BLAST RESISTANT DESIGN OF STRUCTURES USING ADVANCED MATERIALS AND SYSTEM

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SCHOOL OF INTERDISCIPLINARY RESEARCH
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by

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SCHOOL OF INTERDISCIPLINARY RESEARCH

Submitted

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Dedicated to My Beloved Family

Certificate

This is to certify that the thesis entitled "**BLAST RESISTANT DESIGN OF STRUCTURES USING ADVANCED MATERIALS AND SYSTEM**" which is being submitted by **Ms. Lekhani Gaur (2017SRZ8644)** to the **Indian Institute of Technology (IIT) Delhi** for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of the student's bonafide research work carried out by her. She worked under our supervision for the submission of the thesis, which to our knowledge, has reached the requisite standard as demonstrated by excellent international publications in journals and conferences.

To the best of our knowledge and belief, the contents of her research work have not been submitted in full or in part to any other university or institute to confer a degree or diploma.

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Abstract

The interdisciplinary research reported in this thesis can be broadly classified in two domains of blast resistant design of structures using a) advanced materials, and b) advanced system. The first domain deals with the application of fiber reinforced concrete (FRC) in civil and defense structures subjected to blast and shock loading scenario. Initially, a comprehensive experimental investigation on the shockwave propagation and its attenuation over the shocktube length has been carried out using Nitrogen and Helium gases with three different driver section length of the large scale shocktube installed at IIT Delhi. It is established that the experimental facility can be utilized to simulate both the blast and shock waves with a range of peak reflected pressure (0.3 – 2.2 MPa), Mach Number (1.38 - 2.23), and positive impulse (1.8 – 34 kPa-s) with the suitable combination of driver pressure, driver section length and driver gas.

Thereafter, the dynamic response of concrete slabs with planar dimensions 580 mm × 580 mm and two thicknesses (30 and 50 mm) under shock load has been analyzed using both strain gauges and digital image correlation (DIC) with shocktube. Herein, M50 grade of concrete with two fibers (basalt and steel) have been considered with four combinations namely, plain cement concrete (PCC), steel FRC, basalt FRC, hybrid FRC (steel and basalt) with total fiber content 0.5%. Static characterization of all four materials has been done using compressive strength, split tensile strength, and flexural strength tests at quasi-static loading conditions prior to dynamic experiments. The improved ductility and toughness of concrete mix due to inclusion of fibers are observed in both static and dynamic experiments. It is demonstrated that hybrid FRC outperforms the mono FRC and PCC under blast load conditions.

The second domain of present research deals with the application of inertia based dynamic vibration absorber (IDVA) in blast resistant sandwich panels. In this context, a prototype of ball screw inerter has been designed, and an experimental setup of an inerter in series with spring–dashpot elements has been developed and characterized using a dynamic Universal Testing Machine (UTM) over a frequency range from 0.5 to 10 Hz. Further, a numerical study has been carried out which delineates the nonlinear elasto-plastic analysis of two steel plates sandwiched with mechanical elements (spring-dashpot-inerter) based DVA subjected to a uniformly distributed blast load on one of its surfaces. This steel plates' assembly is transformed into an equivalent multi degree of freedom (MDOF) system using transformation factors. A detailed parametric study has been carried out for comparative assessment of performance of different configurations of IDVAs under blast load and a novel configuration

has been proposed which performs best among all the configurations. Further, the nondimensional parametric and optimization studies of this novel configuration-based assembly, have been carried out when subjected to a range of blast load in terms of scale distance. It was concluded that the combined effect of the various components of the attachment (plate thickness, inertance, stiffness and damping) to the front plate plays the key role in deciding the performance in terms of back plate deformation and force transmissibility.

