RELIABILITY OF FIBER-REINFORCED POLYMER COMPOSITE STRUCTURES IN EXTREME LOADING CONDITIONS

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by

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DEPARTMENT OF CIVIL ENGINEERING

submitted

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DEDICATION

Dedicated to my beloved parents, brothers, and grandparents, for whom I wanted to work harder every day, to all the women who struggled and made a lot of sacrifices to fulfil their dreams every day, and to all the teachers who believed in their students and encouraged them to find their own identity.

CERTIFICATE

This is to certify that the Ph.D. thesis titled “**RELIABILITY OF FIBER-REINFORCED POLYMER COMPOSITE STRUCTURES IN EXTREME LOADING CONDITIONS**” being submitted by **KUSUM SAINI** to the Indian Institute of Technology (IIT) Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of the bonafide research work carried out by her. She worked under my supervision for the submission of this Ph.D. thesis, which to my knowledge has reached the requisite standard as demonstrated by excellent publications in international journals and conferences.

Further, the contents of her research work, in full or in part, have not been submitted to any other institute or university for the award of any degree or diploma to the best of my knowledge and belief.

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ABSTRACT

The current developing advanced civil infrastructure are moving towards lightweight structures due to their benefits with cost effectiveness, easy to transport, sustainability, reduced waste, and lesser inertial forces. Lightweight structures can be advantageously used for emergency shelters, defense facilities, and other structures geographically located at places that pose complex construction and transportation challenges. These structures can also be used to build structures that protect army soldiers from harsh environmental conditions and man-made attacks at the forward posts. Structures at such posts could be subjected to blast, impact, and extreme weather and pose significant challenges, especially for structures at high altitude areas. Lightweight rapidly deployable modular structures that can be assembled from prefabricated lightweight building units could be suitable structures for the aforementioned applications. Therefore, this study aims to assess the behavior of different lightweight and high-performance building units made of fiber-reinforced polymer (FRP), FRP and foam sandwich, ultra-high-performance concrete (UHPC), natural fiber-reinforced foamed concrete (NFRFC), and bio-composites under various loadings for modular structures. Compared to other conventional structural materials, composite materials generally have better physical and mechanical properties, such as low density, low thermal expansion coefficient, high specific strength, and high specific stiffness. As a result, composite materials are suitable for use in civil structures subjected to extreme loading conditions. However, there are various uncertainties associated with composites, including variability in material properties and applied loads. Therefore, it is essential to investigate the behavior of composites considering these uncertainties.

In this study, suitable numerical models are developed for FRP, FRP and foam sandwich, UHPC, and NFRFC building units subjected to extreme loadings. Moreover, a finite element model is developed for a full-scale FRP and foam sandwich modular structure subjected to various blast load scenarios. Different deterministic and probabilistic numerical investigations are conducted on the building units and structures subjected to static and blast loads. Furthermore, the effect of different protection coatings, i.e., foamed concrete and polyurea, on the blast resistance of the building units is studied. The application of polyurea coating enhances the blast resistance of the structures significantly. Notably, the behavior of the FRP composites, having various configurations, is studied under different blast load scenarios. Here, the failure of the FRP composites is determined by implementing various failure criteria, namely, the maximum stress, Tsai-Hill, Hoffman, and Tsai-Wu failure criteria. Moreover, the stochastic performance assessment of the FRP composite is conducted using Monte Carlo simulation and generalized polynomial chaos methods in this doctoral research. In addition to the building units, a selected connection, i.e., anchor channel, is investigated under static and high-rate loadings. Experimental studies are also conducted to assess the behavior of FRP and foam sandwich beams, and anchor channels under static loads. Indentation failure in the FRP facesheet and shear failure in the foam core are obtained as the most governing failures in the sandwich composite beams. Concrete edge breakout is obtained as a dominating failure mode for anchor channels under shear load. Furthermore, the effect of moderate and high loading rates on the anchor channel shows enhancement in the influence of structural inertia and further increases the localized failure around the anchor channel.

