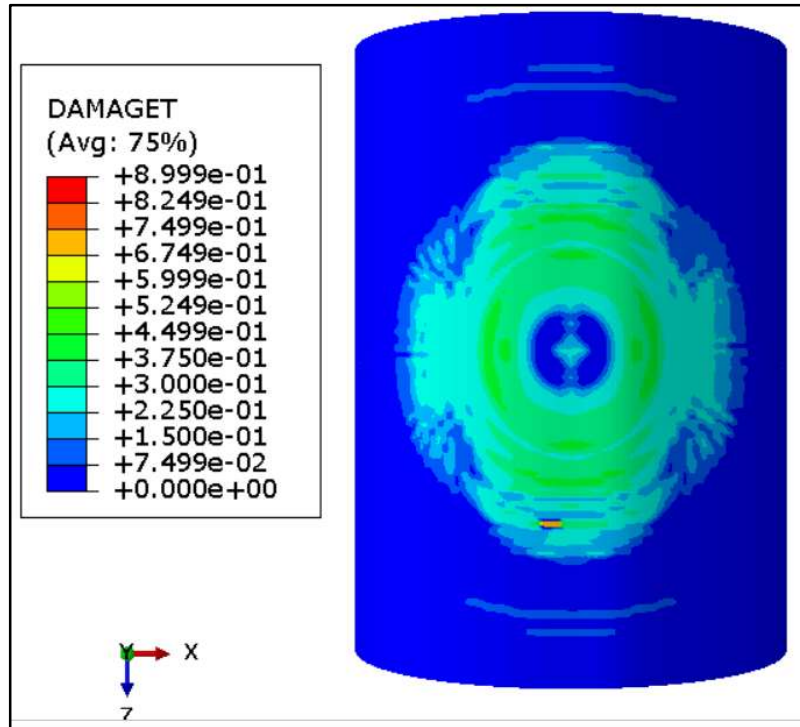


Figure 23: SCPB-300-10-0.5

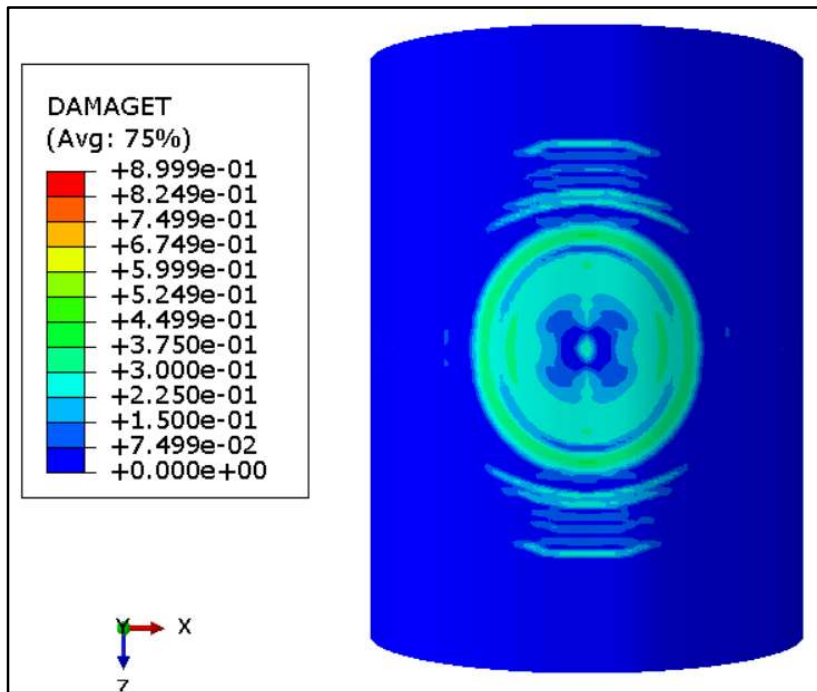


Figure 24: SCPB-500-10-0.5

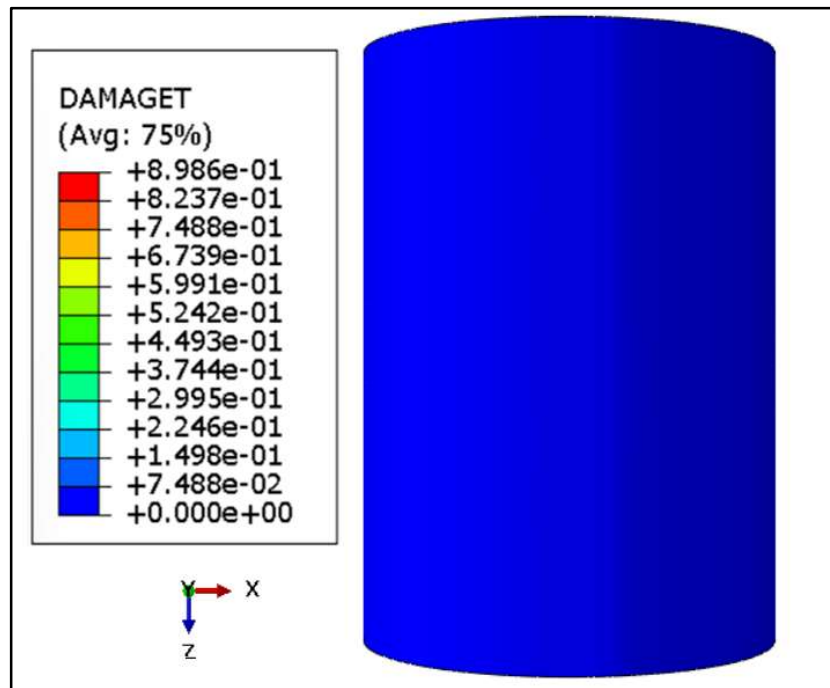


Figure 25: SCPB-200-1-1

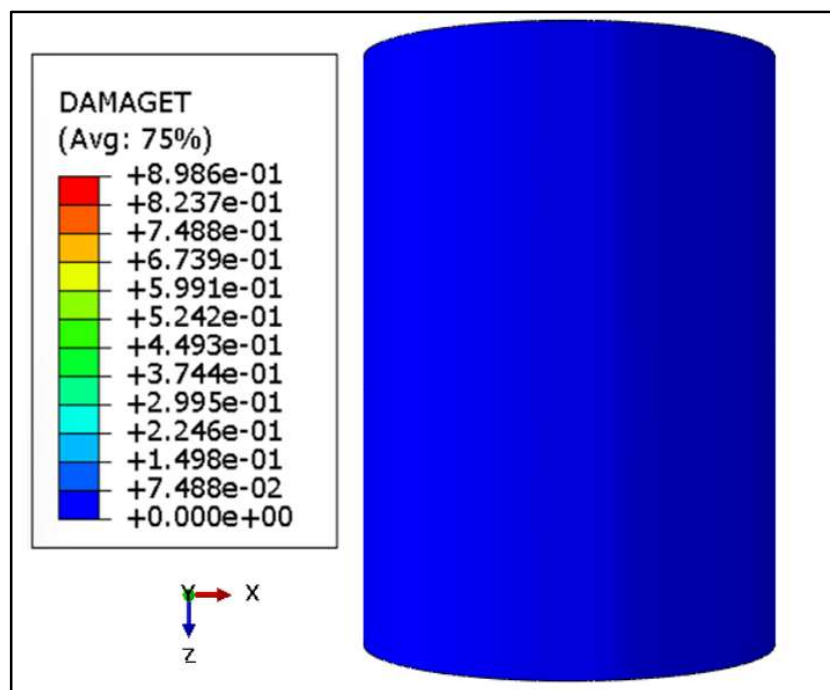


Figure 26: SCPB-250-1-1

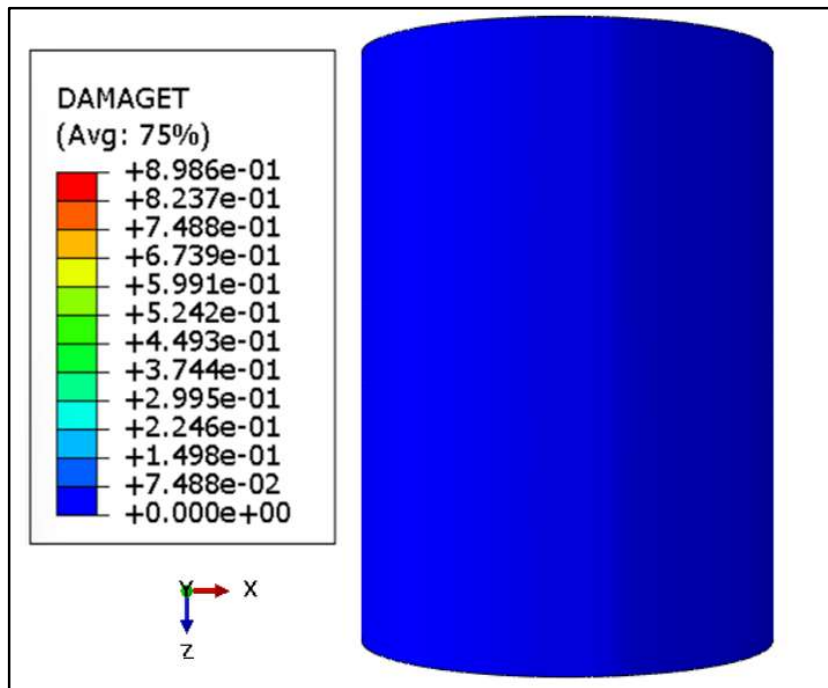


Figure 27: SCPB-300-1-1

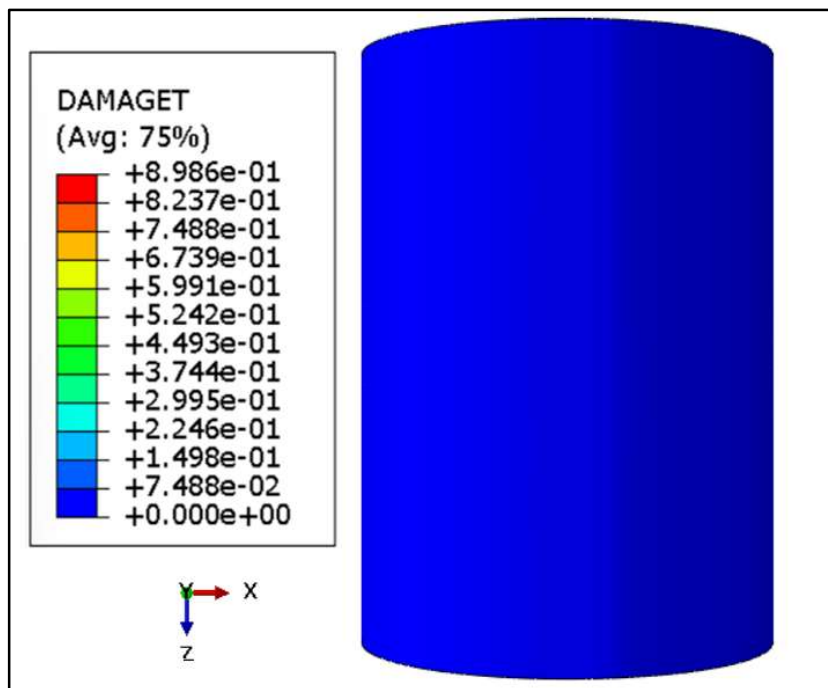


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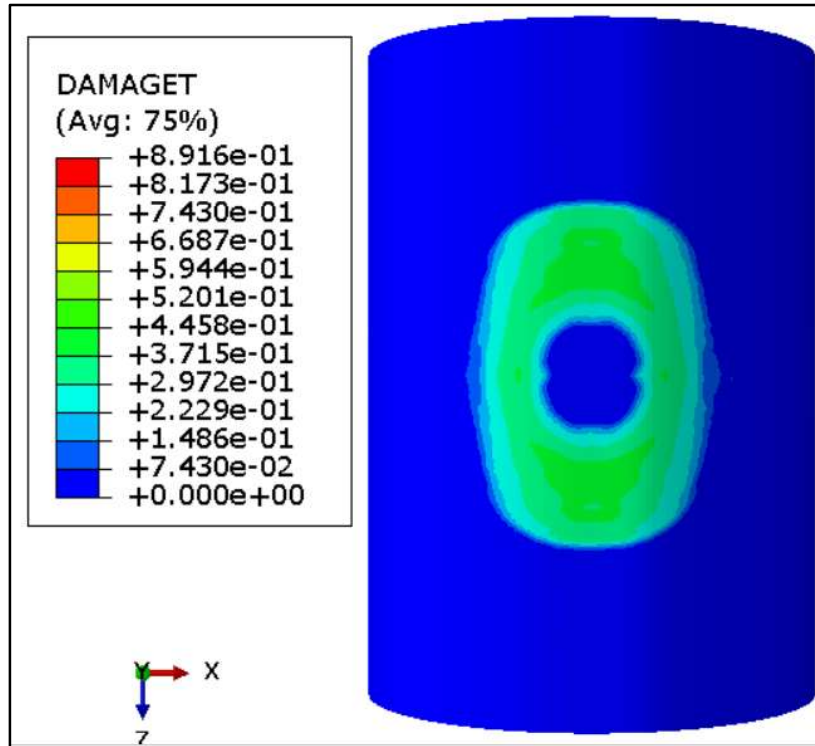


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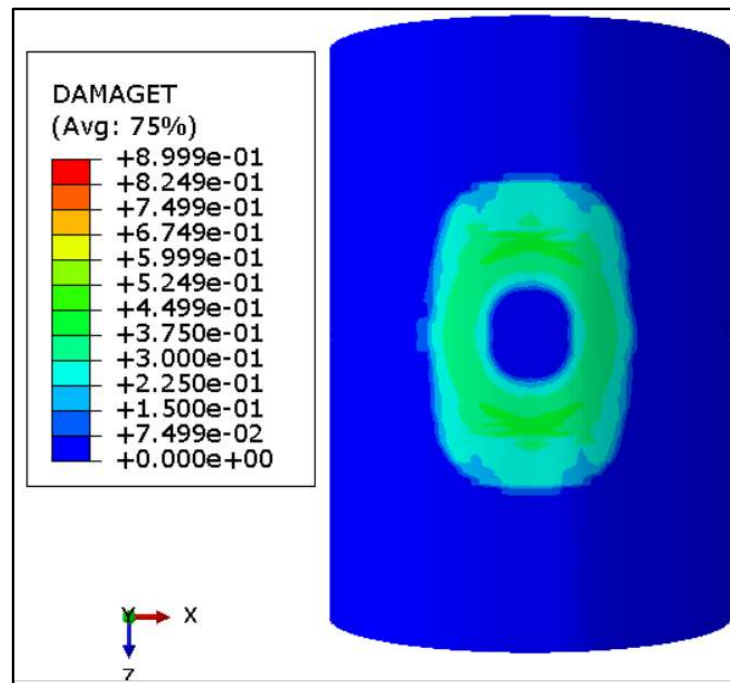


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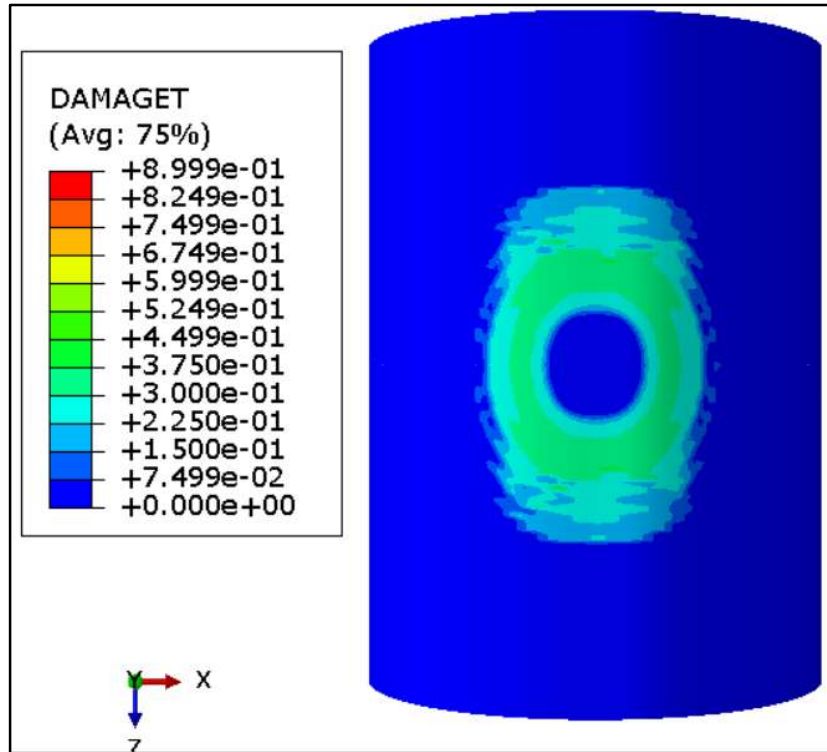


