IMPROVEMENT OF HYBRID III 50TH PERCENTILE FINITE ELEMENT MODEL FOR SLIDING CONFIGURATION MOTORCYCLIST IMPACT

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To my family and my love

without which this aim

would have not been possible
I pay due thanks to all the people that helped me during this period of thesis, starting from my colleagues, at the university and at work, to the researchers and the big group at the LaST laboratory.

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Contents

IMPROVEMENT OF HYBRID III 50TH PERCENTILE FINITE ELEMENT MODEL FOR SLIDING CONFIGURATION MOTORCYCLIST IMPACT... I

ACKNOWLEDGEMENT........................................................................................................... V

CONTENTS ................................................................................................................................ VII

LIST OF FIGURES ........................................................................................................................... X

LIST OF TABLES ............................................................................................................................ XIV

ABSTRACT ...................................................................................................................................... XVII

CHAPTER 0 ESTRATTO IN ITALIANO ............................................................... XIX

  0.1 OBIETTIVI DEL LAVORO...................................................................................................... XIX
  0.2 STATO DELL’ARTE ................................................................................................................ XX
  0.3 PROVE SPERIMENTALI ......................................................................................................... XXI
  0.4 SIMULAZIONI NUMERICHE ............................................................................................... XXIV
  0.5 RISULTATI E SVILUPPI FUTURI .................................................................................... XXVI

CHAPTER 1 INTRODUCTION .................................................................................. 1

  1.1 ROAD SAFETY IN MOTORCYCLIST DOMAIN ................................................................. 1
  1.2 THE ROLE OF THE ATD ...................................................................................................... 5
  1.3 REFERENCE REGULATION STANDARD ......................................................................... 7
  1.4 OBJECTIVES OF THE WORK ............................................................................................ 9
  1.5 STRUCTURE OF THE THESIS WORK ............................................................................... 10

CHAPTER 2 STATE OF THE ART ........................................................................ 11

  2.1 HYBRID III TEST DEVICE ............................................................................................... 11
2.2 NUMERICAL MODELS FOR ATD ................................................................. 14
   2.2.1 LSTC STANDING HYBRID 50TH PERCENTILE ...................................... 15
   2.2.2 GDTECH STANDING HYBRID 50TH PERCENTILE .................................... 17
2.3 MODELS COMPARISON AND REFERENCE ATD IDENTIFICATION ................. 19

CHAPTER 3 EXPERIMENTAL TESTS ................................................................. 21
3.1 EXPERIMENTAL TESTS INTRODUCTION .................................................. 21
3.2 DROP TESTS .......................................................................................... 22
   3.2.1 TESTING PROCEDURES .................................................................... 23
   3.2.2 DROP TESTS OF THE HEAD ............................................................. 24
   3.2.3 DROP TESTS WITH HELMET ............................................................ 32
3.3 FULL SCALE EXPERIMENTAL TESTS ....................................................... 41
   3.3.1 TESTING PROCEDURES .................................................................... 41
   3.3.2 FULL SCALE TEST ON CONCRETE NEW-JERSEY BARRIER ................... 42
   3.3.3 FULL SCALE TEST ON STEEL CMPS ............................................... 45