Climate change has become a worldwide problem, and many conventional construction materials are contributing to the carbon footprint. Stubble burning also causes a huge amount of greenhouse gas emissions (GHG) in many countries every year. Therefore, the environmental impacts of stubble burning in India and alternative bio-composite production have been compared. Subsequently, the use of natural fibers in civil engineering structures is studied as an alternative to conventional construction materials. Finally, an initial production of prototype bio-composite building units is carried out. The production of the building units is accomplished through a startup initiated as part of this doctoral study. Thus, this doctoral research contributes to reliable modular structures made of lightweight and high-performance materials subjected to extreme loadings.

सार

वर्तमान समय में उन्नत बुनियादी निर्माण के लिए हल्के ढांचे उन्की लागत प्रभावशीलता, स्थानांतरण में सरलता, स्थिरता, कम अपशिष्ट, और कम जड़त्वीय बलों के कारण एक प्राथमिकता बन गए हैं। हल्के ढांचो का उपयोग आपातकालीन आश्रयों के लिए, रक्षा सुविधाओं के लिए, और भौगोलिक रूप से जटिल निर्माण और परिवहन चुनौतियों का सामना करने वाले स्थानों पर स्थित संरचनाओं के लिए लाभप्रद रूप से किया जाता है। इन ढांचो का उपयोग उन संरचनाओं के निर्माण के लिए भी किया जा सकता है जो सेना के सैनिकों को कठोर पर्यावरणीय परिस्थितियों और सीमाओं पर मानव निर्मित हमलों से बचाते हैं। ऐसी सुरक्षा चौकीयों पर संरचनाएं विस्फोट और संघात के सम्पर्क में हो सकती हैं, और कठोर मौसम भी संरचानाओ के लिए चुनौतियां पैदा कर सकता है। मॉड्यूलर संरचनाएं, जो तेजी से परिनियोजन योग्य होती है और इन्हे पूर्वनिर्मित हल्की भवन इकाइयों को जोड़ने से बनाया जा सकता है, ऐसी संरचनाए उपरोक्त अनुप्रयोगों के लिए उपयुक्त हो सकती हैं। इसलिए, इस अध्ययन का उद्देश्य विभिन्न बलो के तहत रेशो से प्रबलित बहुलक (रेब), रेब और फोम सैंडविच, अति उच्च प्रदर्शन वाली कंक्रीट (अप्रकं), प्राकृतिक रेशो से प्रबलित फोमयुक्त कंक्रीट (प्रारेफोकं), और जैव समिश्रित इकाइओ के व्यवहार का आकलन करना हैं। आमतौर पर पारंपरिक संरचनात्मक सामग्रियों की तुलना में समिश्रित सामग्रियों में बेहतर भौतिक और यांत्रिक गुण होते हैं, जैसे की कम घनत्व, कम तापीय विस्तार गुणांक, उच्च विशिष्ट शक्ति, और उच्च विशिष्ट कठोरता। परिणामस्वरूप, उच्च बलो की स्थितियों के अधीन संरचनाओं में समिश्रित सामग्रियों का उपयोग उपयुक्त है। हालाँकि, समिश्रित निर्माण सामग्रीयो में विभिन्न भौतिक गुणों और बलो से अनिश्चितताएँ जुड़ी होती हैं। इसलिए, इन अनिश्चितताओं को लेकर समिश्रित निर्माण सामग्रीयो के व्यवहार की जांच करना आवश्यक है।

इस अध्ययन में, रेब, रेब और फोम सैंडविच, अप्रकं, प्रारेफोकं, और जैव समिश्रित इकाइओ के लिए उपयुक्त अभिकलनात्मक निदर्श विकसित किए गए हैं। इसके अलावा, विभिन्न विस्फोटक बलो परिदृश्यों के अधीन पूर्ण पैमाने पर रेप्रब और फोम सैंडविच मॉड्यूलर संरचानाओ के लिए एक अभिकलनात्मक निदर्श विकसित किया गया है। विभिन्न स्थैतिक और विस्फोटक बलो के अधीन इन भवन इकाइयों और संरचानाओ की नियतात्मक और प्रसंभाव्य अभिकलनात्मक जांच की गई है। इसके अलावा, भवन इकाइयों के विस्फोटक बल प्रतिरोध के लिए विभिन्न सुरक्षा लेप, जैसे की फोमयुक्त कंक्रीट और पॉलीयूरिया के प्रभाव का अध्ययन किया जाता है। पॉलीयूरिया लेप के अनुप्रयोग से संरचनाओं की विस्फोटक प्रतिरोधक क्षमता काफी बढ़

