DESIGN AND DEVELOPMENT OF A LABORATORY BASED MECHANISM FOR TESTING OF BLAST MITIGATION MATERIAL SYSTEMS

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by

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This thesis is dedicated to my beloved parents, whose unwavering support and guidance have profoundly shaped my journey; to my teachers, whose wisdom and encouragement have inspired my pursuit of knowledge; to my siblings, who have been my lifelong companions and motivators; to my siblings-in-law and in-laws, who were there to listen to success and failure stories; to the curious niblings for their thought provoking queries; to my wonderful wife, whose love and patience have been my anchor throughout this endeavour; and to my toddler, who fills my life with joy and purpose. Thank you all for being the pillars of strength in my life.

Certificate

This is to certify that the PhD thesis titled **"Design and Development of a Laboratory based Mechanism for Testing of Blast Mitigation Material Systems"** submitted by **Dhruv Narayan** to the **Indian Institute of Technology Delhi** for the degree of **Doctor of Philosophy**, is an original work carried out under my supervision.

The research presented in this thesis has been conducted with integrity and diligence, contributing valuable insights to the field of Instrumentation and Blast Mechanics. The candidate has demonstrated a high level of commitment and dedication throughout the research process, exhibiting both intellectual rigour and creativity in addressing complex problems.

I have closely monitored the progress of this research, providing guidance and support at each stage. The candidate has shown exceptional ability in conducting independent research, critically analysing data, and synthesizing information from various sources. This work reflects not only the candidate's capabilities but also their passion for advancing understanding in their area of study.

Furthermore, I confirm that, to the best of my knowledge, the results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma. This assertion underscores the originality and authenticity of the work presented herein.

The candidate has adhered to all ethical standards required for conducting research, ensuring that all necessary approvals were obtained where applicable. The research was conducted with respect for all relevant guidelines and regulations, reflecting a commitment to academic integrity.

In conclusion, I wholeheartedly endorse this thesis for submission as part of the requirements for the PhD degree. I believe that this work will make a meaningful contribution to the field and serve as a foundation for future research endeavours.

Date:
Place:

Prof. Naresh Bhatnagar
Department of Mechanical Engineering,
Indian Institute of Technology Delhi.

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This thesis is a testament not only to my efforts but also to the collaborative spirit that has surrounded me throughout these years of academic pursuit. To all those who have played a role in this journey - thank you for your kindness, encouragement, patience, and belief in me when I needed it most.

-Dhruv Narayan

Abstract

Explosions or blasts may be dangerous or lethal to humanity. Explosions kill humans through shock wave, splinters and impact against walls and heavy objects. Special personal protection equipment (PPE) are required to ensure safety while working in situations where explosions are anticipated such as terrorist attacks, military warfare, de-mining and bomb disposal. These PPEs are as heavy as 26 kg and it is difficult to perform the above mentioned duties while wearing them. Therefore research is required to develop new generation of materials that can mitigate the effect of explosions.

Development of lightweight material systems for blast mitigation applications requires regular experimentation. As blast experiments are expensive and hazardous, alternative experimental methods need to be explored. This thesis is an exploration towards a laboratory based testing method for assessing the performance of materials against blast loading. It is an attempt towards development of a testing method that may help avoid field blast tests, or at least reduce the frequency of field testing. The testing methodology under consideration includes simultaneous impact of PU foam projectiles and Fragment Simulating Projectiles (FSPs) onto a target panel. The foam impact provides a shock loading similar to blast loading and FSP impact simulates the impact due to splinters.

This PhD research is a comprehensive approach towards development of a laboratory based mechanism for testing of blast mitigation material systems from scratch. This research work includes design and fabrication of a single stage air gun for propelling the projectiles, fabrication and calibration of a ballistic chronograph to measure the projectile speed, characterization of PU foam used for impact experiments, development of various testing fixtures, and demonstration of the laboratory based testing methodology.

विस्फ़ोट शामक पदार्थों की प्रणाली का परीक्षण करने हेतु प्रयोगशाला आधारित तंत्र की अभिकल्पना एवं विकास

सारांश

विस्फोट या धमाके मानवता के लिए घातक या मारक हो सकते है। विस्फोट मनुष्यों को प्रघाती तरंगों, अति द्रुत गतिमान सूक्ष्म खण्डकों और दीवारों या अन्य भारी वस्तुओं पर आघात के माध्यम से मारते हैं। आतंकवादी हमले, सैन्य युद्ध, विस्फोटक सुरंगों या विस्फोटकों का निष्क्रियकरण जैसी गतिविधियों में सुरक्षा सुनिश्चित करने के लिए विशेष व्यक्तिगत सुरक्षा उपकरण की आवश्यकता होती है। ये उपकरण २६ किलोग्राम तक भारी होते हैं और इन्हें पहनकर उपर्युक्त कर्त्तव्यों का पालन करना कठिन होता है, इसलिए विस्फोट के प्रभाव को कम करने हेतु आधुनिक विस्फोट शामक पदार्थ विकसित करने के लिए गहन अनुसंधान की आवश्यकता है।