CHAPTER 4 NUMERICAL SIMULATIONS ............................................................. 49
4.1 THE FE MODEL OF HYBRID III ............................................................... 49
   4.1.1 GENERAL CHECK ON THE ENTIRE MODEL ........................................ 50
   4.1.2 MODEL OF THE HEAD OF THE HYBRID III ........................................ 52
   4.1.3 HEAD MODEL CALIBRATION ............................................................. 54
   4.1.4 NECK MODEL .................................................................................. 56
4.2 FE MODEL OF THE FULL-FACE PROTECTIVE HELMET ......................... 59
   4.2.1 HELMET MODEL CALIBRATION ....................................................... 61
   4.2.2 HEAD AND HELMET MODELS VALIDATION WITH RSVVP .............. 66
4.3 SAFETY BARRIERS MODEL ..................................................................... 67
   4.3.1 MODEL OF THE CONCRETE NEW-JERSEY BARRIER ......................... 68
   4.3.2 MODEL OF THE STEEL CMPS ......................................................... 69
4.4 FULL SCALE IMPACT SIMULATIONS ....................................................... 71
   4.4.1 IMPACT AGAINST THE NEW-JERSEY CONCRETE BARRIER ............... 74
   4.4.2 IMPACT AGAINST THE STEEL CMPS ............................................. 77
   4.4.3 FULL SCALE POST CENTRED IMPACT SIMULATION ....................... 81
   4.4.4 FULL SCALE MID-SPAN IMPACT SIMULATION .................................. 82
CHAPTER 5 NUMERICAL - EXPERIMENTAL CORRELATION................. 85

5.1 AVAILABLE TERMS OF COMPARISON ........................................... 86
5.2 RESULTS FOR THE CONCRETE NEW-JERSEY IMPACT .................... 87
5.3 RESULTS FOR THE STEEL CMPS IMPACT ..................................... 89
  5.3.1 POST CENTRED IMPACT CORRELATION .................................. 90
  5.3.2 MID-SPAN IMPACT CORRELATION ......................................... 93

CHAPTER 6 CONCLUSIONS AND FUTURE DEVELOPMENTS ............... 97

6.1 FUTURE DEVELOPMENTS ................................................................. 98

BIBLIOGRAPHY .................................................................................. 99

APPENDIX A HYBRID II HEAD NUMERICAL DROP TEST ............... 103
  A.1 NUMERICAL MODEL OF THE HEAD OF THE HYBRID II .................. 103

APPENDIX B FULL SCALE IMPACT SIMPLIFIED MODEL OF CMPS .. 107
  B.1 POST CENTRED FULL SCALE IMPACT SIMULATION .................... 107
  B.2 MID-SPAN FULL SCALE IMPACT SIMULATION ............................. 109
List of figures

