

FORMULATION OF AN ENERGY ABSORPTION MODEL FOR A PTW TO ESTIMATE PRE-IMPACT SPEED IN REAL-WORLD ROAD CRASH

KULDEEP SINGH



**DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

NOVEMBER 2021

© **Indian Institute of Technology Delhi (IITD), New Delhi, 2021**

FORMULATION OF AN ENERGY ABSORPTION MODEL FOR A PTW TO ESTIMATE PRE-IMPACT SPEED IN REAL-WORLD ROAD CRASH

by

KULDEEP SINGH

Department of Mechanical Engineering

Submitted

**in fulfilment of the requirements of the degree of Doctor of Philosophy
to the**



INDIAN INSTITUTE OF TECHNOLOGY DELHI

NOVEMBER 2021

AUTHORS DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of my thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis will be made electronically available to the public.

KULDEEP SINGH

CERTIFICATE

This is to certify that the thesis entitled “**Formulation of an energy absorption model for a PTW to estimate pre-impact speed in real-world road crash**” being submitted by **Mr. Kuldeep Singh** to the Indian Institute of Technology Delhi for the award of Doctor of Philosophy in the Department of Mechanical Engineering is a record of bonafide research work carried out by him. He has worked under our guidance and has fulfilled the requirements for the submission of the thesis, which, in our opinion, has reached the requisite standard.

The results in this thesis have not been submitted in part or full, to any University or Institute for the award of degree or diploma.

Dr. Anoop Chawla

Professor

Department of Mechanical Engineering

Indian Institute of Technology Delhi

Dr. Sudipto Mukherjee

Professor

Department of Mechanical Engineering

Indian Institute of Technology Delhi

ACKNOWLEDGEMENTS

In the beginning, I would like to thank God Almighty for providing me the strength, courage, and determination to earn the biggest dream of my life. I have been inspired by many scientists and researchers working in road safety throughout my research journey, which led me to pursue this work. Also, being an avid motorcycle rider raised the curiosity to explore the issues related to motorcyclist safety and how i can contribute to this.

The direction towards this work is also a result of being a part of a pilot project collecting accident data from National Highway-8 connecting Delhi to Jaipur in collaboration with NATRiP and led by IIT-Delhi under the guidance of Dr. Anoop Chawla as the academic partner. This project aims to collect road traffic accident (RTA) data such as vehicle damage and occupant injuries from hospitals and insurance companies and conduct an in-depth analysis and reconstruction.

I would like to express my utmost respect and gratitude to my doctoral supervisors Prof. Anoop Chawla and Prof. Sudipto Mukherjee, for their invaluable guidance and help in building up my research acumen at the same time.

I would also like to thank my Student Research Committee (SRC)- Dr. S. P. Singh (SRC Chairman), Dr. D.K. Dubey (Internal Expert) and Dr. Vasant Matsagar (External Expert) for evaluating my work, providing critical suggestions, and helped me look at research from a larger perspective.

I wish to express my gratitude to my colleagues- Devendra Kumar, Milan Chandarana, Ved Vyas from the Impact and Dynamic lab for their help and support in carrying out experimental work for this research. I have learned a lot working with them. My gratitude also goes to my colleagues at Impact lab- Dr. Wondwosen Ayelework, Dr. Garima Chawla, Dr. Piyush Gaur,

Dr. Hariharan Sankarasubramaniam, Dr. Kanhaiyalal Mishra, Dr. Sumedha Premi, Dr. Khyati Verma, Mr. Aman Vikram, Mr. Sanyam Sharma, Mr. Mayank Rai, Mr. Hiren Nakrani, Mr. Mitesh Lalwani, Mr. Amrit Lal, Mr. Aditya Sinha, Mr. Rabindra kar who also motivated and supported me throughout these years. I would also like to thank all the people who knowingly and unknowingly inspired me in many ways throughout these years.

Finally, I could not have completed this thesis without the support of my parents and younger brother.

