COMPUTATIONAL STUDIES USING FINITE ELEMENT ANALYSIS FOR MITIGATING HEAD INJURIES DURING HELMETED IMPACTS

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Computational studies using finite element analysis for mitigating head injuries during helmeted impacts

By

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CERTIFICATE

*This is to certify that the thesis titled "**Computational studies using finite element analysis for mitigating head injuries during helmeted impacts**" being submitted by **Mr Manish Kumar** to the **Indian Institute of Technology Delhi**, for the award of the degree of **Doctor of Philosophy** in Transportation Research and Injury Prevention Centre is a bonafide research work carried out by him under our supervision and guidance. The research work presented in this thesis has not been submitted in parts or in full to any other University or Institute for the award of any degree or diploma.*

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ABSTRACT

This study investigates the influence of factors such as peak linear acceleration and peak rotational acceleration which affect the head kinematics, during different kinds of impacts involving motorcycle helmets. Traditional helmets, which predominantly mitigate translational motion, and have limited efficacy in countering rotational forces that contribute significantly to head injuries. The thesis examines the role of variations in the coefficient of friction at the anvil-helmet shell and the headform-foam interfaces on the linear and rotational accelerations. The implications of helmet and headform mismatches due to improper helmet fit, the role of helmet shell thickness and coatings on helmet shell made form ABS plastic, in influencing head kinematics are studied. The potential benefits of impact-resistant coatings applied to helmet shells, fabricated through thermo-vacuum forming of ABS plastic sheets, are demonstrated. The results provide insights into the extent to which such coatings mitigate linear acceleration during impacts, emphasizing their potential to enhance rider safety. The research work also discusses the effect of presence of strap and multiple on head kinematic parameters.

Oblique impacts during motorcycle accidents lead to high angular acceleration of the head resulting in severe injury to the brain. For bicycles, advanced helmets such as MIPS helmet and WaveCel helmet are commercially available which claim to attenuate the effects of rotational motion of the head during helmet impact. The effectiveness of these helmets in dissipating the rotational and linear acceleration of the head is analyzed computationally for different impacts. The role of the coefficient of friction between the foam and MIPS liner in MIPS helmet and energy absorbed due to crushing and sliding in WaveCel helmets is analyzed. The MIPS helmet, while effective in front and rear oblique impacts, does not perform in side impacts. For the liner used

in WaveCel helmet the crumple and glide mechanism attributed to its performance was not evident in numerical simulations. A new design using low density EPS and high-density foams is shown to significantly attenuate the rotational and linear acceleration of the head.

सार

यह अध्ययन मोटरसाइकिल हेलमेट से संबंधित विभिन्न प्रकार के प्रभावों के दौरान सिर की गति-विज्ञान को प्रभावित करने वाले कारकों, जैसे अधिकतम रैखिक त्वरण तथा अधिकतम घूर्णीय त्वरण, के प्रभाव का विश्लेषण करता है। पारंपरिक हेलमेट मुख्यतः रैखिक गति को कम करने के लिए बनाए जाते हैं, परंतु वे घूर्णीय बलों का प्रभावी रूप से प्रतिरोध करने में सीमित होते हैं, जबकि यही बल सिर की गंभीर चोटों में महत्वपूर्ण भूमिका निभाते हैं।

इस शोध में निहाई–हेलमेट बाह्य आवरण तथा कृत्रिम सिर–फोम संपर्क सतहों पर घर्षण गुणांक में परिवर्तन के रैखिक एवं घूर्णीय त्वरण पर प्रभाव का अध्ययन किया गया है। अनुचित फिटिंग के कारण हेलमेट और कृत्रिम सिर के बीच असंगति, हेलमेट के बाह्य आवरण की मोटाई तथा एबीएस प्लास्टिक से निर्मित बाह्य आवरण पर लगाए गए परतों की भूमिका का भी विश्लेषण किया गया है, ताकि यह समझा जा सके कि ये कारक सिर की गति-विज्ञान को किस प्रकार प्रभावित करते हैं।