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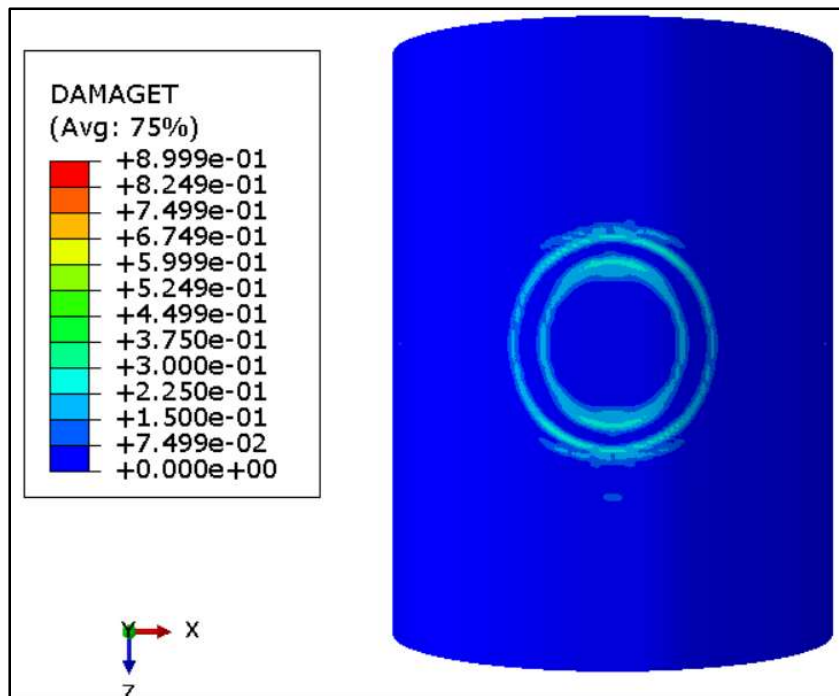


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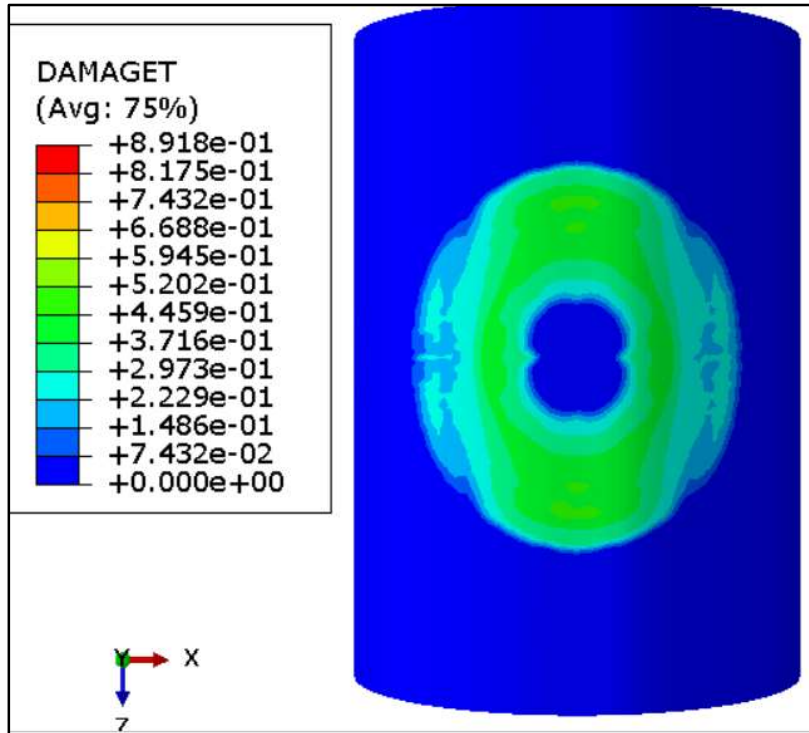


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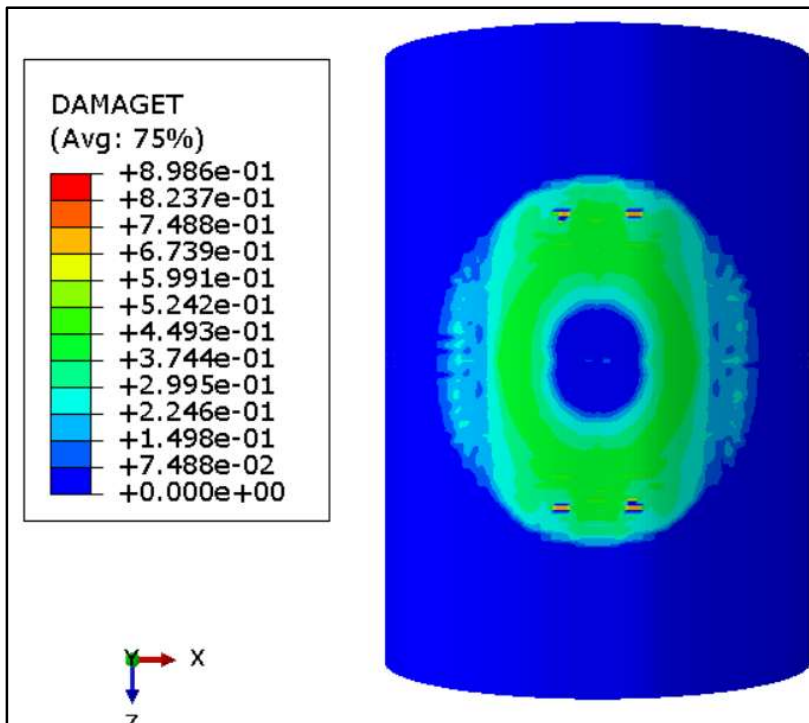