जाती है। विशेष रूप से, विभिन्न विन्यासो वाले रेब समिश्रित इकाइओ के व्यवहार का अध्ययन विभिन्न विस्फोटक बल परिदृश्यों के तहत किया गया है। यहां, रेब समिश्रित इकाइओ की विफलता मापन के लिए विभिन्न मानदंडों, जैसे की मैक्सीमम स्ट्रेस, साई-हिल, हॉफमैन और साई-वू विफलता मानदंडों को लागू किया गया है। इसके अलावा, इस वाचस्पति अनुसंधान में मोंटे कार्लो अनुकरण और जेनेरलाइज़्ड पोलीनोमिअल केओस विधियों का उपयोग करके रेप्रब समग्र का प्रसंभाव्य प्रदर्शन का आकलन किया गया है। भवन इकाइयों के अलावा, एक चयनित कनेक्शन, एंकर चैनल की जांच स्थैतिक और उच्च दर बलो के तहत की गयी है। रेब और फोम सैंडविच बीम और एंकर चैनलों के व्यवहार का आकलन स्थैतिक बलो के तहत प्रायोगिक अध्ययन भी किया गया हैं। रेब फेसशीट में इंडेंटेशन विफलता और फोम कोर में कतरनी विफलता को सैंडविच मिश्रित बीम में प्रमुख विफलता के रूप में प्राप्त किया जाता है। एंकर चैनलों में कंक्रीट किनारे का टूटना प्रमुख विफलता का माध्यम प्राप्त किया गया है। इसके अलावा, एंकर चैनलों में मध्यम और उच्च दरों के बलो के प्रभाव में संरचनात्मक जड़त्व बल के प्रभाव में वृद्धि मिली है, जो स्थानीय विफलताओ जैसे की चैनल के चारों ओर अपरूपण दरारो को बढ़ाता है।

जलवायु परिवर्तन एक विश्वव्यापी समस्या बन गई है और कई पारंपरिक निर्माण सामग्रियां भी कार्बन उत्सर्जन के रूप में इसमे योगदान देती है। पराली जलाने से भी हर साल कई देशों में भारी मात्रा में ग्रीनहाउस गैस उत्सर्जन (ग्रीगैउ) होता है। इसलिए, भारत में पराली जलाने और वैकल्पिक जैव समिश्रित इकाइओ के उत्पादन के पर्यावरणीय प्रभावों की तुलना की गई है। इसके बाद, पारंपरिक निर्माण सामग्रियों के विकल्प के रूप में, बुनियादी ढांचो में प्राकृतिक रेशो के उपयोग का अध्ययन किया गया है। अंत में, जैव समिश्रित आदिरूप इकाइयों का परीक्षित उत्पादन किया जाता है। जैव समिश्रित भवन निर्माण इकाइयों का उत्पादन, स्टार्टअप के माध्यम से इस वाचस्पति अनुसंधान अध्ययन के हिस्से के रूप में शुरू किया गया है। इस प्रकार, यह वाचस्पति अनुसंधान विभिन्न प्रकार के बलो के अधीन हल्के और उच्च प्रदर्शन सामग्रियों से बने विश्वसनीय मॉड्यूलर संरचनाओं में योगदान देता है

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

3D	Three-dimensional
ACI	American concrete institute
ANN	Artificial neural networks
BRB	Bamboo reinforced beam
CDP	Concrete damage plasticity
CE	Concrete edge failure
CFD	Computational fluid dynamics
CFRP	Carbon fiber-reinforced polymer
CLPT	Classical laminate plate theory
COV	Coefficient of variation
CRC	Coir fiber-reinforced concrete
CSA	Crow search algorithm
DIF	Dynamic increase factor
DOF	Degree of freedom
EN	European
EPS	Expanded polystyrene
ETA	European technical assessment
ETPS	European technical product specification
FBr	Fiber breakage
FBu	Fiber buckling
FE	Finite element
FFRP	Flax fiber-reinforced polymer
FI	Failure index
FORM	First order reliability method
FOS	Factor of safety
FRP	Fiber-reinforced polymer
FSDT	First-order shear deformation theory
gPC	Generalized polynomial chaos
GHG	Greenhouse gas
GA	Genetic algorithm
GFRP	Glass fiber-reinforced polymer
GP	Gauss point