विस्फ़ोट शामक पदार्थों की प्रणाली को विकसित करने के लिये निरन्तर परीक्षण करते रहना आवश्यक है। विस्फोट सम्बन्धित प्रयोग अत्यधिक महंगे और घातक होते हैं इसलिये इस सन्दर्भ में वैकल्पिक प्रयोगात्मक विधियों के विकास की आवश्यकता है। यह शोध एक प्रयोगशाला आधारित परीक्षण विधि की अभिकल्पना और विकास की ओर एक प्रयास है जो विस्फ़ोट शामक पदार्थों की प्रणालियों के प्रदर्शन का प्रघाती तरंगों के भारण के विरुद्ध, मूल्यांकन करने में सहायता कर सकता है।

इस नवीन परीक्षण विधि की सहायता से, विस्फ़ोट शामक पदार्थों के विकास सम्बंधित शोध की, मैदानी विस्फोट परीक्षणों पर निर्भरता को समाप्त किया जा सकता है, या न्यूनातिन्यून, शोध के लिए आवश्यक मैदानी विस्फोट परीक्षणों की आवृत्ति को कम किया जा सकता है। विचाराधीन परीक्षण पद्धति में एक लक्ष्य पटल पर पोलीयूरीथेन (पीयू) फेन प्रक्षेप्य और खंडक अनुरूपी प्रक्षेप्य के संयुक्त आघात समावेशित है। पीयू फेन प्रक्षेप्य विस्फोटजनित तरंगों के समान प्रघाती भारण प्रदान करता है और खंडक अनुरूपी प्रक्षेप्य अति द्रुत गतिमान खण्डकों के कारण होने वाले प्रभाव को अनुरूपित करता है।

यह विद्यावारिधि अनुसंधान विस्फोट शामक पदार्थों की प्रणालियों के परीक्षण हेतु एक प्रयोगशाला आधारित तंत्र के विकास के लिए एक व्यापक समुपस्थान है। इस अनुसंधान कार्य में एक एकल चरण वायु प्रक्षेपित गोलिकास्त्र, जो फेन प्रक्षेप्य को वेग प्रदान करने के लिए है, की अभिकल्पना और निर्माण, एक प्राक्षेपिक गतिमापक यंत्र, जो प्रक्षेप्य की गति को मापता है, का निर्माण तथा अंश-शोधन, पीयू फेन पदार्थ, जो उपघात परीक्षण के लिए उपयोग किया गया है, के यांत्रिक गुणधर्मों का निश्चायन, विभिन्न स्थायीकर उपकरणों का विकास एवं निर्माण, और प्रयोगशाला आधारित परीक्षण पद्धति का प्रदर्शन समावेशित हैं।

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Abbreviations

Abbreviation	Expansion
ALPORAS	A brand name for a lightweight, closed-cell aluminium foam
ARDUINO	A brand name for microcontroller boards
B4C	Boron Carbide
BARC	Bhabha Atomic Research Center
BFD	Back Face Deformation
CoE	Center of Excellence
DIA-CoE	DRDO Industry Academia-Center of Excellence
FSP(s)	Fragment Simulating Projectile(s)
GSQR	General Staff Qualitative Requirements
HP	High Pressure
HSC	Hardened Steel Core
IITD	Indian Institute of Technology Delhi
IR	Infra-red
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LP	Low Pressure
micro-CT	micro Computed Tomography
MP	Medium Pressure
NIJ	National Institute of Justice, USA
PU	Polyurethane
PVC	Poly Vinyl Chloride
ROI	Region of Interest
STANAG	Standardization Agreement
TNT	Tri Nitro Toluene
UHMWPE	Ultra High Molecular Weight Poly Ethylene

Symbols

Symbol	Description
$\dot{\epsilon}$	Strain rate
$\dot{varepsilon}_0$	Reference strain rate
ε	Strain
ε_D	Densification strain of foam material
η	Polytropic efficiency of given thermodynamic process
γ	Ratio of specific heats for given gas
γ_f	Ratio of specific heats for gas present in front of the projectile
$\mathcal{H}$	Heaviside function
$\phi_1, \phi_2, y, \theta_D, \theta_T$	Local substitution variables
$\psi(\varepsilon)$	A linear function of strain used to define material model
ρ	Mass density of the given material
σ	Stress
σ_Y	Plateau strength of foam material at given strain rate
σ_Y^0	Plateau strength of foam material at reference strain rate
A	Cross section area of the projectile
a	Speed of sound of the given medium
a_{f0}	acoustic speed corresponding to gas present in front of the projectile
a_0	Speed of sound corresponding to initial chamber pressure
$A_0, ..A_n$	Parameters used in various constitutive models
b	Blast wave decay parameter
$B_1, ...B_6$	Parameters used in various constitutive models
C_{el}, C_{pl}	Speed of elastic and plastic stress waves, respectively
D	Distance between chronograph checkpoints A and B
d	Distance between IR source and IR sensor
D_0	Internal diameter of the gun breech/chamber
d_0	Stand off distance of blast
D_1	Internal diameter of the gun barrel
d_1	Diaphragm separating main chamber and buffer chamber
d_2	Diaphragm separating buffer chamber and gun barrel
E	Elastic Modulus
F	Force
F_{design}	Design load of fixture F2
F_{Euler}	Euler buckling load for slender members of fixture F2
fps	Frames per second captured by the camera
g	Acceleration due to gravity
h	height from which ball is dropped
L	Length of gun barrel
l	Instantaneous value of impacted length
L_0	Initial length of foam projectile
L_c	Length of chamber/breech
L_i	Final Impacted length of foam projectile