Kuldeep Singh

Indian Institute of Technology, Delhi

ABSTRACT

*To estimate damage energy and related impact speed for a typical Indian PTW crash, this work addresses the research question, “**Is there a deformation-based energy model to estimate impact speed of a PTW in crash reconstruction studies?**”*

Estimation of the damage energy related to significant energy absorbing components under dynamic loading has been quantified. A component-level testing under dynamic loading conditions was conducted for the tubular structure of a PTW in a crash. Deformation measurement and the absorbed energy were quantified from a three-point bending test under a drop tower test setup. The FE model of the front fork tube under bending load conditions was validated using experimental data. The Finite Element (FE) and Multi(-Rigid)-Body (MB) models of a typical Indian PTW (Engine capacity: 100 cc) were developed and partially validated in a rigid wall crash test. The feasibility of using a FE PTW model in a crash was evaluated and compared to a similar class of PTW used in the crash tests for a frontal impact against the door of a passenger vehicle (PV). The energy absorbed and related impact speed of the developed PTW FE model against a FE model of the passenger vehicle used in the simulation was reasonable.

A real-world PTW crash with damage details was selected from National Highway-8 (NH-8) database collected by IIT-D and reconstructed in FE. The events in the FE simulation, the direction of motion, and the final rest position after impact were correlated. The damage energy and deformation of the front fork in FE analysis were reasonably correlated with experimental data. A method to predict energy absorbed and related impact speed based on the damage component was demonstrated. Hence this study serves as a good starting point to predict impact speed based on damage details of significant energy absorbing components of a typical Indian PTW in a real-world road traffic accident (RTA).

सार

एक विशिष्ट भारतीय पीटीडब्ल्यू दुर्घटना के लिए क्षति ऊर्जा और संबंधित प्रभाव गति का अनुमान लगाने के लिए, यह कार्य अनुसंधान प्रश्न को संबोधित करता है, "क्या दुर्घटना पुनर्निर्माण अध्ययनों में पीटीडब्ल्यू की प्रभाव गति का अनुमान लगाने के लिए विरूपण-आधारित ऊर्जा मॉडल है?"

गतिशील लोडिंग के तहत महत्वपूर्ण ऊर्जा अवशोषित घटकों से संबंधित क्षति ऊर्जा का अनुमान लगाया गया है। एक दुर्घटना में पीटीडब्ल्यू की ट्यूबलर संरचना के लिए गतिशील लोडिंग स्थितियों के तहत एक घटक-स्तरीय परीक्षण किया गया था। एक ड्रॉप टॉवर परीक्षण सेटअप के तहत तीन-बिंदु झुकने परीक्षण से विरूपण माप और अवशोषित ऊर्जा की मात्रा निर्धारित की गई थी। बेंडिंग लोड स्थितियों के तहत फ्रंट फोर्क ट्यूब के एफई मॉडल को प्रयोगात्मक डेटा का उपयोग करके मान्य किया गया था। एक विशिष्ट भारतीय पीटीडब्ल्यू (इंजन क्षमता: 100 सीसी) के परिमित तत्व (एफ-ई) और मल्टी-(कठोर)-बॉडी (एम-बी) मॉडल विकसित किए गए और कठोर दीवार दुर्घटना परीक्षण में आंशिक रूप से मान्य किए गए। एक दुर्घटना में एक एफ-ई पीटीडब्ल्यू मॉडल का उपयोग करने की व्यवहार्यता का मूल्यांकन किया गया था और एक यात्री वाहन (पी.वी.) के दरवाजे के सामने सामने के प्रभाव के लिए दुर्घटना परीक्षणों में इस्तेमाल किए गए पीटीडब्ल्यू के समान वर्ग की तुलना में। सिमुलेशन

में इस्तेमाल किए गए यात्री वाहन के एफ-ई मॉडल के खिलाफ विकसित पीटीडब्ल्यू एफ-ई मॉडल की ऊर्जा अवशोषित और संबंधित प्रभाव गति उचित थी।

IIT-D द्वारा एकत्र किए गए राष्ट्रीय राजमार्ग-8 (NH-8) डेटाबेस से क्षति विवरण के साथ एक वास्तविक-विश्व PTW दुर्घटना का चयन किया गया और एफ-ई में पुनर्निर्माण किया गया। एफ-ई सिमुलेशन में घटनाएं, गति की दिशा, और प्रभाव के बाद अंतिम आराम की स्थिति सहसंबद्ध थी। एफ-ई विश्लेषण में फ्रंट फोर्क की क्षति ऊर्जा और विरूपण प्रयोगात्मक डेटा के साथ उचित रूप से सहसंबद्ध थे। क्षति घटक के आधार पर अवशोषित ऊर्जा और संबंधित प्रभाव गति की भविष्यवाणी करने की एक विधि का प्रदर्शन किया गया। इसलिए यह अध्ययन एक वास्तविक दुनिया सड़क यातायात दुर्घटना (आरटीए) में एक विशिष्ट भारतीय पीटीडब्ल्यू के महत्वपूर्ण ऊर्जा अवशोषित घटकों के नुकसान के विवरण के आधार पर प्रभाव की गति की भविष्यवाणी करने के लिए एक अच्छा प्रारंभिक बिंदु के रूप में कार्य करता है।