Figure 34: SCPB-250-10-1

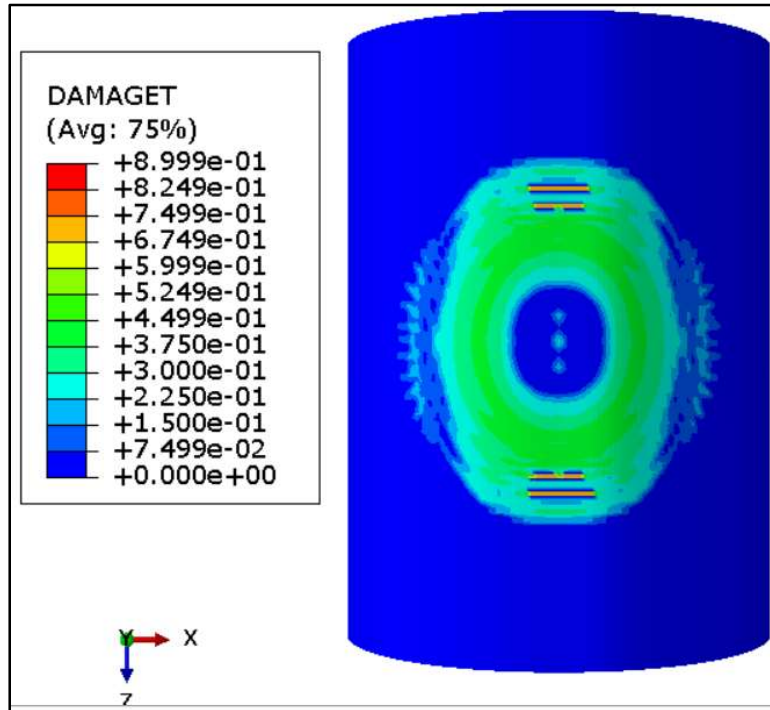


Figure 35: SCPB-300-10-1

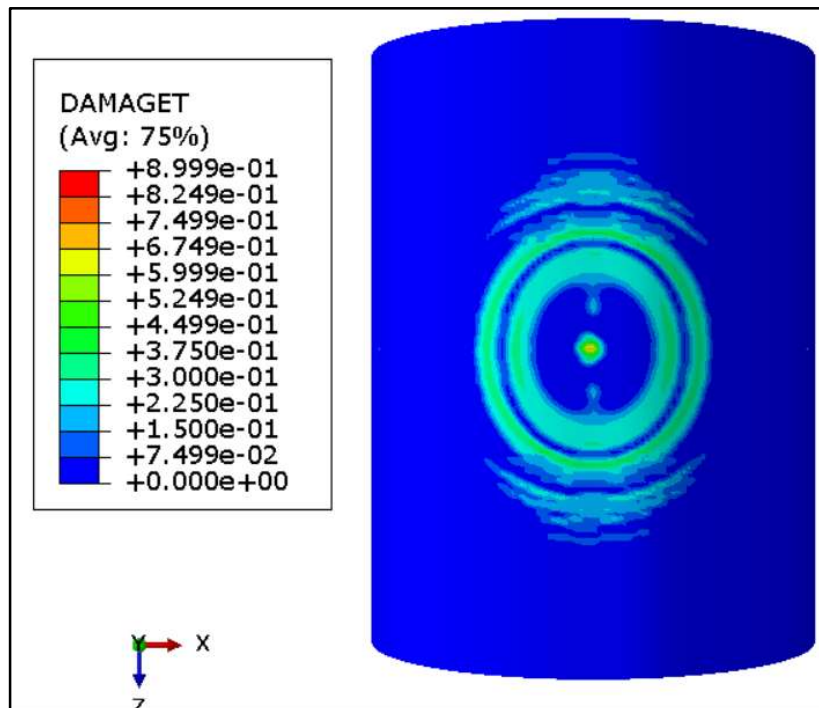


Figure 36: SCPB-500-10-1

Appendix B: Principal stress contour plot

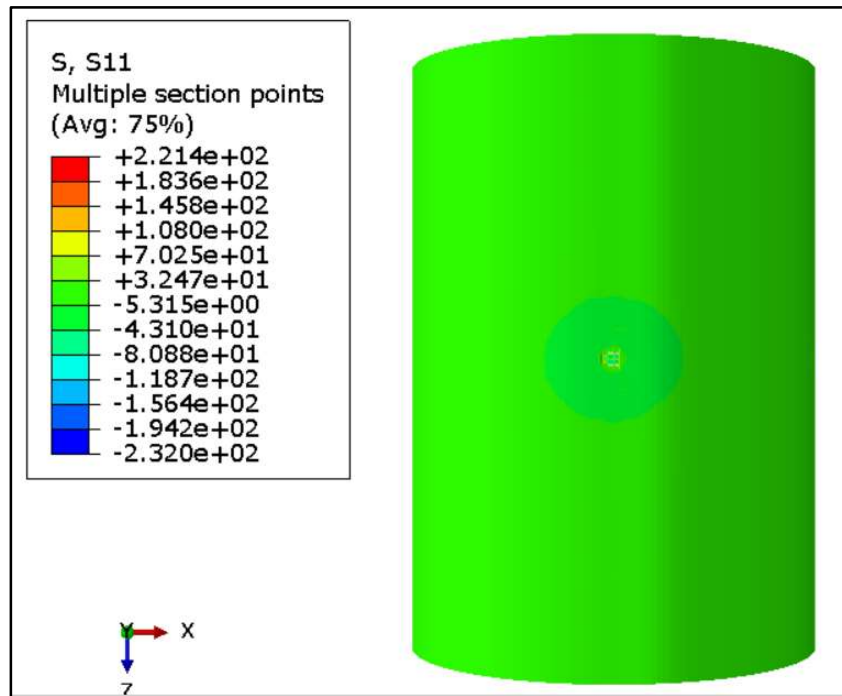


Figure 37: SCPB-200-1-0.1

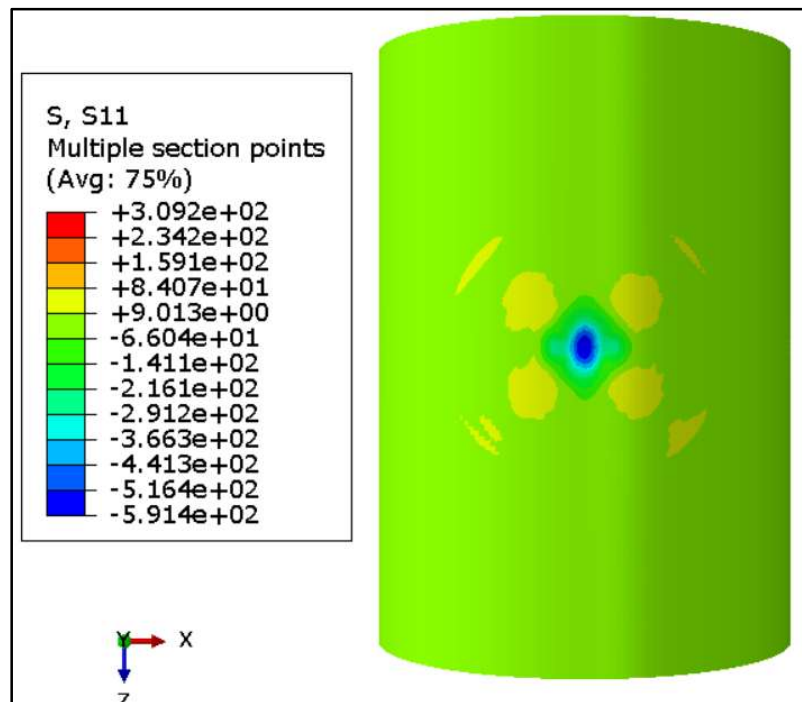


Figure 38: SCPB-200-5-0.1

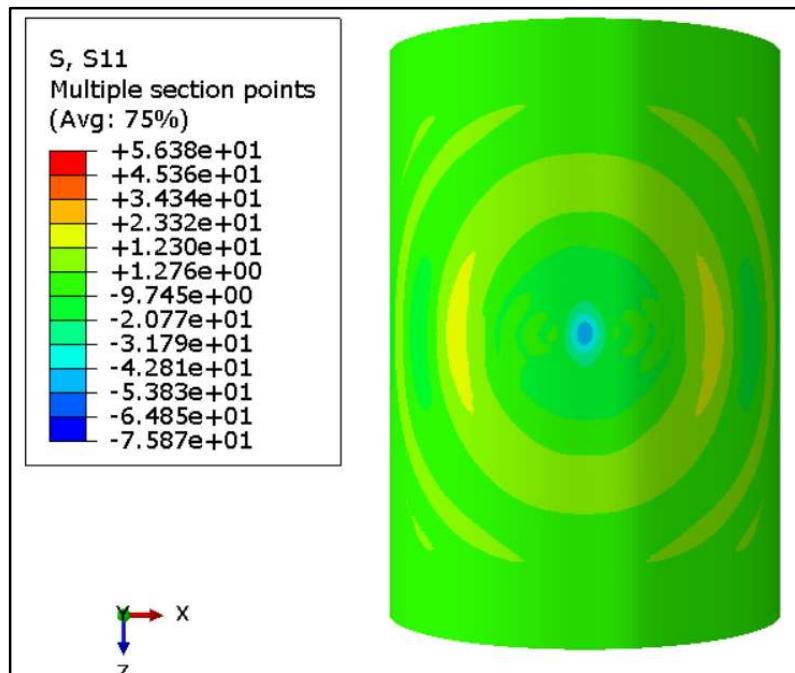


Figure 39: SCPB-200-1-0.25

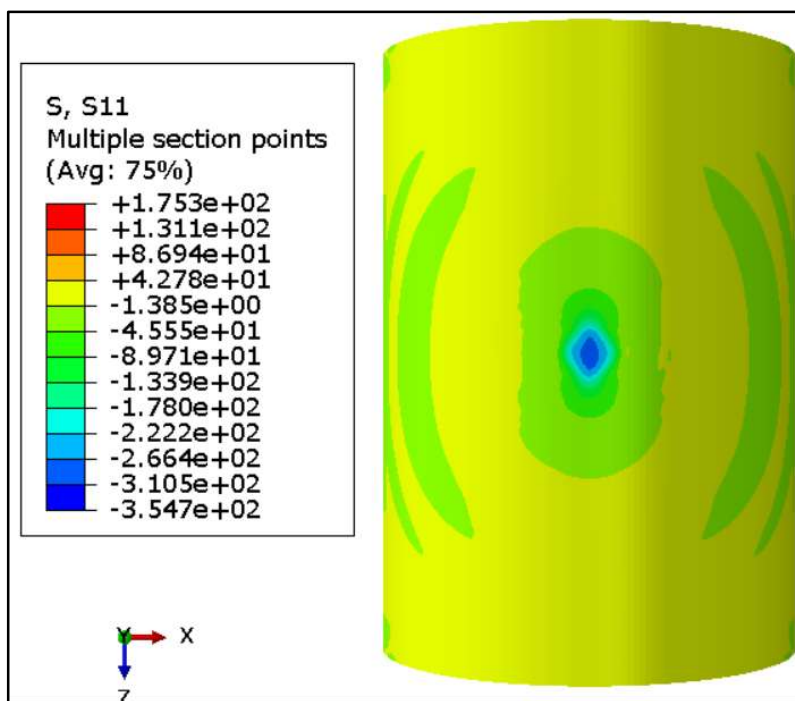


Figure 40: SCPB-200-5-0.25

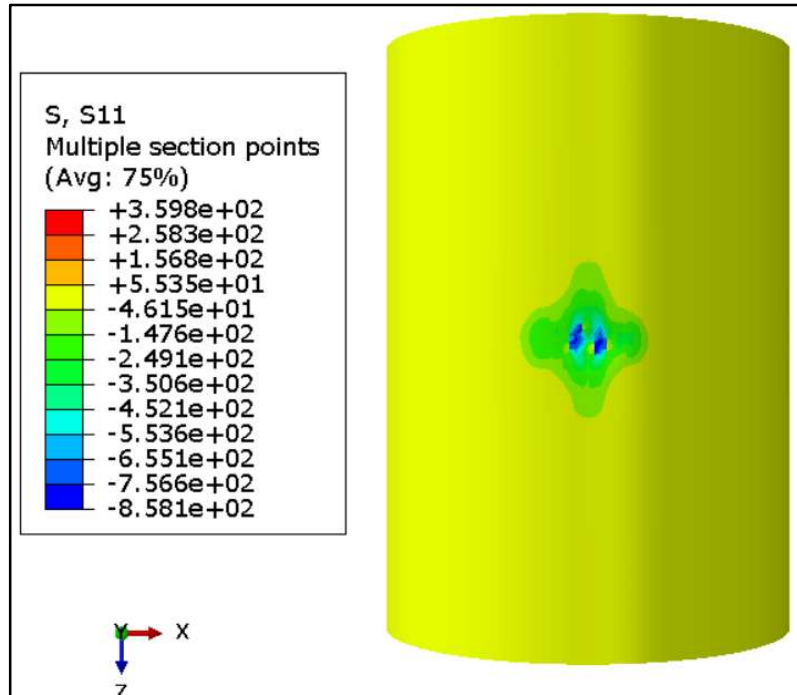


Figure 41: SCPB-200-10-0.25

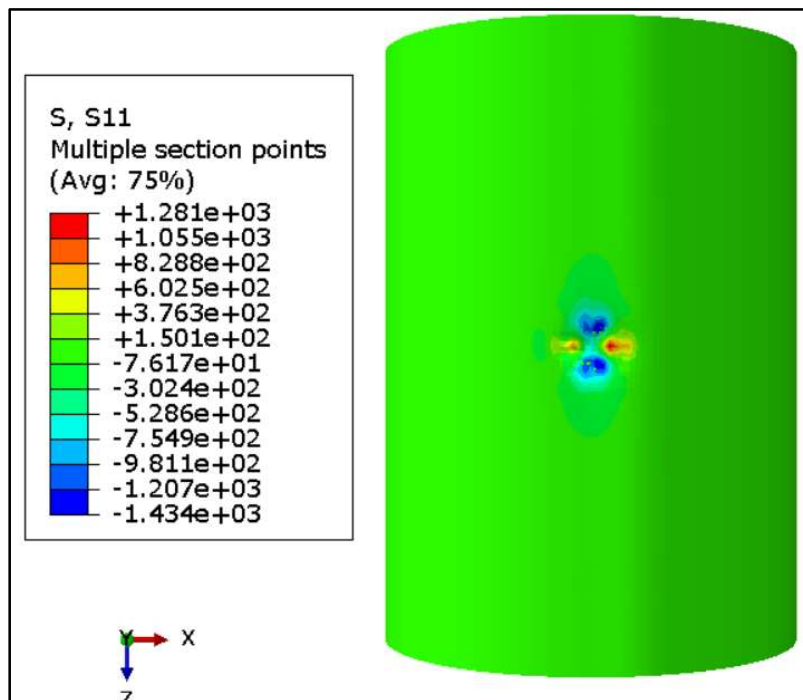


Figure 42: SCPB-200-25-0.25

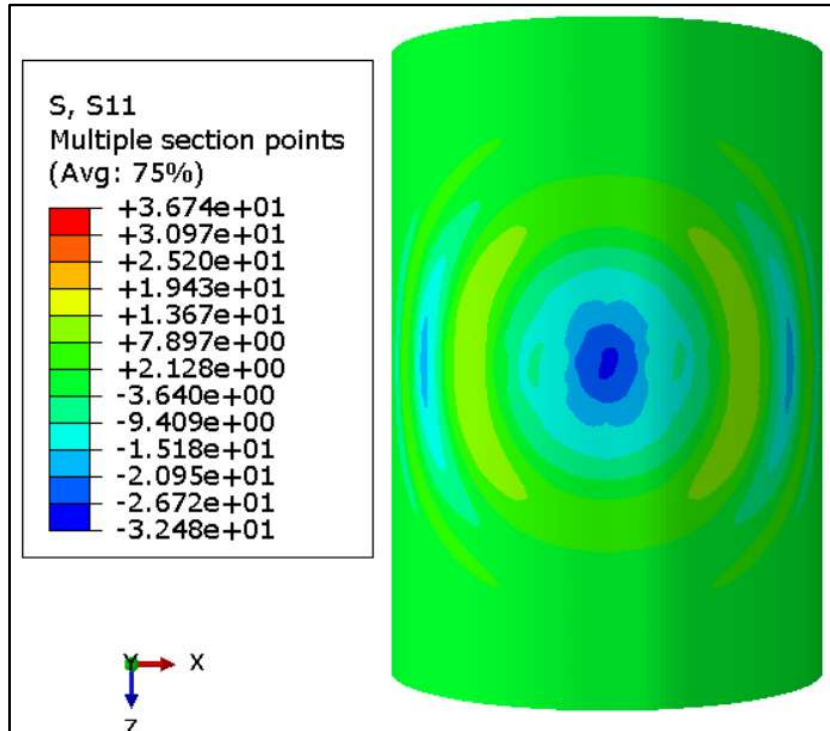