GWP	Global warming potential
HAA	High altitude area
HRC	Hybrid fiber-reinforced concrete
HS	High strength
HSDT	Higher-order shear deformation theory
IIT	Indian institute of technology
IRD	Industrial research and development
IS	Indian standard
JFRCM	jute fabric reinforced cement mortar
JFRP	Jute fiber-reinforced polymer
LCA	Life-cycle assessment
LVDT	Linear variable differential transformers
MC	Matrix crushing
MCS	Monte Carlo simulation
MS	Modular structure
MSF	Matrix shear failure
MS-C	Modular structure with blast load applied on the curved wall of the structure
MS-F	Modular structure with blast load applied on the flat wall of the structure
NBC	National building code
NFC	Natural fiber composite
NFRP	Natural fiber-reinforced polymer
NS	Normal strength
PDF	Probability density function
PEEK	Polyether ether ketone
PUE	Polyurea applied on external face of the structure
PUI	Polyurea applied on internal face of the structure
QS	Quasi-static
RC	Reinforced concrete
RSD	Rate-sensitive dynamic
RSM	Response surface methodology
RSS	Rate-sensitive static
SAN	Styrene acrylonitrile

SCP	Sandwich composite panel
SCP-PB	Sandwich composite panel with polyurea at opposite face to blast
SCP-PF	Sandwich composite panel with polyurea at exposed face to blast
SDG	Sustainable development goal
SFEM	Stochastic finite element method
SORM	Second order reliability method
SLS	Serviceability limit state
SRB	Steel reinforced beam
SVR	Support vector regression
TMC	Transverse matrix cracking
TNT	Trinitrotoluene
UHPC	Ultra-high-performance concrete
ULS	Ultimate limit state
UTM	Universal testing machine
WL	Wind load
XPS	Extruded polystyrene

MATHEMATICAL NOTATIONS

a	Length of fiber-reinforced polymer laminated composite plate
A_e	Total area of element
A_s	Plan area of structure
b	Width of fiber-reinforced polymer laminated composite plate
$\boldsymbol{B}$	Strain-displacement relationship matrix
b'	Parameter to control rate of decay of the pressure
c_1	Edge distance of anchor channel
C	Compression force
$\overline{\boldsymbol{C}}$	Stiffness matrix of a lamina
C_{01}, C_{10}	polynomial constants for Mooney-Rivlin hyperelastic material model
CO_2	Carbon dioxide
COV	Coefficient of variation
$\overline{\boldsymbol{d}}$	Displacement vector
$\ddot{\boldsymbol{d}}$	Acceleration vector
$\overline{\boldsymbol{D}}$	Load-strain relationship matrix
$\boldsymbol{d}_0$	Mid-plane displacement vector
d_c	Deflection capacity of a beam
d_s	Deflection of a beam with respect to SLS
d_u	Deflection of a beam with respect to ULS
d_r	Diameter of natural fiber rope
$\boldsymbol{d}_{tnn}$	Displacement vector for a total *tnn* number of nodes
D_1	Compressibility constant for Mooney-Rivlin hyperelastic material model
D_m	Displacement with respect to ultimate shear force
d_f^C	Damage index of fiber in compression
d_f^T	Damage index of fiber in tension
d_m^C	Damage index of matrix in compression
d_m^T	Damage index of matrix in tension
E	Young's modulus of the material