TABLE OF CONTENTS

AUTHORS DECLARATION

CERTIFICATE **i**

ACKNOWLEDGEMENTS **iii**

ABSTRACT **v**

LIST OF FIGURES **xi**

LIST OF TABLES **xvi**

NOMENCLATURE **xvii**

Chapter 1 Introduction **1**

1.1 Background 1

1.2 Accident Reconstruction 6

1.3 Damage based analysis 7

1.4 Computer Simulation Tools for Accident Reconstruction 11

1.5 Need for Energy-based Analysis for PTW Crash 13

1.6 Motivation 14

1.7 Summary 15

Chapter 2 Literature Review **17**

2.1 Introduction 17

2.2 Motorcycle Crash Tests and Semi-Empirical Correlation 17

2.3 Structural Crashworthiness 27

2.4 MB and FE Simulation-based Crash Analysis 33

2.5 Summary 39

Chapter 3 Research Question and Methodology **41**

3.1 Introduction	41
3.2 Need for Damage Based Analysis	41
3.3 Research Question	43
3.4 Research Objective	43
3.5 Research Methodology	45
3.6 Conclusion	47
Chapter 4 Experimental Setup and Methodology	49
4.1 Introduction	49
4.2 Experimental Setup for Three-Point Bending Tests	49
4.3 Identification of Energy-absorbing components	52
4.4 Test Procedure	57
4.5 Test Parameters and Test Matrix	59
4.6 Experimental Results	61
4.7 FE modelling of Front Fork Tube	65
4.8 Real-World Crash Reconstruction	69
4.8.1 Case Description	70
4.9 Summary	72
Chapter 5 Development of Finite Element and Multi-body Model of Indian PTW for Accident Reconstruction	74
5.1 Introduction	74
5.2 Development of typical Indian PTW FE Model	74
5.2.1 Element Type	76
5.2.2 Material Modelling	86
5.3 Validation of PTW Finite Element (FE) model	91
5.3.1 FE Rigid-barrier Simulation Validation	92
5.3.2 FE PTW-Car Simulation	96

5.4 MB PTW Model Validation	100
5.5 Summary	105
Chapter 6 Contributions and Conclusion	107
6.1 Contributions	107
6.2 Limitations	108
6.3 Future Scope	109
REFERENCES	110
Brief Biodata of the Author	120

LIST OF FIGURES

Figure 1: Automobile Domestic Sales Trend.....	3
Figure 2: (a) shows the distribution of fatalities as per the type of road user for the year 2010 (b) shows the distribution of fatalities as per the type of road user for the year 2016 (Source: https://www.who.int/publications/i/item/9789241565684)	4
Figure 3: Road Traffic user's killed (NCRB, 2009-18).....	5
Figure 4: Fatalities distribution among vulnerable road users as per NCRB data (2009-18) (Source: https://ncrb.gov.in/en/accidental-deaths-suicides-india-ads)	5
Figure 5: Damage parameters measurement protocol as per CDC	10
Figure 6: Linear relation between crush and crash energy (adapted from Campbell, 1974)...	10
Figure 7: (a) Wheelbase shortening of the motorcycle (b) Permanent shortening of wheelbase varies linearly with the speed of impact (adapted from Severy et al., 1970).....	18
Figure 8: Kawasaki 1000 cc motorcycle impact (a) at the center of the front right door of the car (b) at front wheels (adapted from Adamson et al., 2002)	19
Figure 9: Motorcycle Wheelbase Change vs. Impact Speed	19
Figure 10: (a) Crash test between a 100 cc PTW and car (b) Linear relationship between wheelbase change and Impact speed (adapted from Hamzah et al., 2014).....	20
Figure 11: (a) steel barrier against which PTW impacts (b) load cell attached behind the steel plates (c) PTW moved using ropes to attain collision test speed and handles tied to retain straight-ahead motion (adapted from Vangi and Cialdai, 2014).....	24
Figure 12: Force recorded for a PTW vs. rigid wall crash test using 3 load cells (adapted from Vangi and Cialdai, 2014).....	25
Figure 13: Image Depicting δ and A , ΔA (adapted from K. S. Tan et al., 2006).....	29