Figure 43: SCPB-200-1-0.5

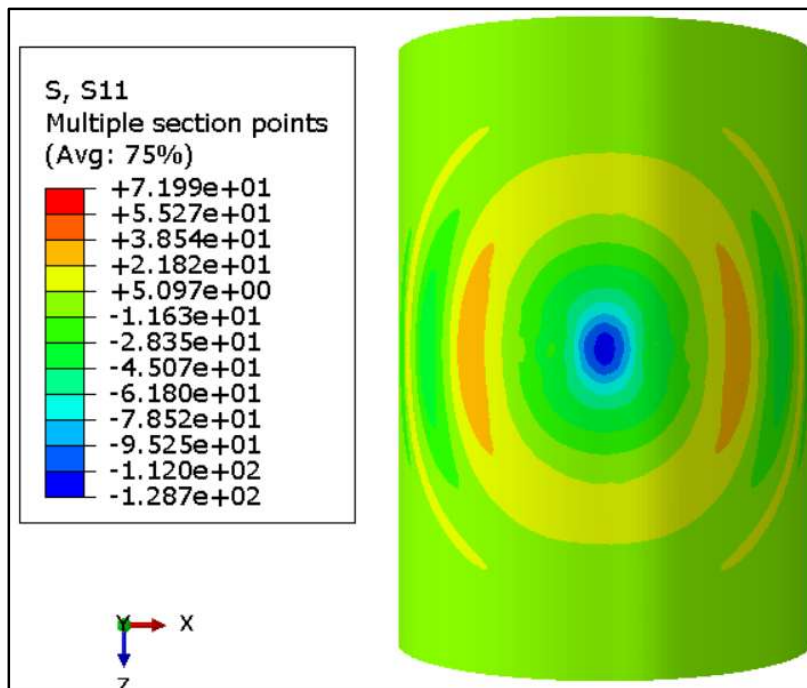


Figure 44: SCPB-200-5-0.5

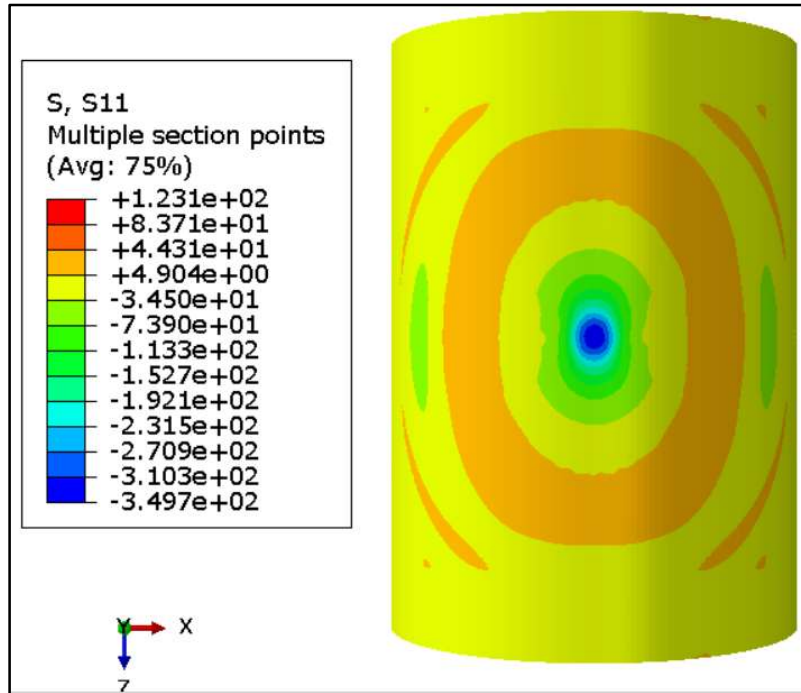


Figure 45: SCPB-200-10-0.5

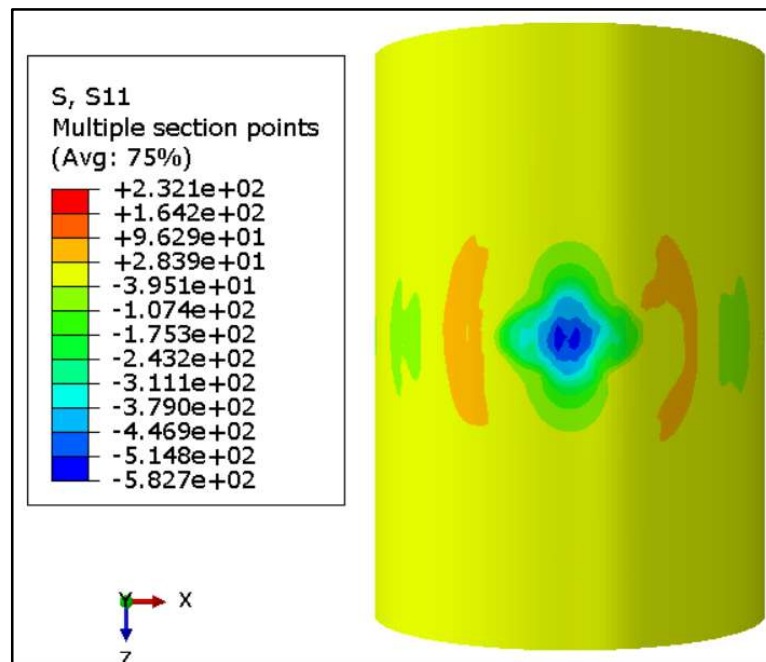


Figure 46: SCPB-200-25-0.5

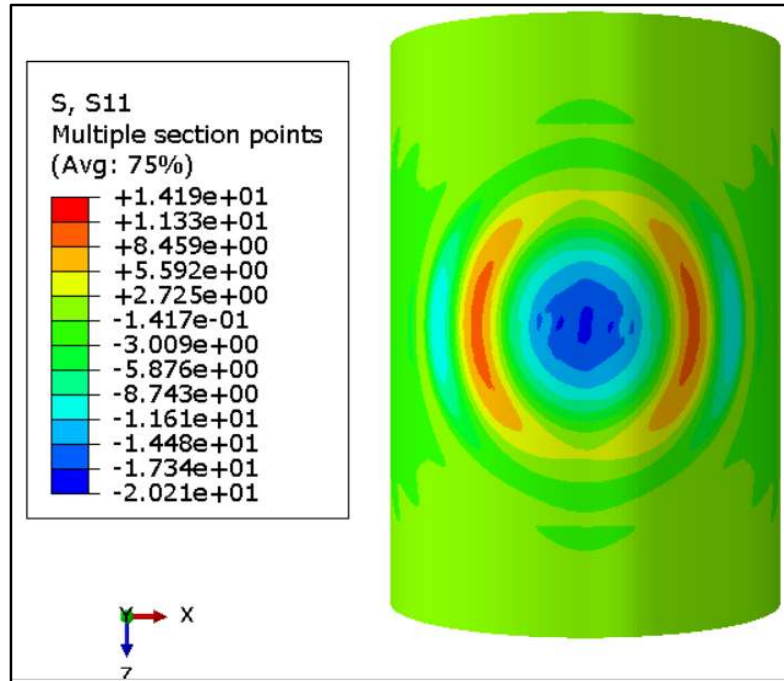


Figure 47: SCPB-200-1-1

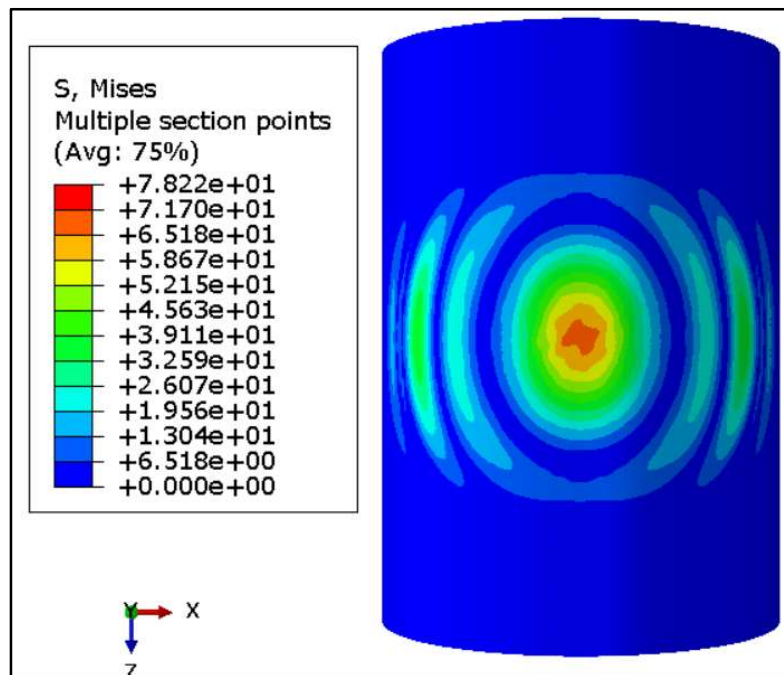


Figure 48: SCPB-200-5-1

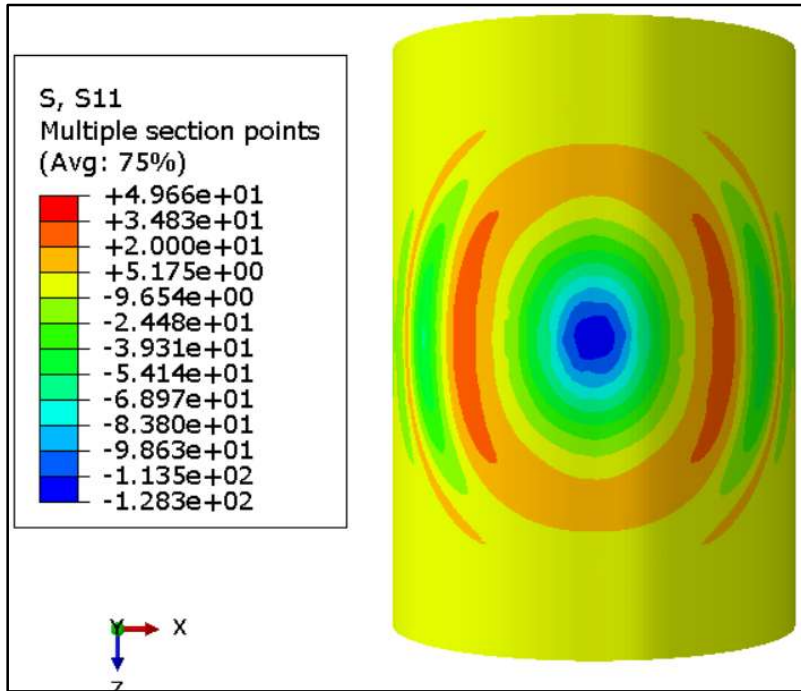


Figure 49: SCPB-200-10-1

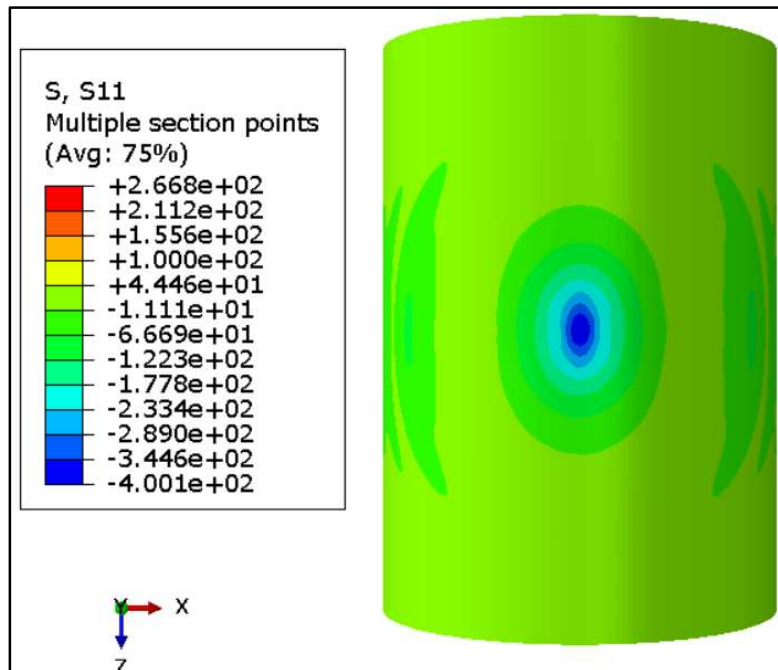


Figure 50: SCPB-200-25-1

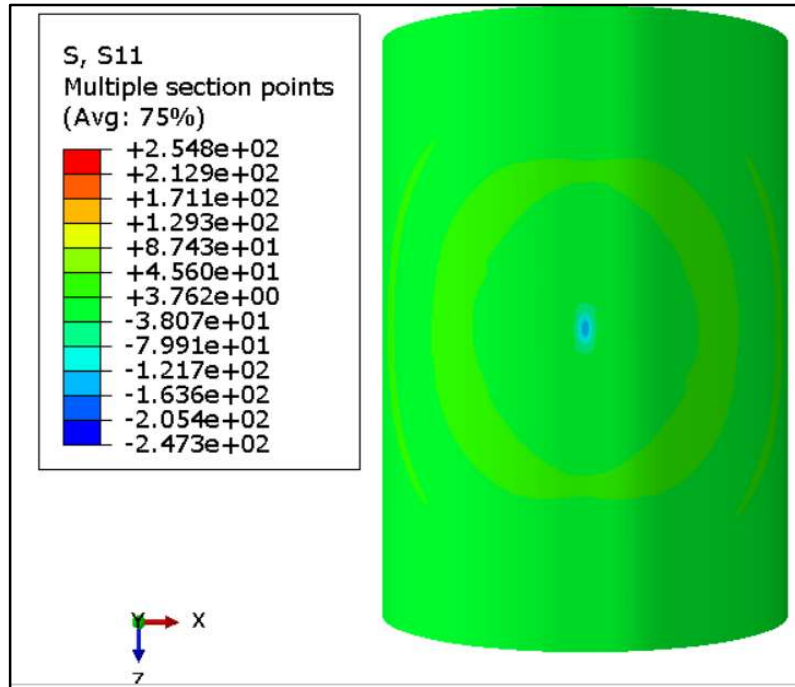


Figure 51: SCPB-250-1-0.1

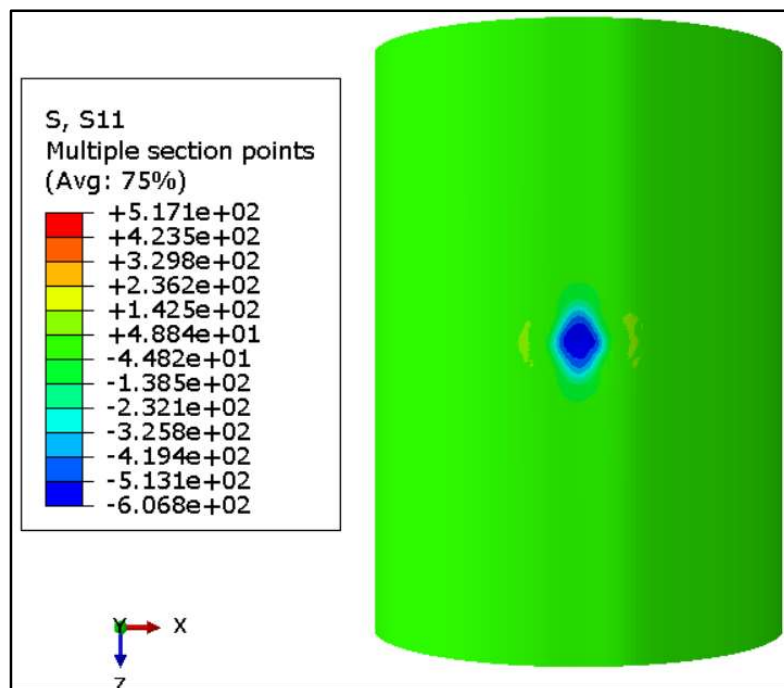


Figure 52: SCPB-250-5-0.1

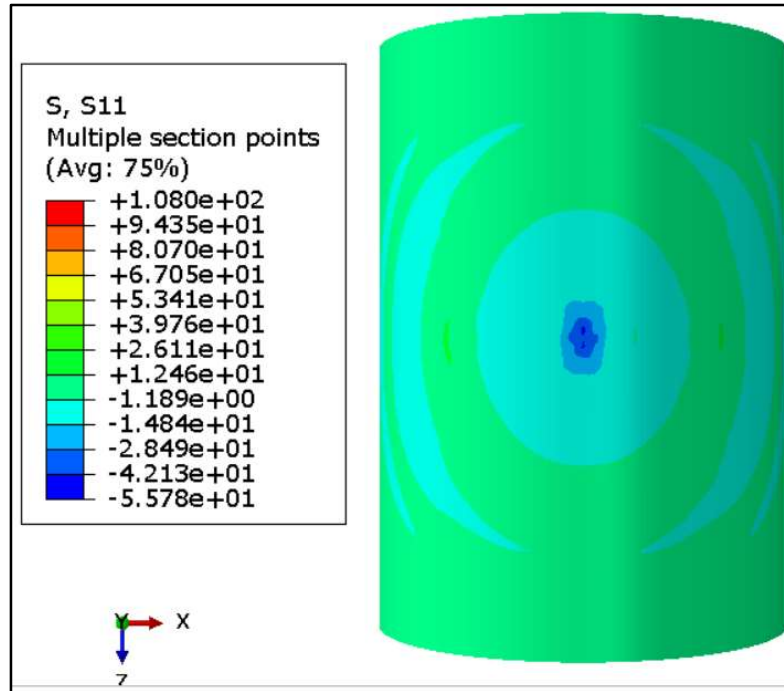