E_{11}	Elastic modulus of FRP laminate in longitudinal local 1 direction
E_{22}	Elastic modulus of FRP laminate in longitudinal local 2 direction
E_c	Elastic modulus of the core material
$E_{composite}$	Elastic modulus of composite
E_{con}	Elastic modulus of concrete
E_f	Elastic modulus of the facesheet material
E_r	Elastic modulus of natural fiber rope reinforcement
E_{steel}	Elastic modulus of steel
EF	Emission factor
$\boldsymbol{F}$	Stress-resultant vector
f_{cc}	Compressive strength of concrete
f_r	Tensile strength of natural fiber rope
f_t	Tensile strength of concrete
F_S	Shear strength of the lamina
F_{xC}	Compressive strength along 1 principal direction of the lamina
F_{yC}	Compressive strength along 2 principal direction of the lamina
F_{xT}	Tensile strengths along 1 principal direction of the lamina
F_{yT}	Tensile strengths along 2 principal direction of the lamina
FE	Fuel efficiency
g	Failure criterion limit for FRP laminate
G_{12}	Shear modulus of FRP laminate in local 12 plane
G_{13}	Shear modulus of FRP laminate in local 13 plane
G_{23}	Shear modulus of FRP laminate in local 23 plane
G_c	Shear modulus of the core material
G_{cc}	Fracture energy of concrete
G_f	Shear modulus of the facesheet material
h	Height of fiber-reinforced polymer laminated composite plate
$\boldsymbol{I}$	Identity matrix

I_c	Moment of inertia of cross-section
$\boldsymbol{K}$	Stiffness matrix
L	Span length of a beam
L_e	Length of eth element
L_f	Length of fiber
L_p	Length of anchor
L_s	Length of the structure
$\boldsymbol{M}$	Inertia matrix
M_c	Moment capacity of a beam
$M_{c,\,B1}$	Moment capacity of beam B1
$M_{c,\,B2}$	Moment capacity of beam B2
$\boldsymbol{M}_s$	Mass matrix of primary structure/superstructure
M_s	Moment of a beam with respect to SLS
M_u	Moment of a beam with respect to ULS
$\boldsymbol{N}$	Shape function vector
N_{alt}	Number of simulations
N_f^{gPC}	Number of failure using gPC
N_f^{MCS}	Number of failure using MCS
$N_{Rk,c}$	Characteristic normal resistance of anchor in concrete failure
$N_{Rk,cb}$	Characteristic normal resistance of anchor in concrete blow-out failure
$N_{Rk,p}$	Characteristic normal resistance of anchor in pull-out failure
$N_{Rk,s}$	Characteristic normal resistance of anchor in steel failure
$N_{Rk,sp}$	Characteristic normal resistance of anchor in concrete splitting failure
$\boldsymbol{O}$	Null matrix
p_0	Ambient pressure in MPa
P	Applied load on a beam
P_f	Probability of failure
P_f^{gPC}	Probability of failure using gPC
P_f^{MCS}	Probability of failure using MCS
$P_{f,\,limit}$	Limiting probability of failure
P_{exp}	External pressure

P_{grip}	Pressure applied on the grip of the laminate
P_{i}	Load required to cause indentation failure in the facesheet
P_{m}	Load required to cause microbuckling
p_{pos}	Positive peak pressure of shock wave
P_{p}	Positive peak pressure due to explosion
P_{s}	Load required to cause shear failure in the core
P_{w}	Load required to cause wrinkling
$p_z(t)$	Pressure of shock wave at time t
q	Magnitude of static pressure
$q(t)$	Peak magnitude of dynamic pressure
Q_{Fuel}	Total fuel consumption per ton of load
$\bar{\boldsymbol{Q}}_{\text{k}}$	Transformed reduced stiffness matrix for the k^{th} lamina
R	Radial distance from the explosive charge center
$\boldsymbol{R}$	Reuter matrix
$\bar{R}$	Reliability of FRP laminate
$\bar{R}^{\text{gPC}}$	Reliability of FRP laminate using gPC
$\bar{R}^{\text{MCS}}$	Reliability of FRP laminate using MCS
R_{s}	Radius of the structure
s	Spacing between anchors
s_{cbo}	Spacing between channel bolts
S_{c}	Stresses in concrete
S_{r}	Stress in natural fiber rope reinforcement
t	Total elapsed time since the beginning of the excitation
T	Tension force
t_{a}	Arrival time of shock wave in ms
t_{c}	Thickness of core in a sandwich panel
t_{f}	Thickness of facesheet in a sandwich panel
t_{pos}	Duration of positive pressure in shock wave
$\boldsymbol{T}_{\text{k}}$	Transformation matrix
T_{p}	Maximum load capacity of anchorage
u	Input vector