Figure 1.1: Road traffic deaths by type of road user, by WHO region [1]........2
Figure 1.2: Example of single beam safety barrier........................................3
Figure 1.3: Example of DMPS (left) and CMPS (right) .................................4
Figure 1.4: Example of integrated steel CMPS..............................................5
Figure 1.5: Severity levels associated maximum value..................................8
Figure 1.6: Severity level for Fz compressive neck force: level I (left) level II
(right)........................................................................................................9
Figure 2.1: 50\textsuperscript{th} percentile Hybrid III device entire model (left) and sectioned
(right)........................................................................................................12
Figure 2.2: LSTC Hybrid III models: front impact automotive (left) standing
(right)........................................................................................................16
Figure 2.3: Neck-head model of LSTC ATD: lateral (left) and sectioned
isometric (right)........................................................................................17
Figure 2.4: GDTech ATD entire lateral (left), and neck-head parts (right): lateral
(up) and sectioned isometric (down).......................................................18
Figure 3.1: Accelerometers, experimental configuration (left) and positive
reading (right)..........................................................................................23
Figure 3.2: Head comparison for Hybrid II (right in each photo) and III (left in
each photo)..............................................................................................25
Figure 3.3: Steel cranium of Hybrid II (left) and Hybrid III (right)...............25
Figure 3.4: Initial configuration for drop test of Hybrid II’s head .................26
Figure 3.5: Acceleration data from Hybrid II drop test (left) and focus on first
rebound (right)..........................................................................................27
Figure 3.6: Acceleration data from Hybrid III drop test (left) and focus on first
rebound (right)..........................................................................................30
Figure 3.7: Activity Helmet from NZI................................................................. 32
Figure 3.8: Initial configuration for Hybrid II helmet drop tests.................. 34
Figure 3.9: Acceleration data from helmet drop tests for Hybrid II head .... 35
Figure 3.10: Acceleration data for drop test with helmet using Hybrid III head 36
Figure 3.11: Superposition of acquired acceleration data from drop test with helmet................................................................. 37
Figure 3.12: Acceleration data from Hybrid II drop test with helmet (left) and focus on first rebound (right) ........................................... 39
Figure 3.13: Module of the concrete new-jersey safety barrier .................... 43
Figure 3.14: Frames from the impact against a new jersey concrete barrier .... 44
Figure 3.15: Frames from the post centred impact against a CMPS ............ 46
Figure 3.16: Frames from the mid-span impact against a CMPS................. 47
Figure 3.17: Permanent plastic deformations on the steel CMPS for post centred (left) and mid-span (right) impact configuration ............... 48
Figure 4.1: Barycentric position for *PART_INERTIAs before (left) and after reset (right)........................................................................... 51
Figure 4.2: Vertical and horizontal sections of head and helmet parts ......... 52
Figure 4.3: Head assembly particular (left) and vertical section (right) ....... 53
Figure 4.4: Mesh refinement for head’s outer skin and steel skull............... 54
Figure 4.5: comparison between experimental and numerical drop test Hybrid III’s head ................................................................. 55
Figure 4.6: Supine neck’s position for the real Hybrid III......................... 57
Figure 4.7: Section of the neck’s assembly for the numerical ATD............ 57
Figure 4.8: Neck’s internal structure modification.................................... 58
Figure 4.9: FE model of full-face helmet ...................................................... 59
Figure 4.10: Inner layer modification for the FE model of full-face helmet.... 60
Figure 4.11: Experimental and numerical initial condition for drop test of head and helmet................................................................. 62
Figure 4.12: Frames from the drop test simulation with helmet............... 63
Figure 4.13: Comparison of acceleration time history for the numerical models of helmet ................................................................. 64
Figure 4.14: Metrics comparison results from the RSVVP program
Figure 4.15: FE model for the concrete new-jersey barrier
Figure 4.16: Profile (left) and module (right) of the integrated CMPS
Figure 4.17: Loading process adopted for the full-scale simulations
Figure 4.18: Frames from the dynamic relaxation output
Figure 4.19: Initial (left) and final (right) frame for dynamic relaxation analysis
Figure 4.20: Yielding stress volumetric deformation curve extension
Figure 4.21: Screen from downstream view new-jersey impact (respectively 0.19, 0.2, 0.22, 0.24, 0.27, 0.3, 0.33, 0.36 [s])
Figure 4.22: Screen from top view new jersey impact (respectively 0.19, 0.2, 0.22, 0.24, 0.27, 0.3, 0.33, 0.36 [s])
Figure 4.23: End component for the CMPS according to the CAD drawings
Figure 4.24: Photographs of failed tests: CMPS and post connection (left) and ATD kept by the barrier (right)
Figure 4.25: Screen from upstream view post centred impact refined barrier (respectively 0.18, 0.22, 0.25, 0.27, 0.30, 0.33, 0.39, 0.47 [s])
Figure 4.26: Screen from upstream view mid-span impact refined barrier (respectively 0.18, 0.2, 0.23, 0.26, 0.28, 0.32, 0.35, 0.40 [s])
Figure 5.1: Experimental and numerical comparison new-jersey impact
Figure 5.2: Comparison of head acceleration time history for the new-jersey impact
Figure 5.3: Experimental and numerical comparison post centred impact on CMPS
Figure 5.4: Time at level graph comparison between experimental and numerical post centred impact
Figure 5.5: Experimental and numerical comparison mid-span impact on CMPS
Figure 5.6: Time at level graph comparison between experimental and numerical mid-span impact
Figure A.1: Head model with reduced thickness for vinyl layer
Figure A.2: Experimental and numerical comparison acceleration time history for Hybrid II 150 mm drop test.
List of tables