Figure 53: SCPB-250-1-0.25

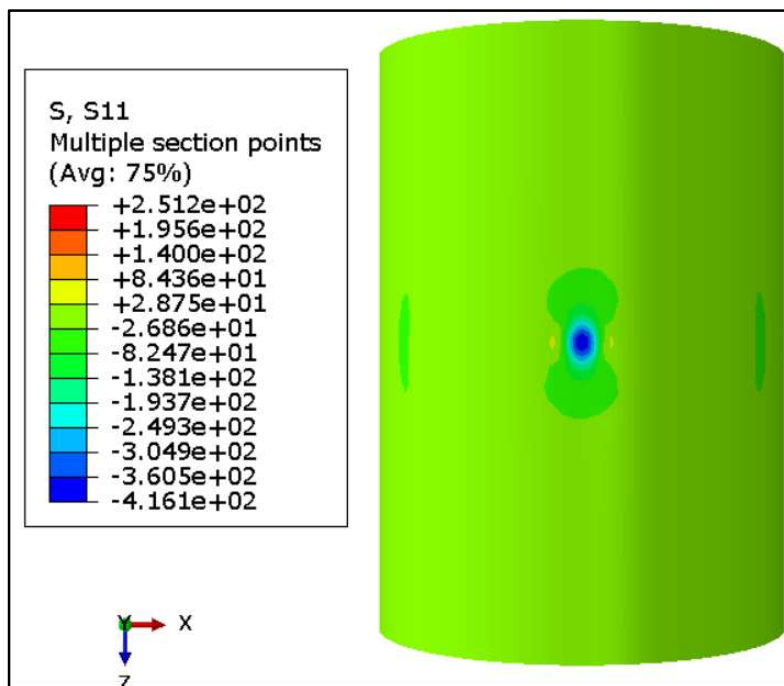


Figure 54: SCPB-250-5-0.25

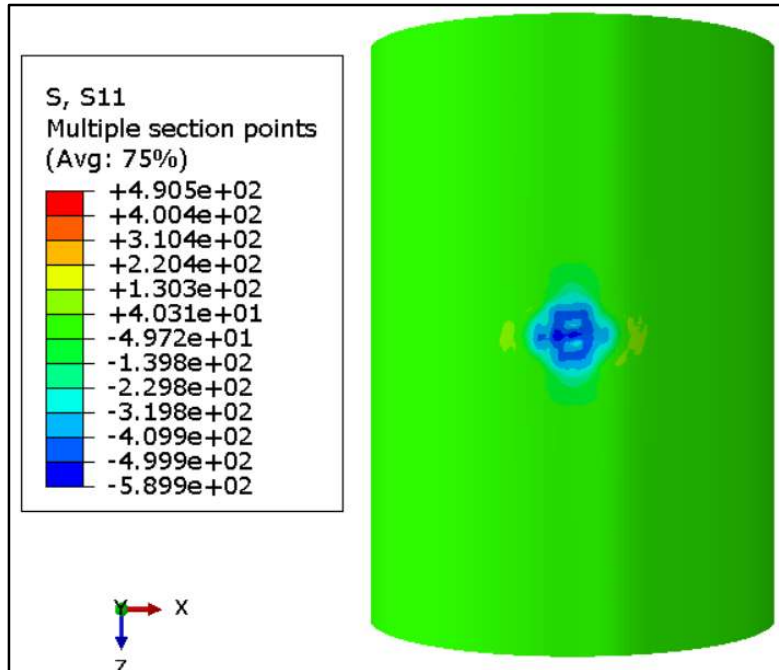


Figure 55: SCPB-250-10-0.25

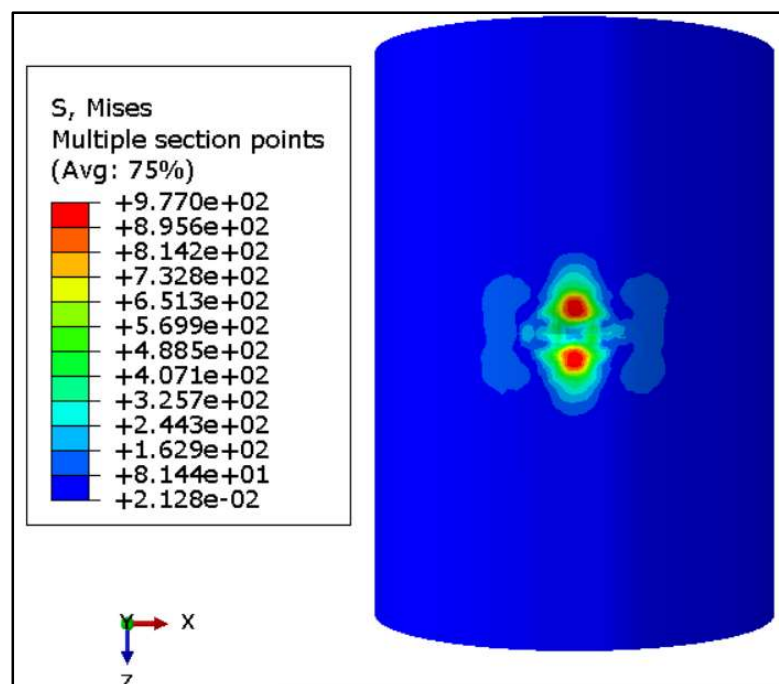


Figure 56: SCPB-250-25-0.25

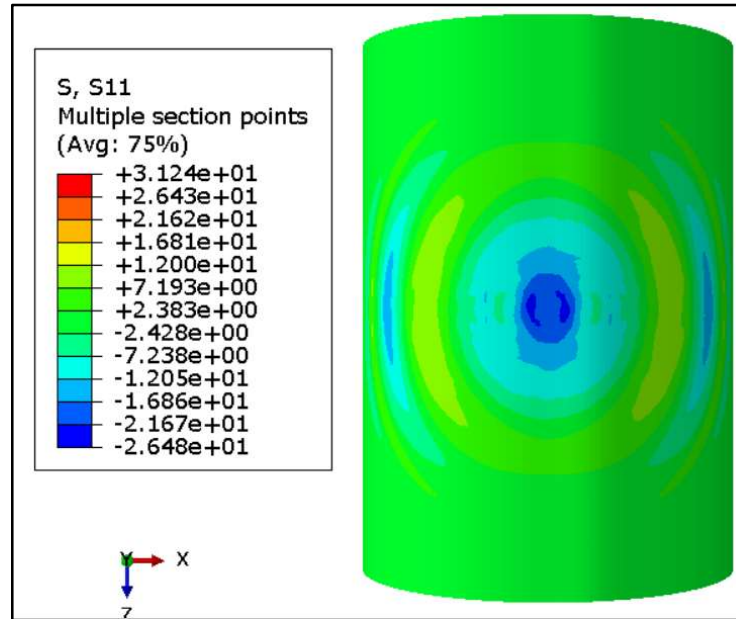


Figure 57: SCPB-250-1-0.5

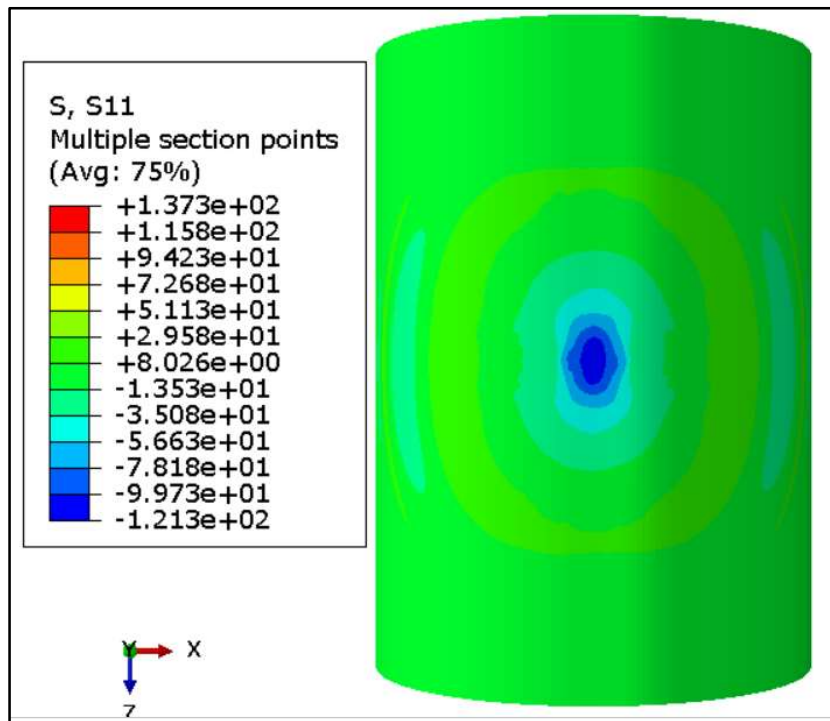


Figure 58: SCPB-250-5-0.5

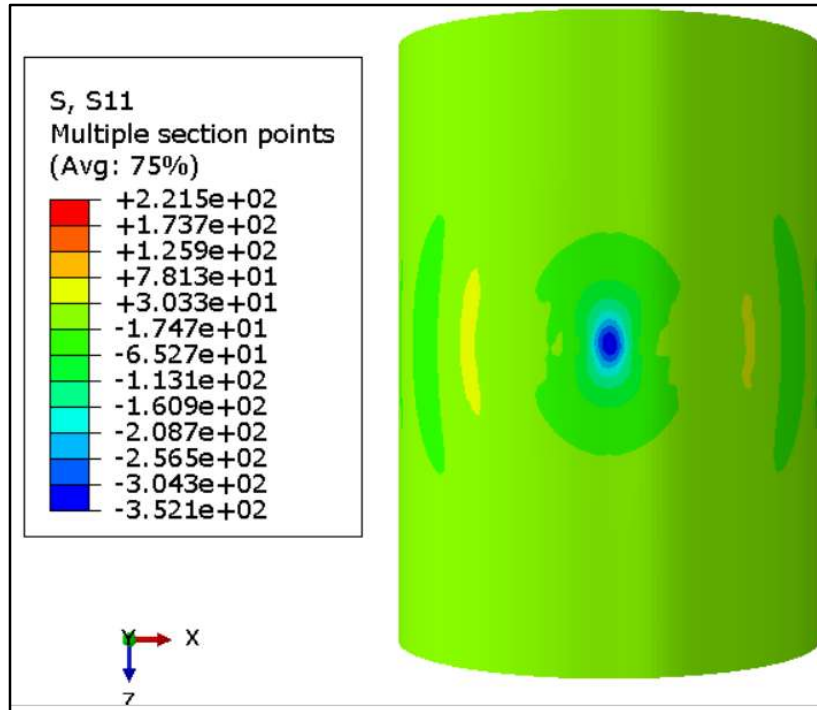


Figure 59: SCPB-250-10-0.5

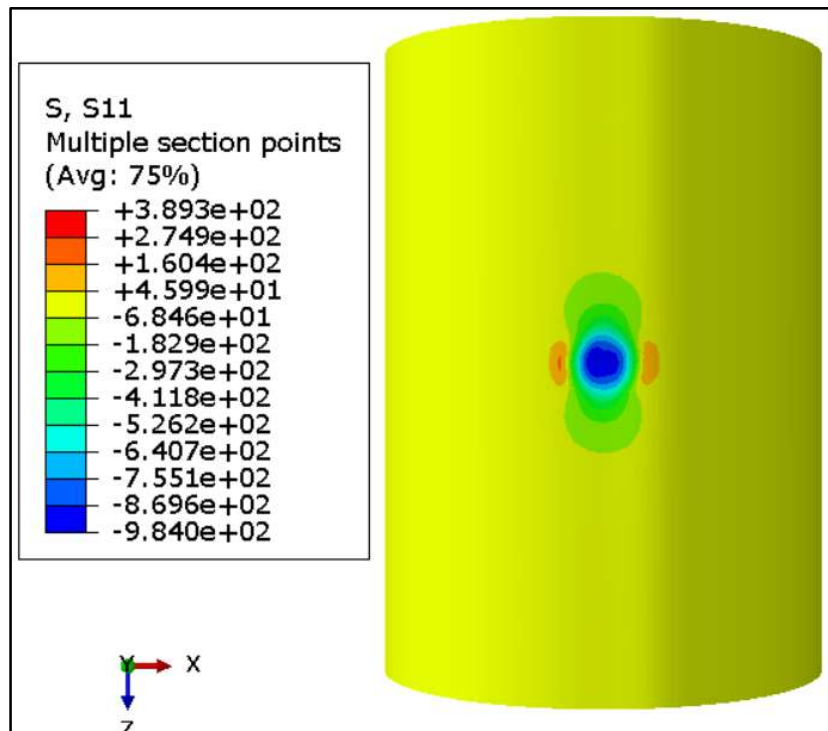


Figure 60: SCPB-250-25-0.5

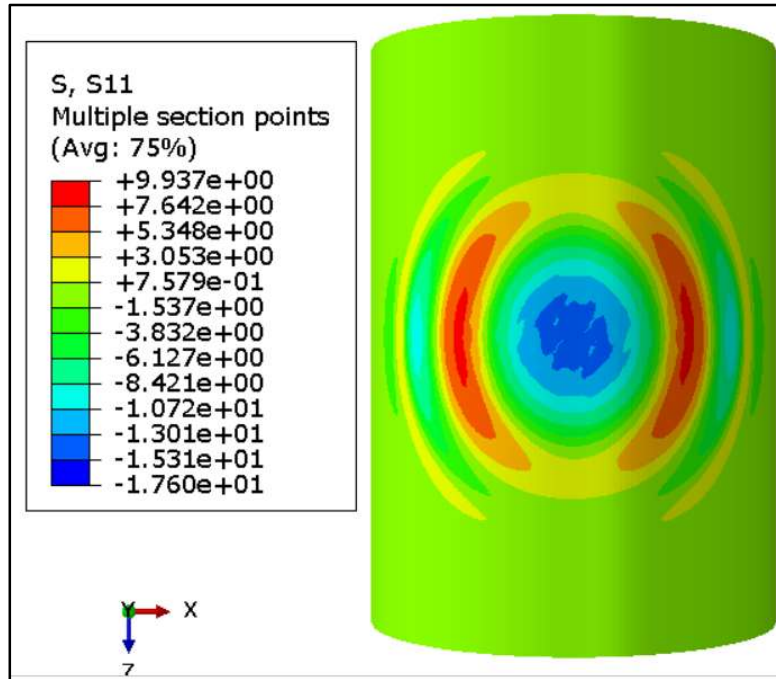


Figure 61: SCPB-250-1-1

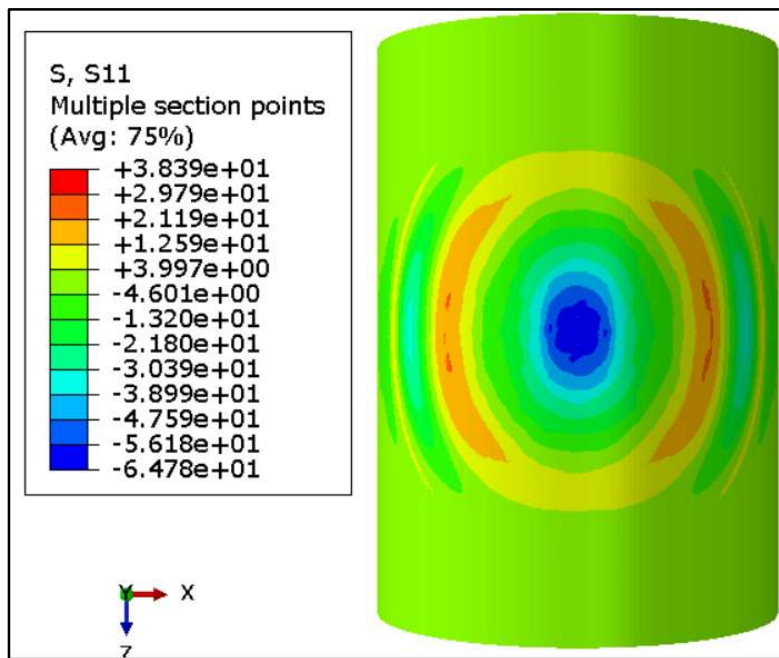


Figure 62: SCPB-250-5-1

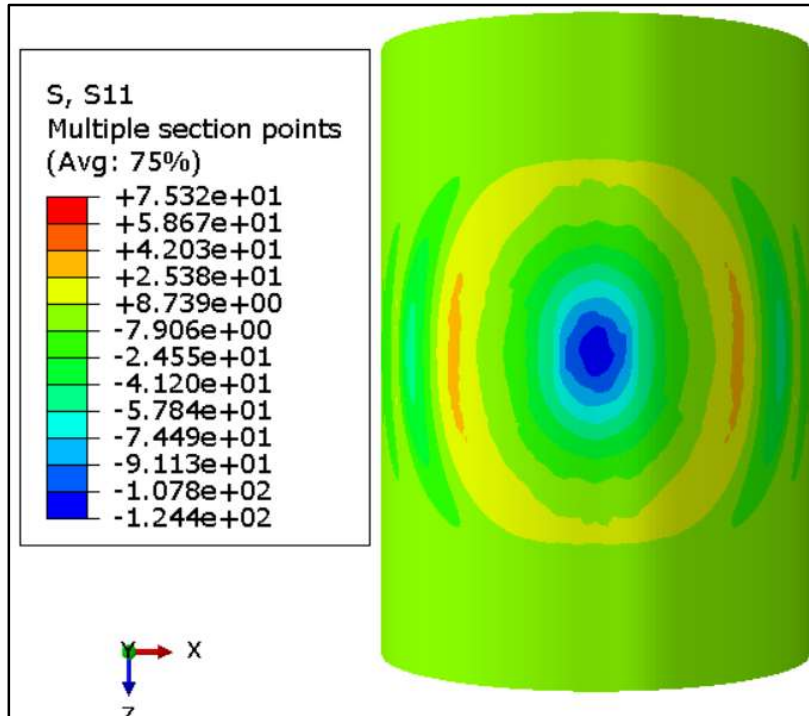