Figure 14: (a) shows the damaged front fork assembly in a pendulum-type impact test (b) shows the deformed clamp bolt. (adapted from Tan et al., 2008)	30
Figure 15: Final state of the three-point bending test (adapted from Tan et al., 2016)	31
Figure 16: (a) showing static test setup and (b) showing dynamic drop-weight test setup (Fujii, 2003).....	32
Figure 17: ISO13232 seven basic configurations (adapted from ISO, 1996c)	35
Figure 18: (a) Full-scale crash test of scooter type PTW and car (b) A PTW and Car MADYMO model representing the full-scale crash test (adapted from Deguchi, 2005).....	36
Figure 19: (a) Handle bending test (b) graph showing load vs. deflection comparison between experimental and simulation of bending test (adapted from Deguchi, 2003).....	37
Figure 20: Comparison of tourer PTW at 45-degree impact angle (a) in a crash test (b) with FE model of PTW (adapted from NAMIKI et al., 2003)	38
Figure 21: Comparison of frame damage in under-ride crash scenario (a) in a crash test of PTW (b) with FE model of PTW (adapted from Kuroe et al., 2004).....	38
Figure 22: FE model of Kawasaki GXZ (adapted from (Mukherjee et al., 2002))	39
Figure 23: Research methodology adopted towards the development of a computational model of components and a typical 100 cc Indian PTW	45
Figure 24: Methodology for estimating energy and Impact velocity of PTW.....	47
Figure 25: Setup of the impact test on the front fork pipe	50
Figure 26: Schematic layout of the setup showing instrumentation used to record data.....	51
Figure 27: Classification of Opposing Vehicle observed from NH-8 data.....	53
Figure 28: Categorization of collision type against opposing vehicle or road infrastructure ..	53
Figure 29: Damage to the (a) front and (b) rear rim of the spoke wheel and (c) alloy wheel .	54
Figure 30: (a) and (b) Bending and twisting (c) and (d) only bending of the front-fork tube...	55
Figure 31: Dent on (a) top, (b) and (c) side of fuel-tank, and (d) crushed fuel tank.....	55

Figure 32: (a) Bending of handle (b) bending of leg-guard (c) crushed front headlight (d) dented exhaust pipe (e) bend chassis, handle and leg-guard	56
Figure 33: (a) Pictures highlighting markers attached to impactor (red box) and pipe (yellow box) (b) Zoom view showing the cross in red and yellow, which trace displacement of the center of the markers.....	58
Figure 34: (a) Front fork assembly (b) Showing application of direction of the force in a frontal crash.....	60
Figure 35: Force-time graph for three-point bend test at 3.5 m/sec.....	62
Figure 36: (a) Impactor velocity before and after impact (b) Impactor displacement and pipe displacement after the first contact starts.....	62
Figure 37: Force vs. Displacement graph for impact at 3.5 m/sec	63
Figure 38: Graphical representation of linear fit for the Energy absorbed vs. bending angle.	64
Figure 39: (a) front fork tube (b) zoom view of one end of the tube showing shell elements.	66
Figure 40: FE representation of three-point bend test setup	67
Figure 41: Experimental and FE simulation contact force comparison.....	68
Figure 42: Comparison of front fork tube deflection in an experimental test and FE simulation.....	69
Figure 43: Damaged rear left side of the parked truck	70
Figure 44: Damage to the (a) front fork and leg-guard and (b) the handle.....	71
Figure 45: (a) Surface geometry model of the engine (b) Surface geometry model of the handle.....	75
Figure 46: Surface geometry model of chassis.....	75
Figure 47: (a) ELFORM2 with one integration point on the surface (b) ELFORM16 with 4 integration points on the surface.....	77
Figure 48: Mesh quality and value of the related parameters for chassis.....	79