सार

इस थीसिस में प्रस्तुत अंतःविषय अनुसंधान को मुख्य रूप से ए) उन्नत सामग्री, और बी) उन्नत प्रणाली का उपयोग करके संरचनाओं के विस्फोट प्रतिरोधी डिजाइन के दो क्षेत्रों में वर्गीकृत किया जा सकता है। पहला क्षेत्र विस्फोट और शॉक लोडिंग परिदृश्य के अंतर्गत नागरिक और रक्षा संरचनाओं में फाइबर प्रबलित कंक्रीट (FRC) के अनुप्रयोग से संबंधित है। प्रारंभ में, आई आई टी दिल्ली में स्थापित बड़े पैमाने के शॉकट्यूब की तीन अलग-अलग ड्राइवर सेक्शन लंबाई के साथ नाइट्रोजन और हीलियम गैसों का उपयोग करके शॉकवेव की क्रमागत उन्नति और शॉकट्यूब लंबाई के साथ इसके क्षीणन पर एक व्यापक प्रयोगात्मक जांच की गई है। यह स्थापित किया गया है कि इस प्रयोगशाला का उपयोग ड्राइवर दबाव, ड्राइवर सेक्शन लंबाई और ड्राइवर गैस के उपयुक्त संयोजन के साथ अधिकतम परावर्तित दबाव (0.3 - 2.2 MPa), मेक संख्या (1.38 - 2.23), और धनात्मक आवेग (1.8 - 34 kPa-s) की सीमा के साथ विस्फोट और शॉक तरंगों दोनों का सृजन करने के लिए किया जा सकता है।

इसके बाद, 580 मिमी x 580 मिमी और दो मोटाई (30 और 50 मिमी) के समतल आयामों वाले कंक्रीट स्लैब की गतिशील प्रतिक्रिया का विश्लेषण स्ट्रेन गेज और डिजिटल इमेज कोरिलेशन (डीआईसी) दोनों का उपयोग शॉकट्यूब से उत्पन्न शॉक लोड के साथ किया गया है। यहाँ, दो फाइबर (बासाल्ट और स्टील) को कंक्रीट के M50 ग्रेड पर चार संयोजनों के साथ उपयोग में लिया गया है, अर्थात् सादा सीमेंट कंक्रीट (पीसीसी), स्टील एफआरसी, बासाल्ट एफआरसी, हाइब्रिड एफआरसी (स्टील और बेसाल्ट) जिसमें कुल फाइबर सामग्री 0.5% है। सभी चार कंक्रीट सामग्रियों का स्थैतिक निस्रूपण, गतिशील प्रयोगों से पहले स्थैतिक लोडिंग स्थितियों में संपीड़न शक्ति, विभाजित तन्य शक्ति और लचीली शक्ति परीक्षणों का उपयोग करके किया गया है। फाइबर के समावेश के कारण कंक्रीट मिश्रण की बेहतर लचीलापन और कठोरता स्थैतिक और गतिशील दोनों प्रयोगों में देखी गई है। यह प्रदर्शित किया गया है कि ब्लास्ट लोड स्थितियों के अंतर्गत हाइब्रिड एफआरसी, मोनो एफआरसी और पीसीसी से बेहतर प्रदर्शन करता है।

वर्तमान शोध का दूसरा क्षेत्र विस्फोट प्रतिरोधी सैंडविच पैनलों में जड़त्व आधारित गतिशील कंपन अवशोषक (IDVA) के अनुप्रयोग से संबंधित है। इस संदर्भ में, बॉल स्क्रू इनर्टर का एक प्रोटोटाइप डिज़ाइन किया गया है, और स्प्रिंग-डैशपॉट तत्वों के साथ श्रृंखला में एक इनर्टर का एक प्रायोगिक सेटअप विकसित किया गया है | 0.5 से 10 हर्ट्ज की आवृत्ति रेंज पर एक गतिशील यूनिवर्सल टेस्टिंग मशीन (UTM) का उपयोग करके इसका गतिशील निस्रूपण किया गया है। इसके अलावा, एक संख्यात्मक अध्ययन किया गया है जो यांत्रिक तत्वों (स्प्रिंग-डैशपॉट-इनर्टर) आधारित DVA के साथ सैंडविच की गई दो स्टील प्लेटों के अरेखीय इलास्टो-प्लास्टिक विश्लेषण को दर्शाता है, जब इसकी एक सतह पर समान रूप से वितरित ब्लास्ट लोड लगाया जाता है | इस स्टील प्लेट्स की असेंबली को परिवर्तन कारकों का उपयोग करके समतुल्य मल्टी डिग्री ऑफ फ्रीडम (एमडीओएफ) प्रणाली में परिवर्तित किया जाता है। ब्लास्ट लोड के अंतर्गत आईडीवीए के विभिन्न विन्यासों के प्रदर्शन के तुलनात्मक मूल्यांकन के लिए एक विस्तृत पैरामीट्रिक अध्ययन किया गया है और एक नया विन्यास प्रस्तावित किया गया है जो सभी विन्यासों में सर्वश्रेष्ठ प्रदर्शन करता है। इसके अलावा, इस नवीन विन्यास-आधारित संयोजन के गैर-आयामी पैरामीट्रिक और अनुकूलन अध्ययन, पैमाने दूरी के संदर्भ में विस्फोट लोड की एक सीमा के अंतर्गत किए गए हैं। यह निष्कर्ष निकाला गया कि सामने की प्लेट पर संलग्नक के विभिन्न घटकों (प्लेट की मोटाई, जड़त्व, कठोरता और अवमंदन) का संयुक्त प्रभाव, पीछे की प्लेट के विरूपण और बल संचरणशीलता के संदर्भ में प्रदर्शन को तय करने में महत्वपूर्ण भूमिका निभाता है |