Figure 63: SCPB-250-10-1

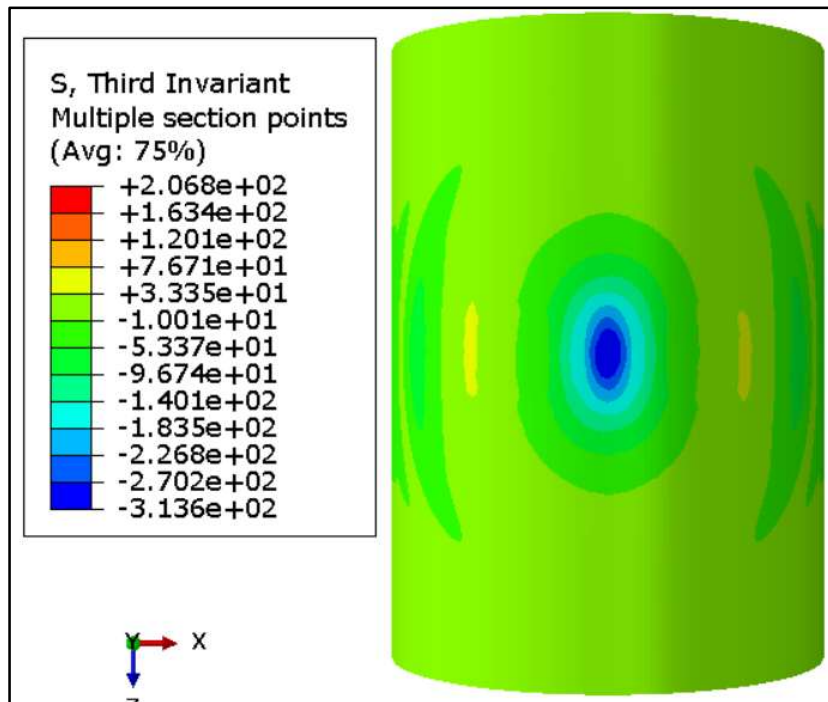


Figure 64: SCPB-250-25-1

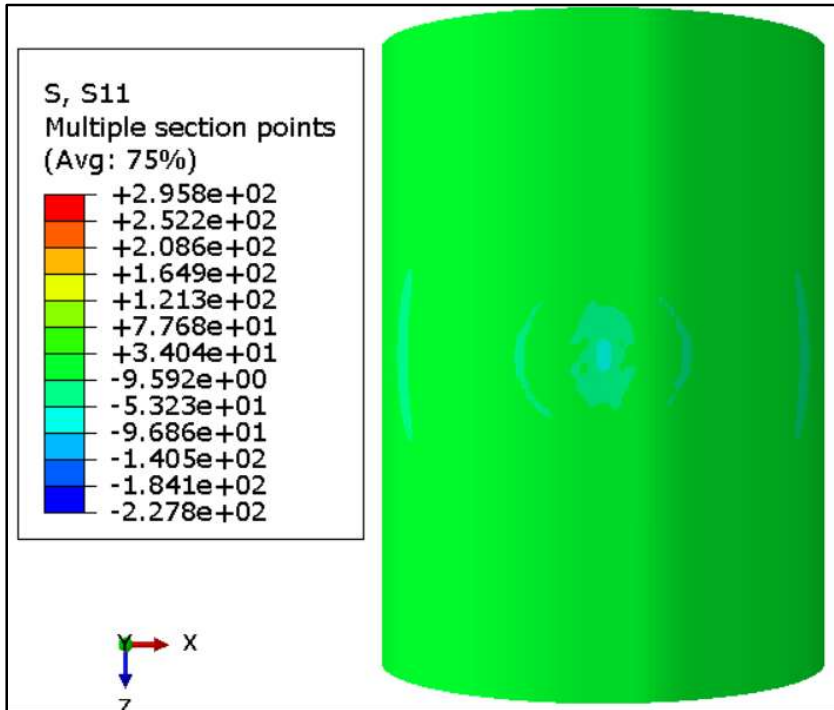


Figure 65: SCPB-300-1-0.1

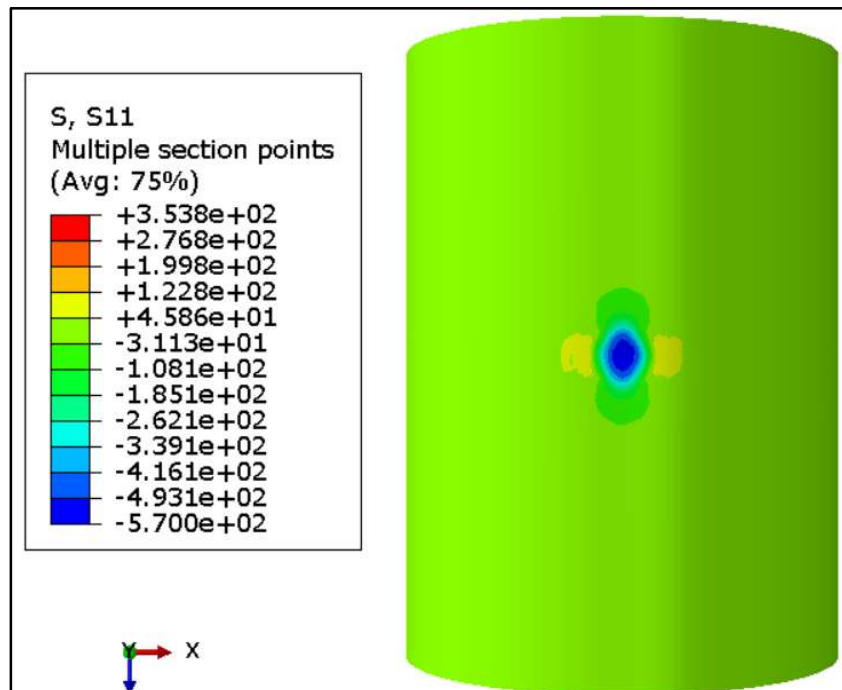


Figure 66: SCPB-300-5-0.1

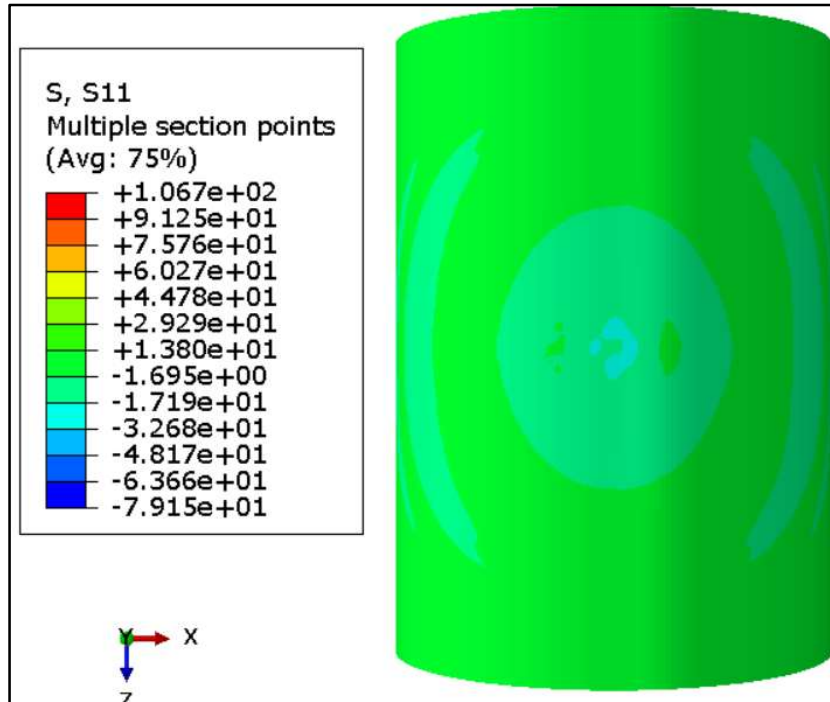


Figure 67: SCPB-300-1-0.25

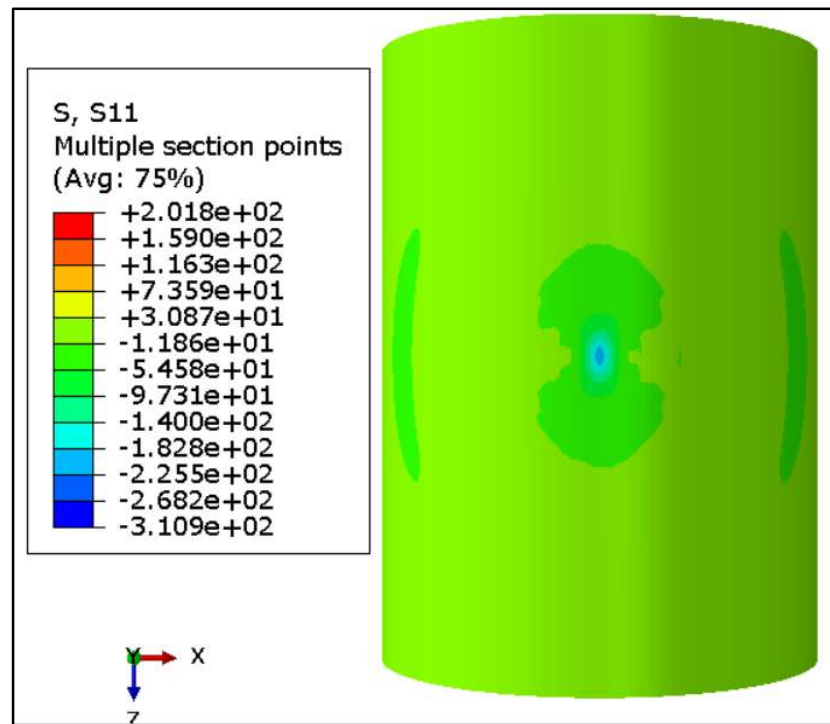


Figure 68: SCPB-300-5-0.25

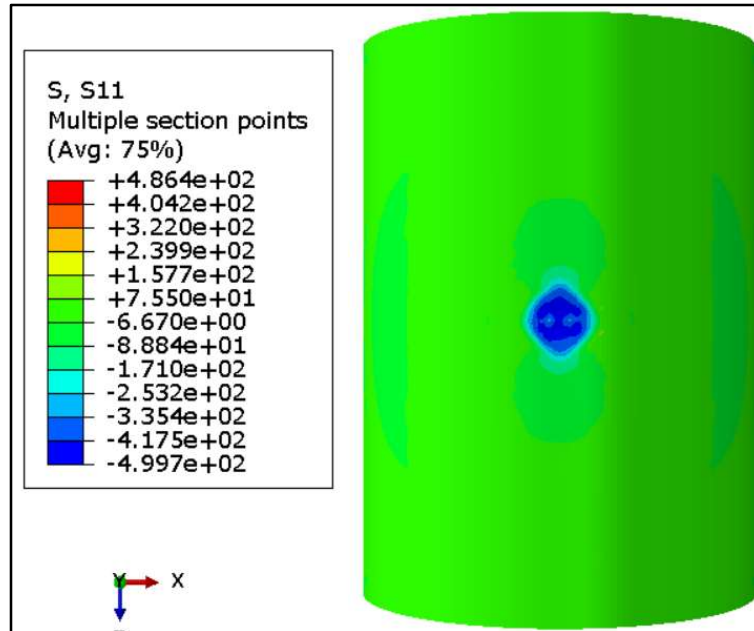


Figure 69: SCPB-300-10-0.25

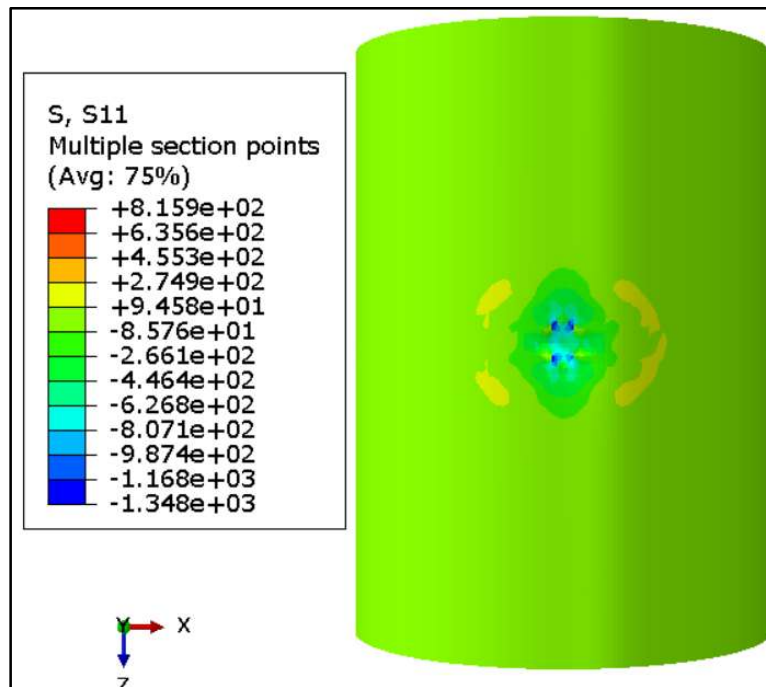


Figure 70: SCPB-300-25-0.25

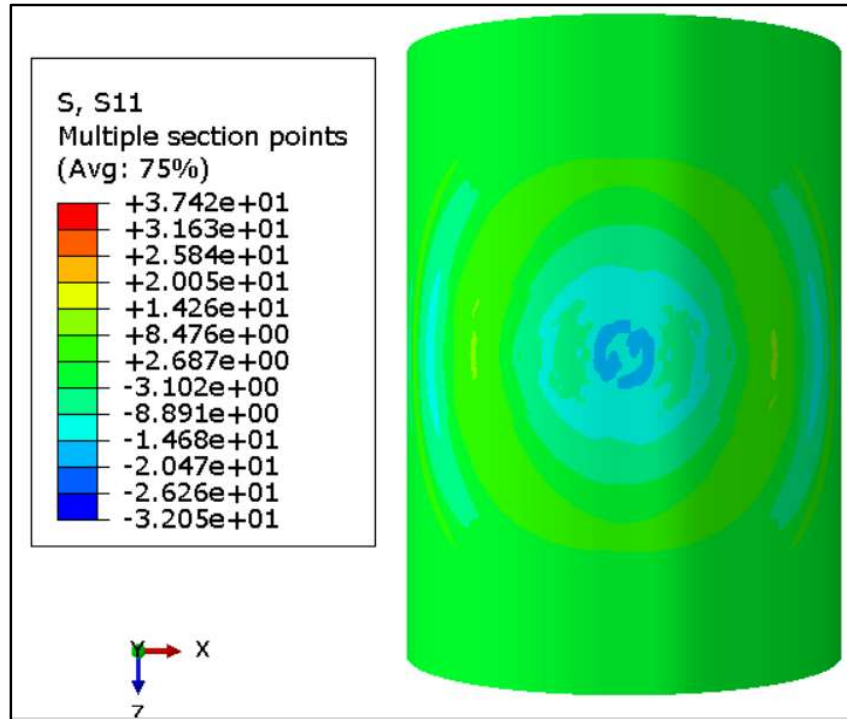


Figure 71: SCPB-300-1-0.5

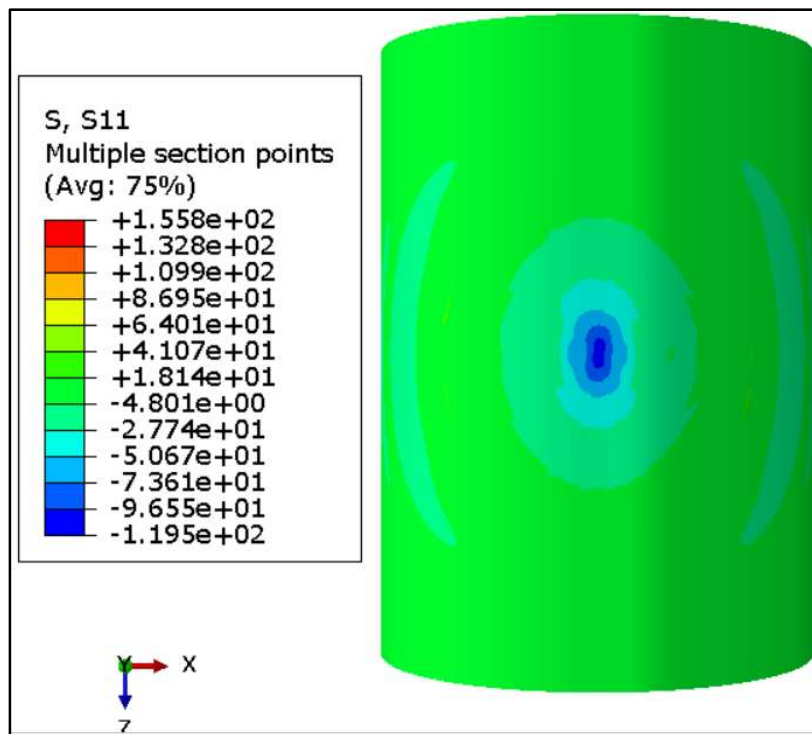


Figure 72: SCPB-300-5-0.5