ताप–निर्वात ढलाई प्रक्रिया द्वारा निर्मित एबीएस प्लास्टिक शीट से बने हेलमेट बाह्य आवरण पर प्रभाव-प्रतिरोधी परतों के संभावित लाभों को भी प्रदर्शित किया गया है। परिणामों से यह स्पष्ट होता है कि ऐसी परतें प्रभाव के दौरान रैखिक त्वरण को कम करने में किस सीमा तक सहायक हो सकती हैं, जिससे चालक की सुरक्षा में वृद्धि संभव है। शोध कार्य में पट्टा की उपस्थिति तथा बहु-स्तरीय संरचना के सिर की गति-संबंधी मापदंडों पर प्रभाव की भी चर्चा की गई है।

मोटरसाइकिल दुर्घटनाओं के दौरान तिर्यक प्रभाव सिर में उच्च कोणीय त्वरण उत्पन्न करते हैं, जिसके परिणामस्वरूप मस्तिष्क को गंभीर चोट लग सकती है। साइकिलों के लिए उन्नत हेलमेट, जैसे बहु-दिशात्मक प्रभाव संरक्षण प्रणाली युक्त हेलमेट तथा तरंग-जाल संरचना वाले हेलमेट, बाज़ार में उपलब्ध हैं, जो प्रभाव के

दौरान सिर की घूर्णीय गति को कम करने का दावा करते हैं। इस शोध में विभिन्न प्रकार के प्रभावों के लिए इन हेलमेटों की रैखिक तथा घूर्णीय त्वरण को कम करने की क्षमता का संगणनात्मक विश्लेषण किया गया है। बहु-दिशात्मक प्रभाव संरक्षण प्रणाली में फोम और आंतरिक परत के बीच घर्षण गुणांक की भूमिका तथा तरंग-जाल संरचना वाले हेलमेट में कुचलन और सरकन के माध्यम से अवशोषित ऊर्जा का भी अध्ययन किया गया है।

अध्ययन से यह पाया गया कि बहु-दिशात्मक प्रभाव संरक्षण प्रणाली युक्त हेलमेट आगे और पीछे से होने वाले तिर्यक प्रभावों में प्रभावी है, परंतु पार्श्व प्रभावों में इसका प्रदर्शन संतोषजनक नहीं है।

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LIST OF SYMBOLS

t	Time
F	Force
M	Mass
$a(t)$	Linear acceleration
$\alpha(t)$	*Angular/rotational acceleration*
ω	Angular/rotational velocity
P	Probability
θ	Angle
I	Moment of Inertia
p	Pressure
σ	Stress
ρ	Density
$u(x,t)$	Displacement vector field
$\dot{u}(x,t)$	Velocity vector field
$\ddot{u}(x,t)$	Acceleration vector field
0	Zero displacement vector $[0\ \ 0\ \ 0]^T$
σ	Cauchy stress tensor
$d\sigma$	Increment of Cauchy stress
ε	Total strain tensor
$d\varepsilon$	Increment of total strain
ε^e	Elastic strain tensor
$d\varepsilon^e$	Increment of elastic strain
ε^p	Plastic strain tensor
$d\varepsilon^p$	Increment of plastic strain
C	Fourth-order elastic stiffness tensor
∇	Gradient (spatial differential) operator
$N(x)$	Matrix of finite element shape functions
$u(t)$	Vector of nodal displacements
M	Mass matrix
C	Damping matrix
K	Stiffness matrix
g_n	Normal gap between contacting surfaces
p_n	Normal contact pressure

LIST OF ABBREVIATIONS

UTM - Universal Testing Machine

FEM - Finite Element Method

HIC - Head Injury Criteria

PLA - Peak Linear Acceleration

PRA - Peak Rotational Acceleration

PAA - Peak Angular Acceleration

CoG/CG - Centre of Gravity

EPS - Expanded Polystyrene

EPP - Expanded Polypropylene

CSF - Cerebrospinal Fluid

ABS - Acrylonitrile butadiene styrene

CAD - Computer Aided Design

UN ECE - United Nations Economic Commission for Europe

MIPS - Multi-directional Impact Protection System

COST - Europe Cooperation in Science and Technology

CoF - Coefficient of Friction

TBI - Traumatic Brain Injury

BrIC - Brain Injury Criteria

CSDM - Cumulative Strain Damage Measure

MPS - Maximum Principal Strain

ATD - Anthropomorphic Test Device