L_s	Length of the slender members of fixture F2
m	Mass of the projectile
M	Modulus function for given material model
m_0	Parameters used in constitutive model
m_g	Mass of gas contained in the chamber
M_x	Mach number of blast wave
Ma	Mach number
N_{pt}	Number of pre-trigger frames required
P	Instantaneous pressure of the system, Pressure behind the projectile
$P_{avg}^{est}, P_{avg}^{exp}$	Average of the estimated/experimental load from PU foam impact
P_{buf}	Pressure in the intermediate buffer chamber
$P_{max}^{est}, P_{max}^{exp}$	Maximum of the estimated/experimental load from PU foam impact
P_{neg}	Maximum negative underpressure of a blast wave
P_{pos}	Maximum positive overpressure of a blast wave
P_{ref}	Reference pressure for blast wave, ambient pressure
P_0	Initial chamber pressure
P_1	Initial pressure in front of the projectile
P_d	Burst pressure of the diaphragm
P_f	Instantaneous pressure in front of the projectile
P_r	Reflected overpressure in front of target as per Kinney Graham approach
R	Specific gas constant for given gas medium
R^2	coefficient of determination for the given curve-fit
R_{bright}, R_{cont}	Resistance used to control brightness/contrast of LCD
R_{lx}, R_{la}, R_{lb}	Series resistance with IR LED at checkpoint A/B
R_{px}, R_{pa}, R_{pb}	Load resistance with photodiode at checkpoint A/B
s	Side of the square cross section of slender members of F2
t	Time variable
t_0	Time after diaphragm burst when projectile speed equals the acoustic speed a_0
$\Delta t^{est}, \Delta t^{exp}$	Estimated/Experimental duration from PU foam impact
T	Time taken by projectile to move from checkpoint A to B
T_{delay}	$T - T_{off}$
t_{neg}	Negative phase duration of a blast wave
$T_{off,lag}$	Time taken by V_a to fall below 2.2 V Threshold voltage
T_{off}	Time taken by projectile to move across a checkpoint
t_{pos}	Positive phase duration of a blast wave
T_{start}, T_{stop}	Time when projectile crosses checkpoint A/B
T_x	Time taken by signal to reach camera
T_y	Time taken by projectile to enter into camera ROI from checkpoint B
t_d	Positive phase duration of blast wave as per Kinney Graham approach
T_K	Temperature in Kelvin
$T_M, T_{delay,M}, T_{off,M}$	Measured Values by the Photodiode circuit
$T_P, T_{off,P}$	Programmed values fed to IR LED circuit
$T_S, T_{delay,S}, T_{off,S}$	Simulated values by the IR LED circuit
u	Particle velocity for given medium
u	Particle displacement (Chapter 5)
u_∞	Theoretical maximum speed of projectile for infinitely long barrel

u_{lim}	Limiting speed of the projectile for non evacuated barrels
u_D	Uncertainty in measurement of distance
u_d	Velocity of a pressure disturbance
u_p	Velocity of the projectile
u_T	Uncertainty in measurement of time
u_v	Uncertainty in the measurement of projectile velocity
V	Instantaneous volume occupied by gas
v	Approach velocity of projectile and target
v	Projectile velocity (Chapter 3)
v_{ball}	Velocity of ball during ball drop test
v_{max}	Maximum measurable speed by given chronograph
V_0	Initial volume occupied by gas, Chamber volume
v_1	Velocity of part of projectile where shock wave has not reached
v_2	Velocity of part of projectile where shock wave has reached
V_x, V_a, V_b	Voltage measured at Photodiode circuit of Checkpoint A/B
v_D	Particle velocity of deformed region of foam projectile
v_d	Particle velocity of foam projectile
w	Size of one foam cell
W_{TNT}	TNT equivalent weight
x	position variable, instantaneous position of projectile
x_0	Position where projectile speed equals the acoustic speed a_0
x_{p1}	Position of projectile where it meets the first reflected rarefaction wave
x_r	Instantaneous position of the reflected rarefaction wave
z	Acoustic impedance of the given gaseous medium (ρa)
Z	Scaled distance of blast