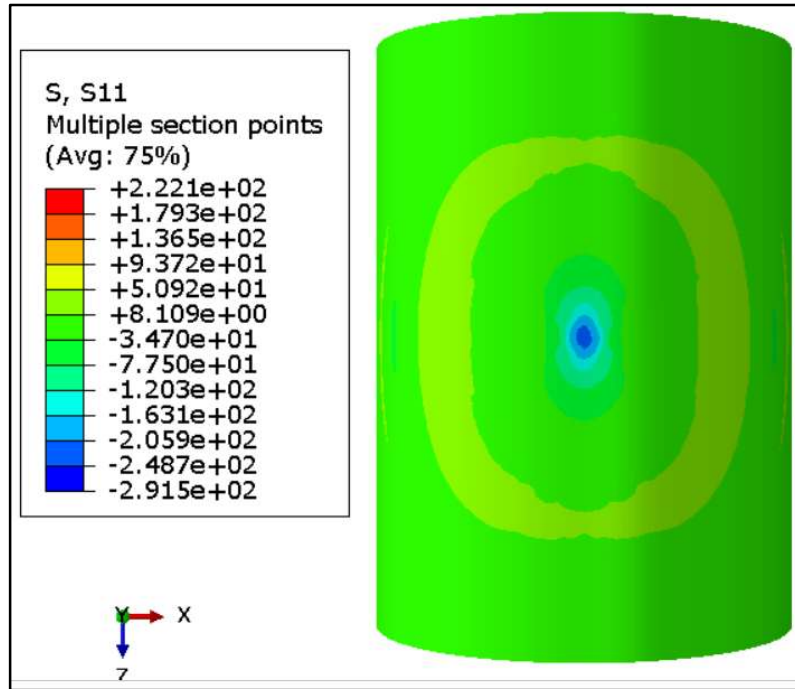


Figure 73: SCPB-300-10-0.5

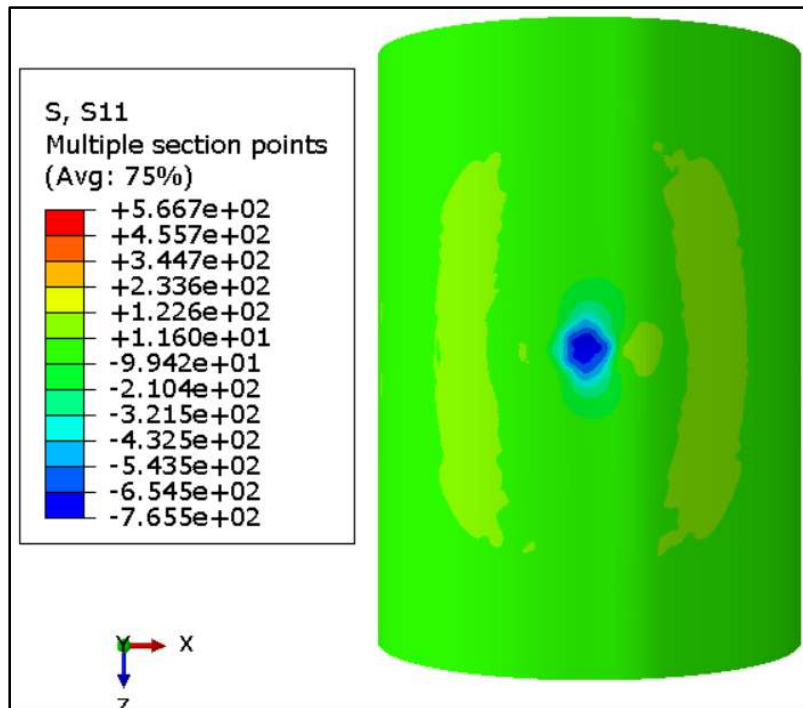


Figure 74: SCPB-300-25-0.5

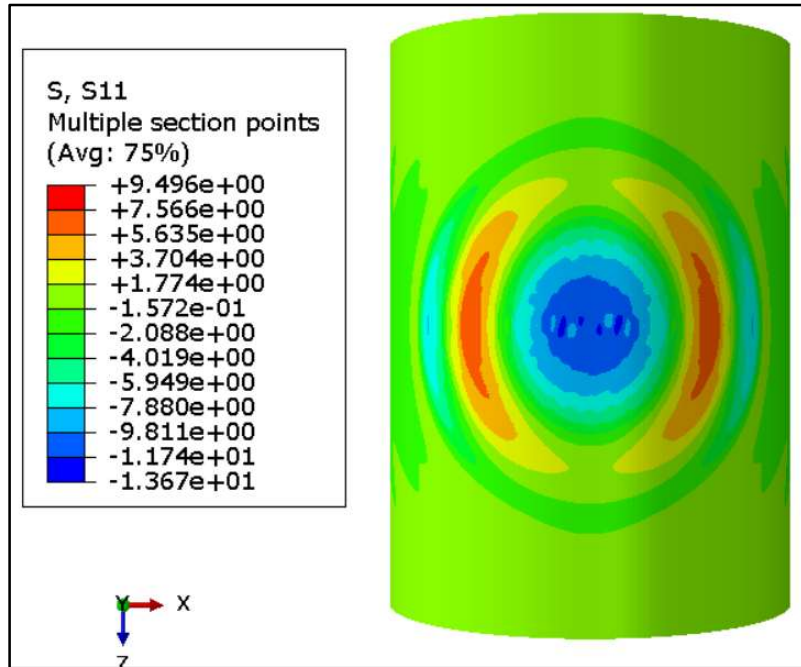


Figure 75: SCPB-300-1-1

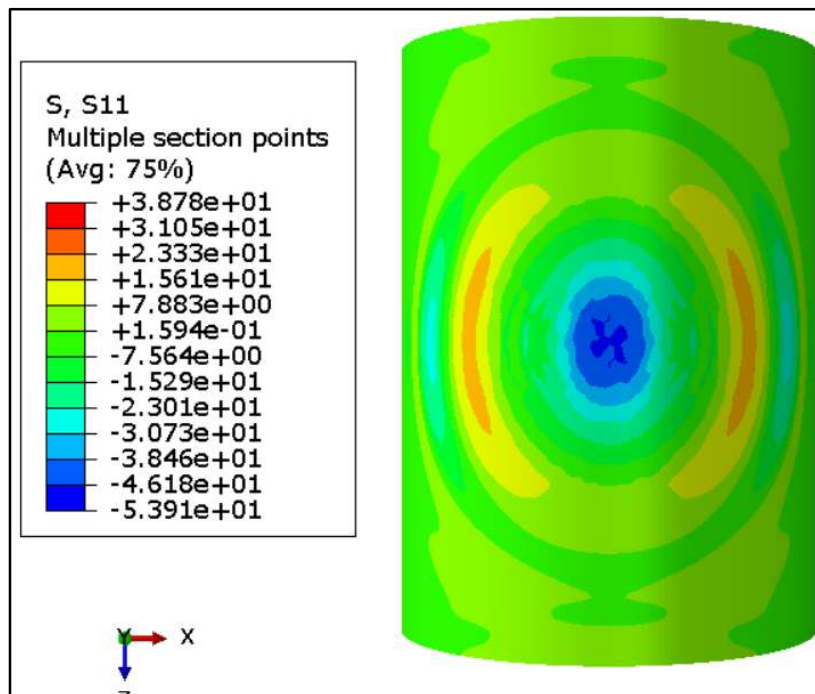


Figure 76: SCPB-300-5-1

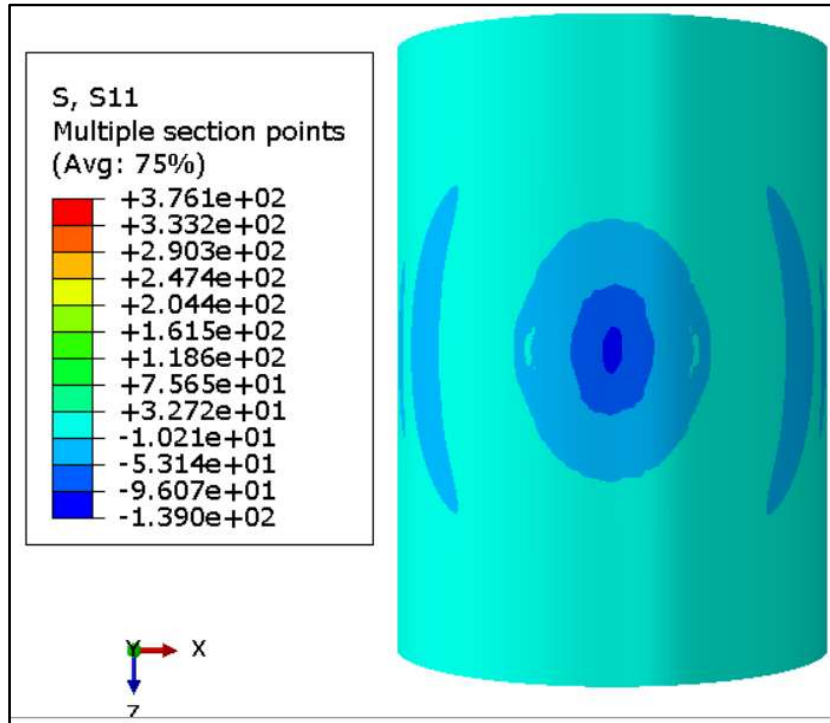


Figure 77: SCPB-300-10-1

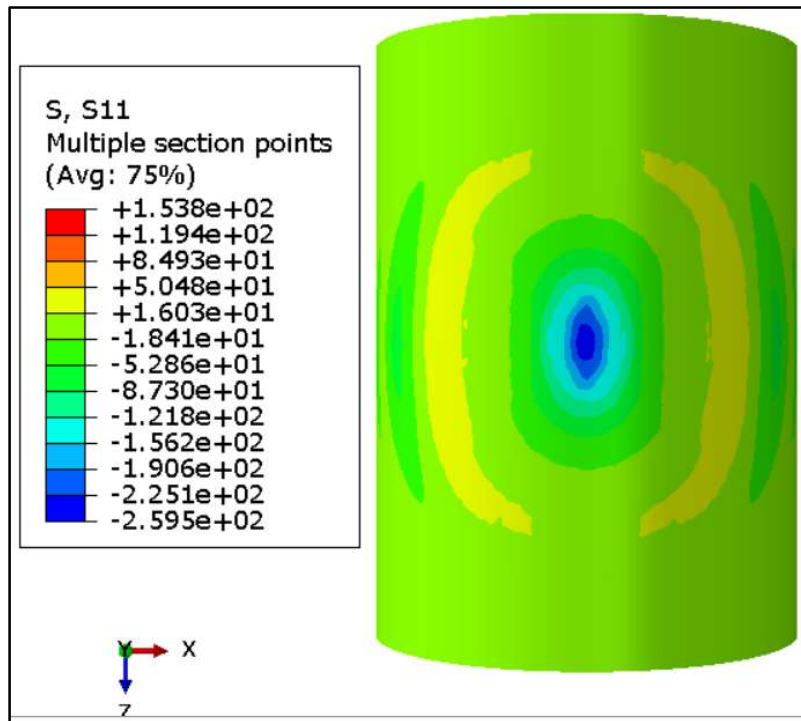


Figure 78: SCPB-300-25-1

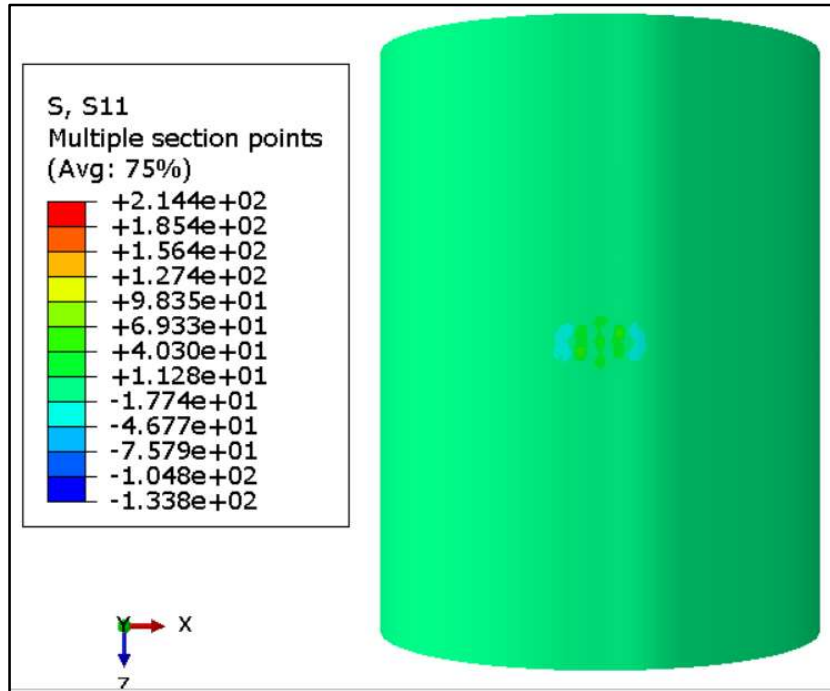


Figure 79: SCPB-500-1-0.1

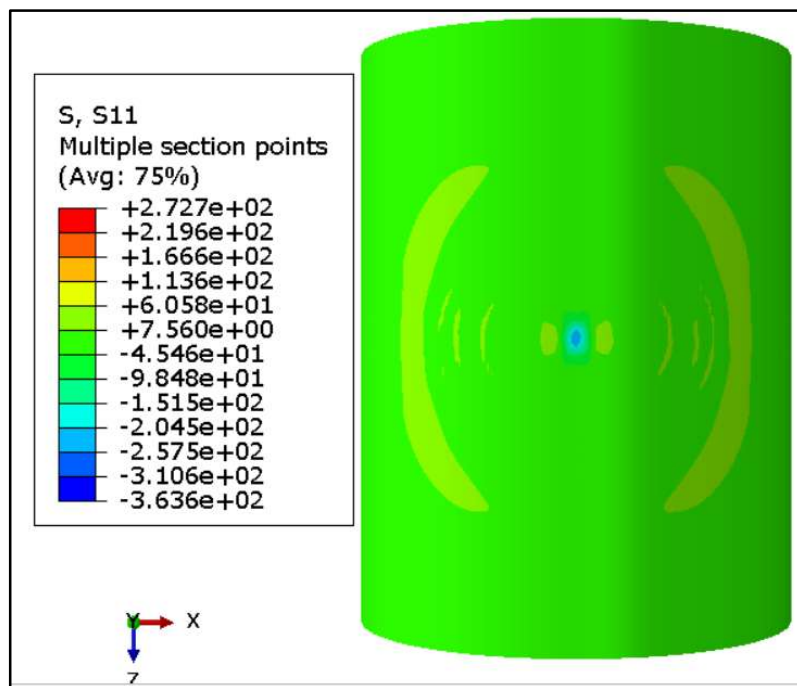


Figure 80: SCPB-500-5-0.1

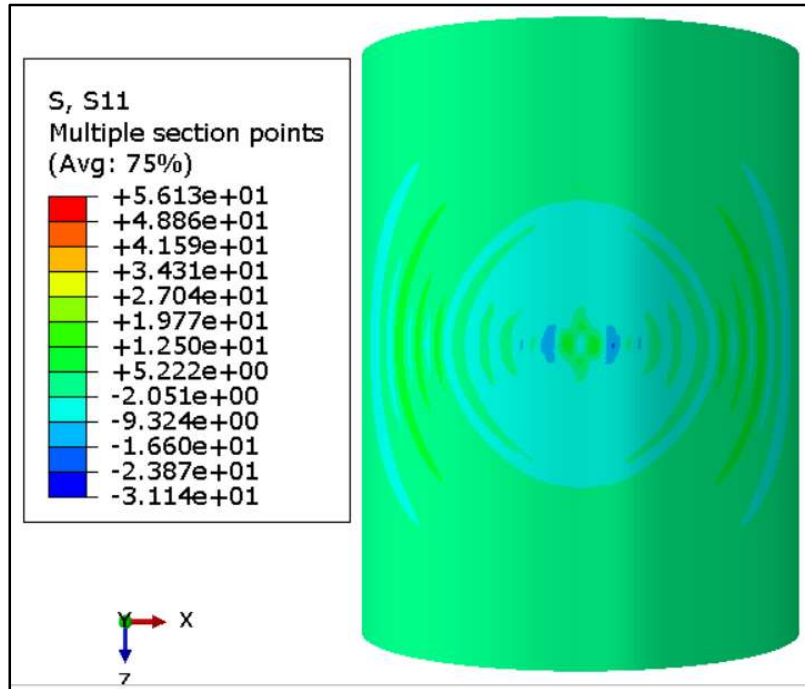


Figure 81: SCPB-500-1-0.25

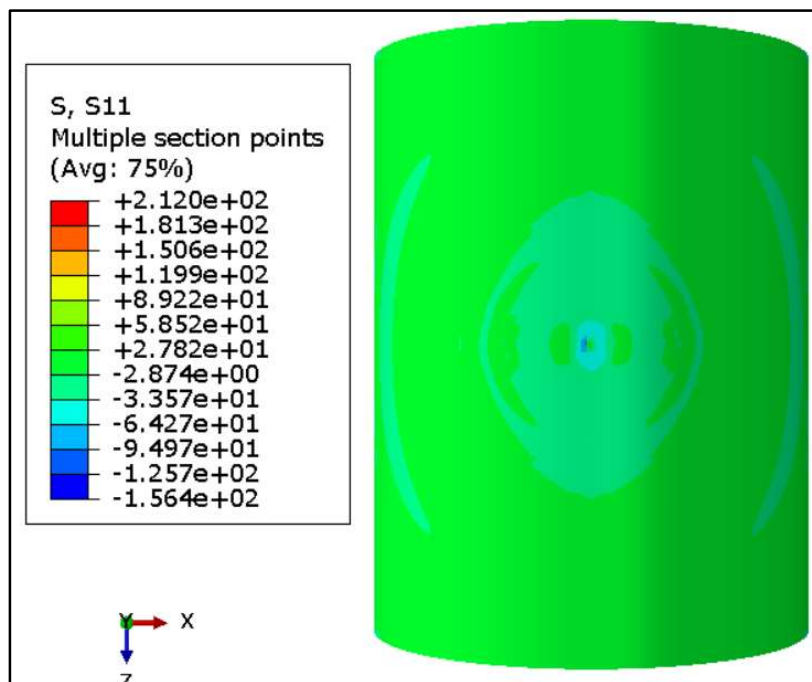


Figure 82: SCPB-500-5-0.25