Figure 49: Mesh quality and value of the related parameters for handle.....	79
Figure 50: Effect of mesh size on the FE model force output	81
Figure 51: (a) Revolute joint between the front wheel hub and hub rod (b) CNRB1 and CNRB2 made on common node.....	82
Figure 52: (a) Wire-frame view showing bolt connection between the upper clamp and FFUT (b) Steering revolute joint.....	83
Figure 53: (a) Revolute joint between chassis and swing-arm using CNRB (red color web structure) (b) Wire-frame view showing CNRB.....	83
Figure 54: (a) Spring and damper elements in LSDYNAS TM (b) Discrete element and translation joint for the front suspension FFUT and FFLT.....	84
Figure 55: Front and rear suspension spring force vs. displacement graph.....	85
Figure 56: The simplified FE model of a typical 100 cc Indian PTW.....	85
Figure 57: Frontal components are numbered and selected to model the FE PTW model	87
Figure 58: Chassis components that are selected to model the FE PTW model.....	87
Figure 59: Stress-strain curve for the FFUT.....	90
Figure 60: Stress-strain curve for alloy wheel/rim	90
Figure 61: Stress-strain curve for CRCS type steel plate	91
Figure 62: Stress-strain curve used for ERW1 type steel tubular structures	91
Figure 63: (a) FE model of typical Indian PTW (b) FE model of Kawasaki (Mukherjee et al., 2002).....	92
Figure 64: Time-step size of shell elements.....	94
Figure 65: Wall forces comparison for present study with (Mukherjee et al., 2002)	95
Figure 66: (a) Top view and (b) side view of PTW-PV crash configuration	97
Fig. 67. Internal Energy vs. wheelbase change (Δw) of PTW for impact on PV front left door center.....	98

Fig. 68. Internal Energy vs. deformation/maximum depth of penetration (<i>d_{car}</i>) of PV for a PTW impact on front left door center.....	98
Figure 69: MB model representation of a typical 100 cc Indian PTW	103
Figure 70: Force-Deflection characteristics for the front wheel (adapted from Fujii, 2003) ..	104
Figure 71: Comparison of wall impact forces between FE model and MADYMO model of Indian PTW.....	105

LIST OF TABLES

Table 1: Literature related to motorcycle crash test experiments in past 2 decades.....	27
Table 2: Test matrix for front fork bending test.....	61
Table 3: Drop tower impact test data for 29 mm diameter front fork (Span length of 360 mm).64	
Table 4: Drop tower impact test data for 31 mm diameter front fork (span length equal to 300 mm).....	65
Table 5: Material properties of front fork upper pipe	66
Table 6: Deformation energy for one front fork tube using formulation developed from the experimental study.....	72
Table 7: Deformation energy for the RTA involving PTW and truck from FE simulation	72
Table 8: Specification of a typical 100c Indian PTW	76
Table 9: Recommended and obtained parameters value.....	78
Table 10: Material for the components as per IS/JIS standards.....	88
Table 11: Material properties of deformable components	89
Table 12: Experimental dataset for PTW and PV crash test.....	100
Table 13: Energy loss value comparison of PTW crash test data obtained from literature data against FE simulation data for similar crash configurations.....	100
Table 14: Rigid body and type of joint.....	102
Table 15: C.G. location of MB model comparison with the physical model	103

NOMENCLATURE

ABBREVIATIONS

ACEM	Association of European Motorcycle Manufacturers
C.G.	Center of Gravity
cc	Cubic Centimeters
CCSA	Centre for Collision Safety and Analysis
CDC	Collision Deformation Classification
CNRB	Constrained Nodal Rigid Bodies
CoE	Conservation of Energy
CRCS	Cold rolled commercial steel
DAQ	Data Acquisition System
DC	Damping Constant
E	Young's Modulus
EES	Equivalent Energy Speed
EL	Effective Length
ELFORM	Element Formulation
FE	Finite Element
FFLT	Front Fork Lower Tube
FFUT	Front Fork Upper Tube
HPC	High Performance Computing
IE	Internal Energy
IIT-D	Indian institute of Technology-Delhi
JARI	Japan Automotive Research Institute

Kg	Kilograms
L	Length
LC	Lower Clamp
M	Mass
MAIDS	Motorcycle Accidents In-depth Study
MATD	Motorcycle Anthropometric Test Devise
MB	Multi-Body
MIROS	Malaysian Institute of Road Safety
Mpa	Mega Pascal
NASS	National Automotive Sampling System
NATRiP	National Automotive Testing R&D Infrastructure Project
NCRB	National Crime Record Bureau
NH-8	National Highway-8
NHTSA	National Highway Traffic Safety Administration
OEM	Original Equipment Manufacturer
OV	Opposing Vehicle
PTW	Powered Two Wheeler
PV	Passenger Vehicle
RWBT	Rigid Wall Barrier Test
SE	Specific Energy
SIAM	Society of International Automotive Manufacturers
SL	Span Lengh
TRL	Transport Research Laboratory
UC	Upper Clamp
V	Velocity

VRU	Vulnerable Road Users
w.r.t	with respect to
WHO	World Health Organisation