Table 2.1: Anthropometric data for the Hybrid III family ........................................13
Table 2.2: Measurement capacity of Hybrid III in head and neck parts. ..............14
Table 3.1: Accelerometers characteristics [4] .........................................................24
Table 3.2: Mass comparison between the head of Hybrid II and III ..................25
Table 3.3: Number of experimental tests with the Hybrid II head ....................26
Table 3.4: Acceleration peaks and HIC$_{36}$ values for drop test of Hybrid II’s head
..........................................................................................................................28
Table 3.5: Acceleration peaks and HIC$_{36}$ values for drop test of Hybrid III’s head
................................................................................................................................31
Table 3.6: Vinyl layer thickness comparison between the head of Hybrid II and
     Hybrid III ........................................................................................................31
Table 3.7: Physical properties of the helmet .......................................................33
Table 3.8: Number of experimental Hybrid II drop tests with helmet .............33
Table 3.9: Head injury criterion values for Hybrid II 450 mm drop test with
     helmet ........................................................................................................35
Table 3.10: Number of experimental tests with the head of the Hybrid II and the
     helmet ........................................................................................................38
Table 3.11: Acceleration peaks and HIC$_{36}$ values for drop test of Hybrid II’s
     head and helmet ..........................................................................................40
Table 3.12: Characteristics for filters used in full scale tests [5] .......................42
Table 3.13: Mass values for the tested 50$^{th}$ percentile Hybrid III at Politecnico di
     Milano ........................................................................................................43
Table 3.14: Impact initial conditions for the impact test against concrete new-
     jersey barrier ............................................................................................44
Table 3.15: Steel CMPS main characteristics .....................................................45
Table 3.16: Mass values for the tested 50th percentile Hybrid III during post centred impact

Table 3.17: Mass values for the tested 50th percentile Hybrid III during mid-span impact

Table 3.18: HIC values obtained from experimental tests on CMPS

Table 4.1: Mass comparison between experimental and numerical head

Table 4.2: Acceleration peaks and HIC36 values comparison Hybrid III head drop

Table 4.3: Reproduced and real mass for the full-face helmet

Table 4.4: Reproduced and real mass for the model of drop test with helmet

Table 4.5: HIC value comparison between numerical and experimental drop with helmet

Table 4.6: Physical properties of the FE model of new-jersey barrier

Table 4.7: Comparison between refined and simplified model of CMPS

Table 4.8: Mass comparison for the sub-parts of the motorcyclist model

Table 4.9: Mass comparison for the entire motorcyclist model

Table 5.1: Experimental numerical comparison for the HIC value in the new-jersey impact

Table 5.2: Results resume for the post centred impact with CMPS

Table 5.3: Working width comparison between experimental and numerical post centred impact

Table 5.4: Results resume for the mid-span impact with CMPS

Table 5.5: Working width comparison between experimental and numerical mid-span impact

Table A.6.1: difference in thickness reproduction in numerical environment for Hybrid II skin

Table A.6.2: HIC value comparison for the 150 mm drop test with the head of the Hybrid II
Roadside safety barriers that are commonly used to restraint impacting vehicles are characterized by exposed elements that represents an excessive hazard for impacting motorcyclists, even if they are well protected by regular suit and helmet. Whilst steel made common barriers accomplish an excellent work restraining vehicles, absorbing part of the high kinetic energy that they bring into a crash, on the other hand they don’t take into account the relative softness of a human body that directly impact against them.