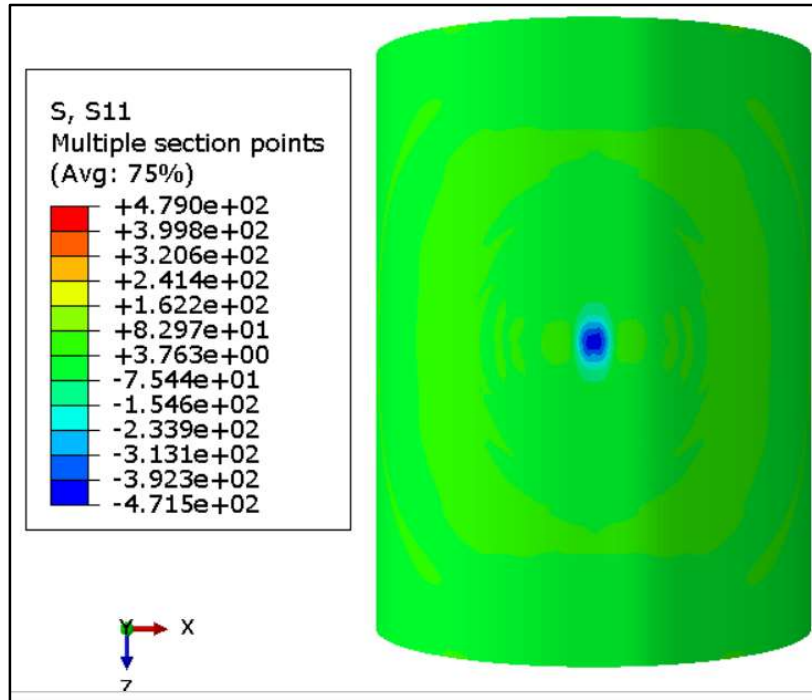


Figure 83: SCPB-500-10-0.25

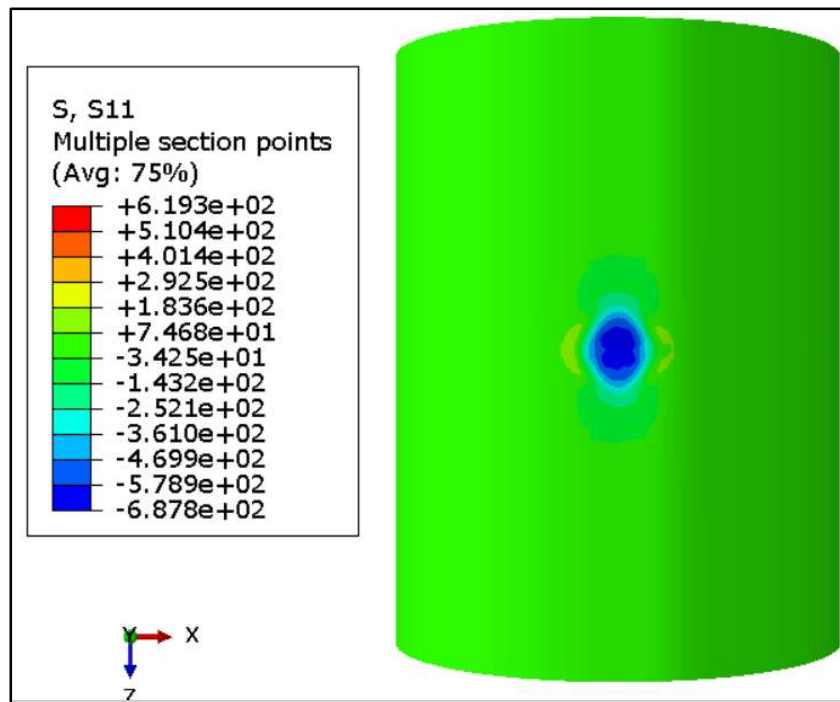


Figure 84: SCPB-500-25-0.25

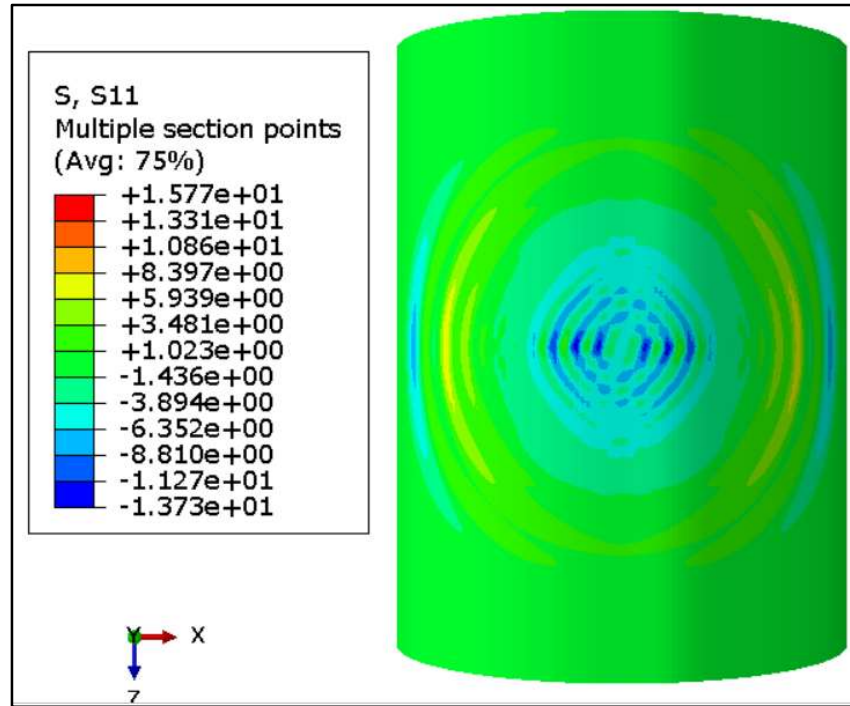


Figure 85: SCPB-500-1-0.5

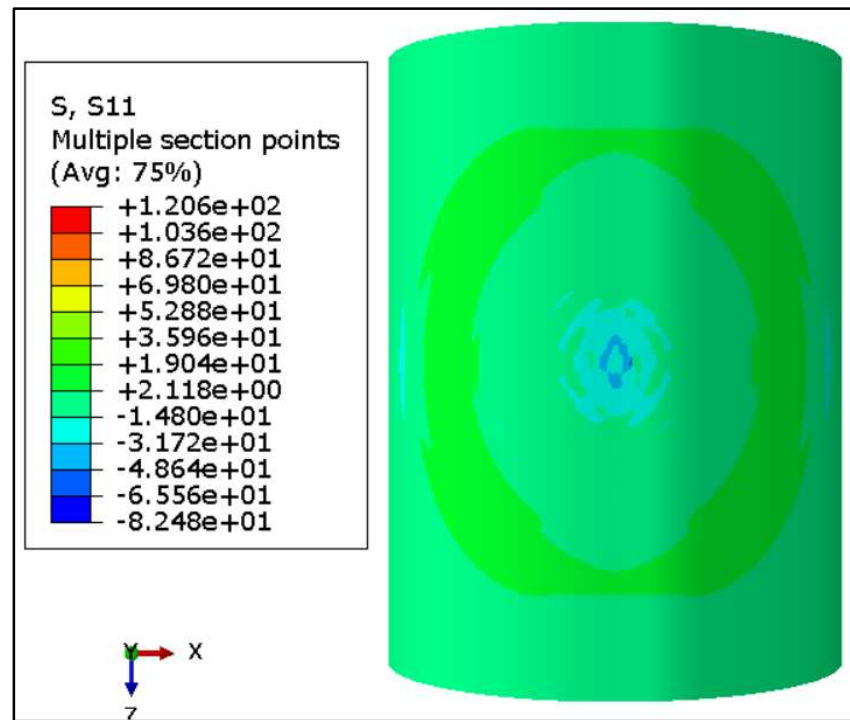


Figure 86: SCPB-500-5-0.5

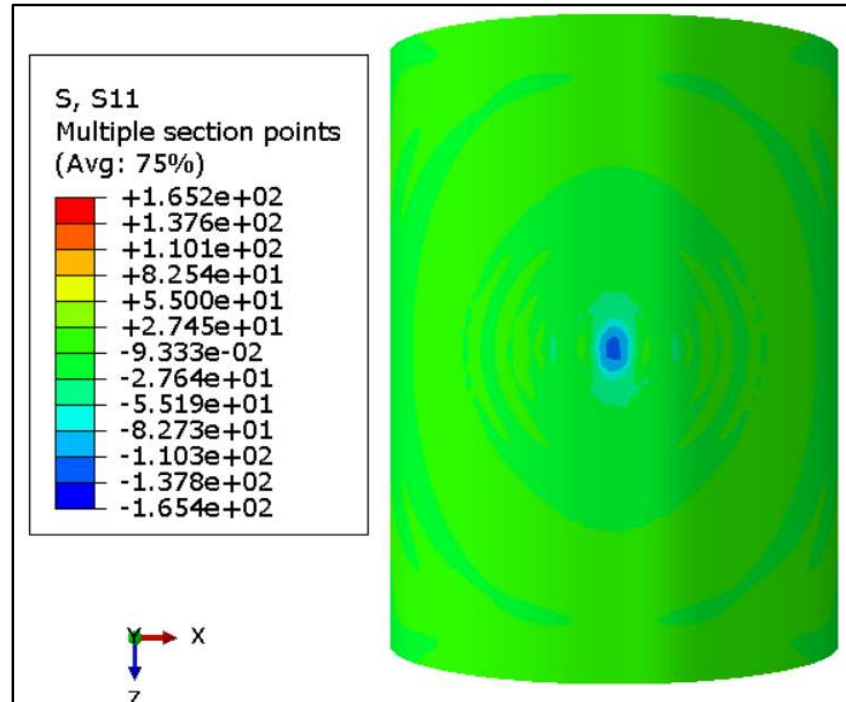


Figure 87: SCPB-500-10-0.5

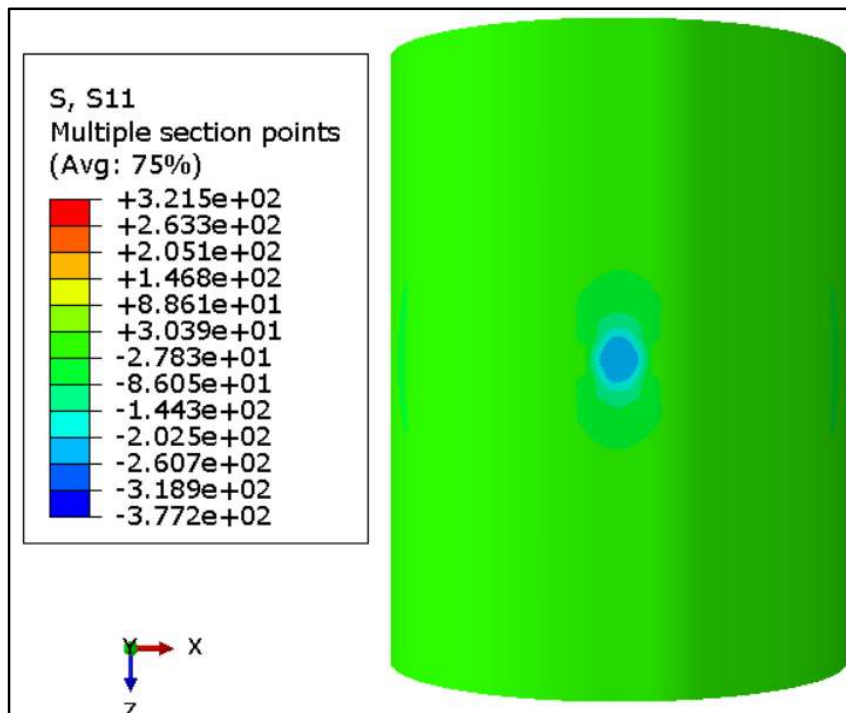


Figure 88: SCPB-500-25-0.5

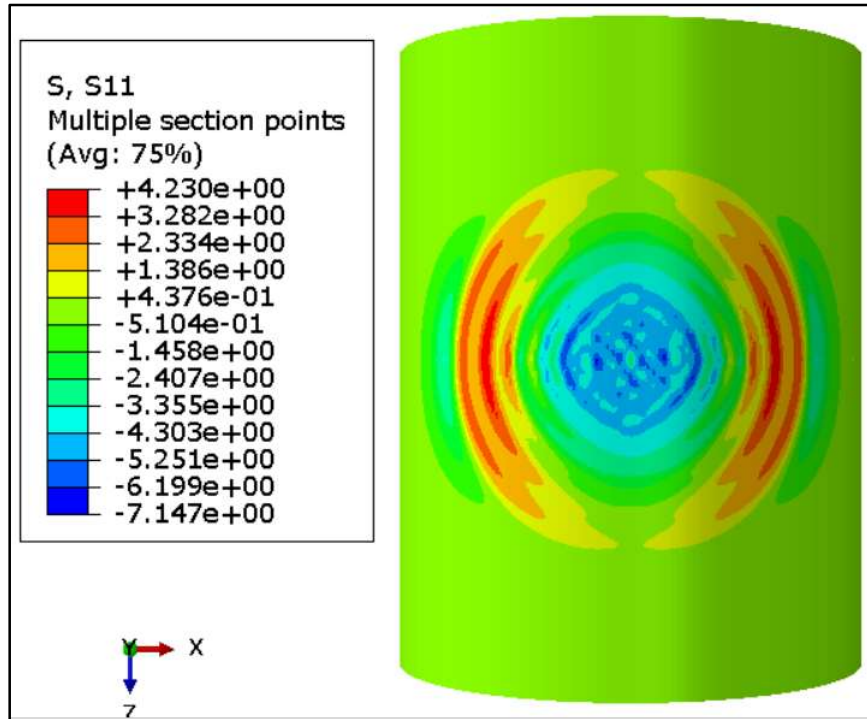


Figure 89: SCPB-500-1-1

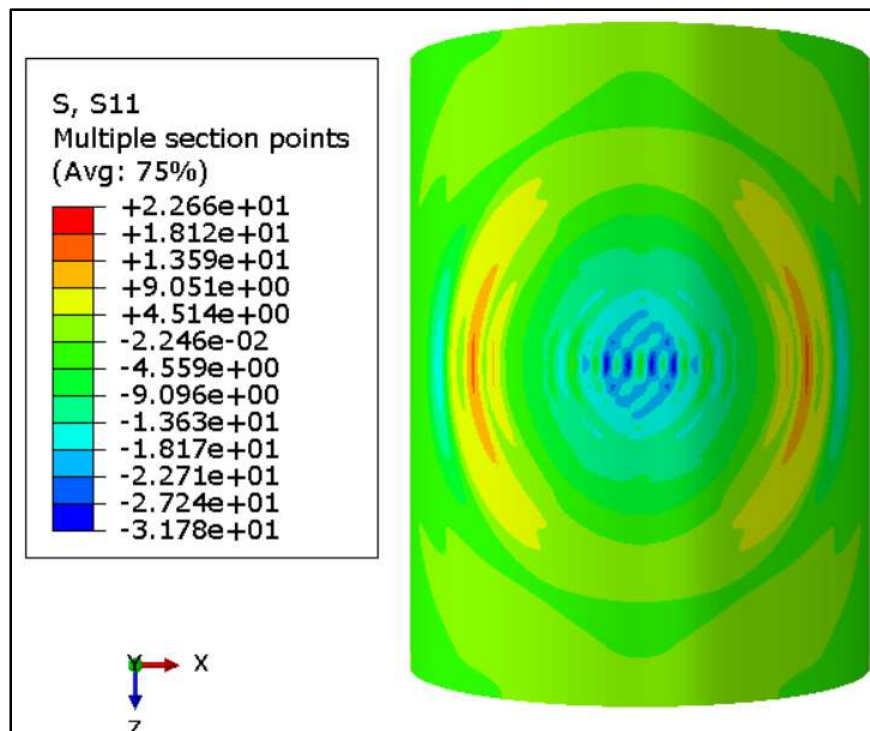


Figure 90: SCPB-500-5-1

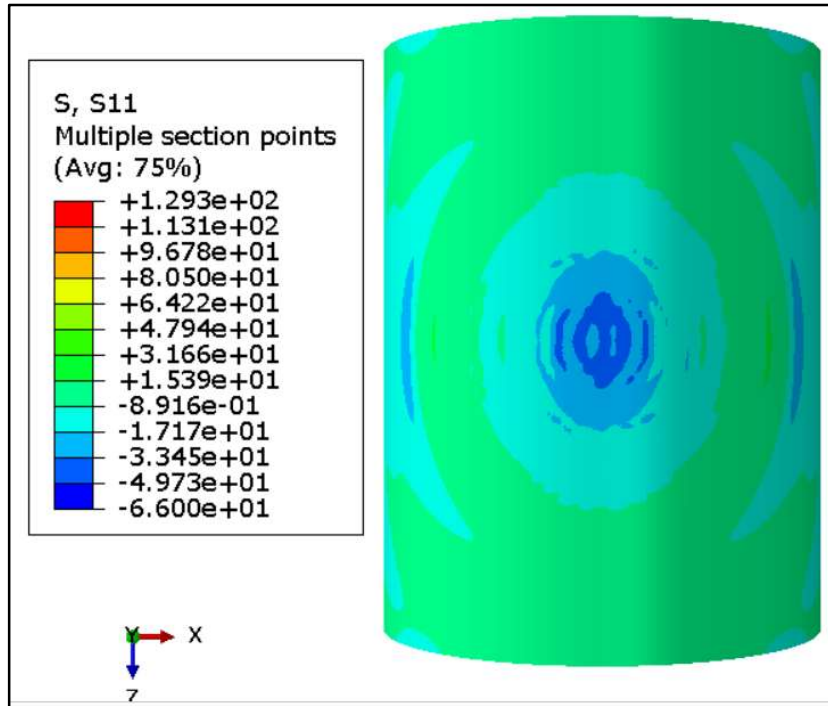


Figure 91: SCPB-500-10-1

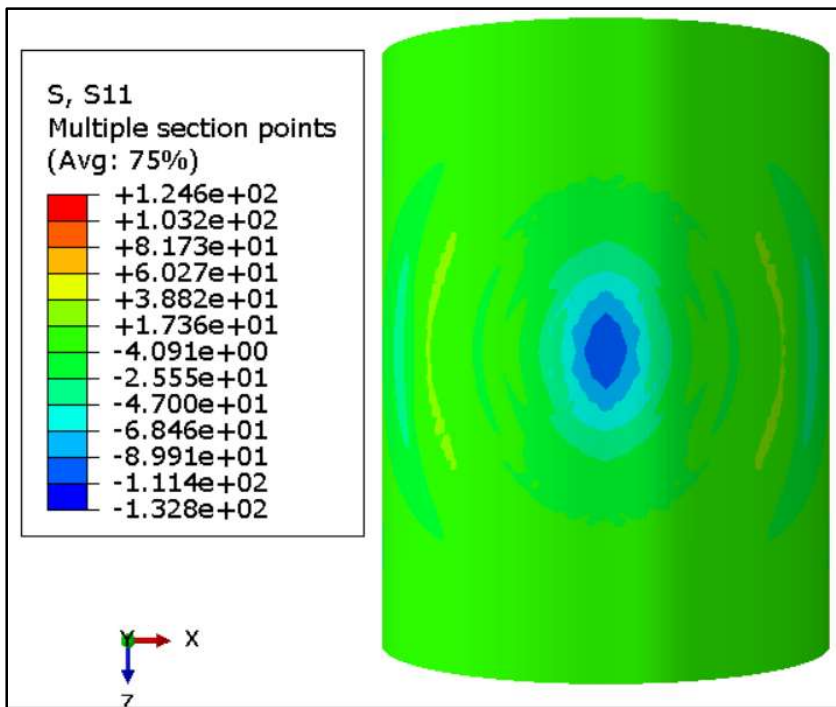


Figure 92: SCPB-500-25-1