u_0	Mid-plane translational displacements along X axis
U_{inner}	Inner perimeter of FRP sample
U_{outer}	Outer perimeter of FRP sample
U_{p}	Perimeter of FRP sample
U_{s}	Linear deviatoric strain energy
v_0	Mid-plane translational displacements along Y axis
w_0	Mid-plane translational displacements along Z axis
W_{L}	Lobbato points
$w,_{\mathrm{x}}$	First order derivative of w with respect to X axis
$w,_{\mathrm{y}}$	First order derivative of w with respect to Y axis
V	Shear force
$V_{\mathrm{Rk,c}}$	Characteristic shear resistance of anchor in concrete edge failure
$V_{\mathrm{Rk,cp}}$	Characteristic shear resistance of anchor in concrete pry-out failure
$V_{\mathrm{Rk,s}}$	Characteristic shear resistance of anchor in steel failure
$N_{\mathrm{Rk,sp}}$	Characteristic resistance of anchor in concrete splitting failure
V_{u}	Ultimate shear force
W	Weight of explosive charge in kg
W_{limit}	Limiting explosive weight
$\boldsymbol{X}_{\mathrm{s}}$	Column vector of floor displacements in the X direction
$\dot{\boldsymbol{X}}_{\mathrm{s}}$	Column vector of floor velocities in the X direction
$\ddot{\boldsymbol{X}}_{\mathrm{s}}$	Column vector of floor accelerations in the X direction
Z	Scaled distance of explosion
Z_{limit}	Limiting scaled distance of explosion
$\boldsymbol{\beta}_{(\chi)}$	A vector of the unknown coefficients for a specific point at which response shall be obtained
β	Reliability index
ξ	Random variable
Δ	Slip between reinforcement and concrete
Δt	Small time interval
ε	Error

$\boldsymbol{\varepsilon}$	Strain vector for a lamina
$\boldsymbol{\varepsilon}_0$	Mid-plane strain vector
ε_{ij}	Components of macroscopic strain tensor
ε_{ik}	Complex Gaussian random number with zero mean
ε_m	Strain at microplane
ε_K, ε_M	Shear strain components at microplane
ε_N	Normal strain at microplane
$\varepsilon^c{}_{xx}$	Strain in concrete
$\varepsilon^r{}_{xx}$	Strain in reinforcement
θ_k	Angle of fibers in the k^{th} lamina with respect to the major principal axis (i.e., X -axis) of the laminate coordinate system
θ_x	Rotations about X axis
θ_y	Rotations about Y axis
$\bar{\kappa}$	Shear correction factor
ν_{12}	Poisson's ratio of FRP laminate for load applied in the 1 direction and strain in the 2 direction
ν_{21}	Poisson's ratio of FRP laminate for load applied in the 2 direction and strain in the 1 direction
ρ	Air density
$\boldsymbol{\sigma}$	Stress vector for a lamina
σ_{11}	Normal stress in direction 1 in local coordinate system
σ_{22}	Normal stress in direction 2 in local coordinate system
σ_D	Deviatoric stress
σ_{ij}	Components of macroscopic stress tensor
σ_K, σ_M	Shear stresses at microplane
σ_N	Normal stress at microplane
σ_V	Volumetric stress
τ_{12}	Shear stress in 12 plane in local coordinate system
φ_x	Shear rotation in $X-Z$ plane

φ_y	Shear rotations in $Y-Z$ plane
$\psi_{ch,c}$	Factor for the effect of the corner on the characteristic resistance
$\psi_{ch,e}$	Factor for the effect of edge distance on the characteristic resistance
$\psi_{ch,h}$	Factor for the effect of thickness of concrete member on the characteristic resistance
$\psi_{ch,s}$	Factor for the effect of influence of neighboring anchors on the characteristic resistance
$\psi_{h,sp}$	Factor for the effect of thickness of concrete member on the characteristic resistance
ω	Angular frequency of wind