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Nomenclature

b	Inertance
C	Damping coefficient of the plate per unit area
C_e	Equivalent damping coefficient of the plate per unit area
C_{iso}	Damping coefficient of connecting dashpot element
D_{stiff}	Equivalent dynamic stiffness
K	Stiffness of the plate per unit area
K_e	Equivalent stiffness of the plate per unit area
K_{iso}	Stiffness of connecting spring element
K_L	Load factor
K_M	Mass factor
K_{LM}	Load mass factor
K_R	Resistance factor
m	Inertance ratio
m_1	Mass per unit length
M	Total mass of the plate per unit area
M_1	Total mass of the front plate per unit area
M_2	Total mass of the back plate per unit area
M_e	Equivalent mass of the plate per unit area
M_{1e}	Equivalent mass of the front plate per unit area
M_{2e}	Equivalent mass of the back plate per unit area
P	Total force acting on the structure
P_e	Equivalent force acting on the structure
p(x)	Distributed load
R	Resistance of the structure
R_e	Equivalent resistance of the structure
R_{el}	Resistance of the structure at yield deformation
T_{S1}	Settling time of front plate
T_{S2}	Settling time of back plate
Y_{1max}	Peak deformation of front plate
Y_{3max}	Peak deformation of back plate
y_{el}	Yield deformation of the plate
$y_{el,eq}$	Equivalent yield deformation of the plate with bilinear modeling
γ_1	First natural frequency of 2DOF system
γ_2	Second natural frequency of 2DOF system
Δ_1	Permanent deformation of the front plate
Δ_2	Permanent deformation of the back plate
σ	Stress

ε	Equivalent plastic strain
$\dot{\varepsilon}^*$	Dimensionless plastic strain rate
$\phi(x)$	Characteristic shape
ω_n	Natural frequency of the plate
ω_{1n}	Natural frequency of the front plate
ω_{2n}	Natural frequency of the back plate
ω_A	Average frequency
ω_B	Beat frequency
ζ	Damping ratio
ξ_1, ξ_2	Effective damping ratios
a_1	Velocity of sound ahead of shock wave
a_2	Velocity of sound behind shock wave
i_+	Positive impulse of reflected shock wave
i_-	Negative impulse of reflected shock wave
P_1	Initial pressure in driven section
P_2	Incident pressure behind the shock front
P_4	Initial pressure in driver section
P_5	Reflected pressure at driven section end
P_i	Maximum incident overpressure measured at pressure transducer PT_1
P_0	Maximum reflected overpressure measured at pressure transducer PT_0
PT	Pressure transducer
L	Total length of shock tube
L_1	Length of driven section
L_4	Length of driver section
M_s	Mach number
T_1	Temperature of gas ahead of shock wave
T_2	Temperature of gas behind shock wave
γ	Specific heat ratio
ρ_1	Density of gas ahead of shock wave
ρ_2	Density of gas behind shock wave
$\Delta P/\Delta x$	Attenuation of peak incident pressure with distance