To face the problem of a barrier that is not biker friendly, a numerical study is carried out to be capable to predict the motorcyclist behaviour during impacts and to improve the design of roadside barriers. In order to represent the two-wheeler rider during a head front impact against a roadside protection system, the numerical model of Hybrid III anthropomorphic test device (ATD) is used. Many versions of numerical ATD are made available from software developers, some of them simplified and others well detailed in constitutive parts, but they all are designed to behave as human body when he represents the occupant of a crashing vehicle. The numerical model of ATD, as it is, seems to fail reproducing the direct impact of a motorcyclist against a roadside safety barrier. In order to have a reliable instrument to be used during the design of motorcyclist protection systems, an adaptation work has been conducted on the numerical ATD’s model. Different modifications have been introduced on the Finite Element (FE) model of Hybrid III to make it reproduce the behaviour of a two-wheeler rider whose head frontally impacts a safety barrier in sliding configuration. The most
important actions were conducted on the ATD’s head and neck parts and on the numerical model of a full face helmet. In particular, modifications on geometries, material parameters, FE formulation and contact definition were introduced.

The validation process for the developed model passed through the comparison between experimental tests and numerical simulations realized with LS-DYNA FE software. A first calibration was conducted on the head-helmet assembly using a series of drop tests. The head of the Hybrid III was isolated from the device’s body, instrumented with accelerometers in the three directions and freely let drop onto the ground with and without helmet. The acceleration data acquired were so used as statistical basis for the calibration of the numerical head and helmet model. The head model coming from the calibration process was brought back on the Hybrid III and the entire ATD was used to simulate the impacting conditions of different experimental tests.

In order to correlate the entire model, full scale crashes were reproduced: an impact of a motorcyclist rider against a concrete new-jersey and a steel continuous motorcyclist protection system (CMPS) were simulated.

Part of this thesis work has been realized in GDTech S.A. in Liege (BE), and part at LaST laboratories at Politecnico di Milano (IT).

**KEYWORDS:** ATD, HIC, Hybrid III, drop test, FE simulation LS-DYNA, helmet validation, EN 1317-8
0.1 Obiettivi del lavoro

Il motociclista, assieme al pedone ed al ciclista, rappresenta nel panorama della sicurezza stradale uno degli utenti più a rischio, con un numero di morti per anno sempre in crescita. Una ragione fondamentale dell’attuale situazione vissuta dagli utenti di veicoli a due ruote è sicuramente da attribuire alla scarsa formazione che viene impartita sulla sicurezza stradale, talvolta affiancata dalla scarsa vigilanza degli organi di controllo nei confronti del rispetto delle norme di sicurezza. Questo lavoro di tesi mira ad operare su ciò che è possibile fare dal punto di vista ingegneristico per tentare di arginare il problema, o perlomeno di ridurre la fatalità associata agli incidenti stradali che coinvolgono i motociclisti.

In questo lavoro di tesi, svolto per la sua maggior parte presso l’azienda GDTech S.A. e in parte presso i laboratori del LaST del Politecnico di Milano, si è trattato il tema della sicurezza stradale dal punto di vista di un utente estremamente vulnerabile. In particolare si è operato nell’ambito della riproduzione in ambiente numerico delle condizioni di impatto di un motociclista che si trova a colpire una barriera di sicurezza scivolando sull’asfalto a seguito di una caduta dal veicolo. È infatti questo un campo nel quale GDTech S.A., che vanta già una comprovata esperienza nell’ambito della
simulazione numerica di crash, intende costruire la conoscenza necessaria a far fronte alla domanda crescente di simulazioni e prevedano il comportamento di nuovi sistemi di ritenuta in condizioni di impatto di un motociclista.

L’obiettivo principale del lavoro consiste nell’adattare e migliorare un modello ad elementi finiti di manichino antropomorfo, affinché questo sia in grado di predire, con una certa accuratezza, gli indici necessari alla validazione di un sistema di protezione per motociclisti. La base sperimentale di riferimento per la correlazione del modello ad elementi finiti di manichino è rappresentata da prove di caduta libera, effettuate sulla testa del dispositivo, e da alcune prove, svolte precedentemente, di impatto dell’intero manichino contro diverse barriere di sicurezza.

La calibrazione del modello della testa e del casco di protezione rappresenta il primo traguardo, dopo il quale il comportamento del modello completo viene testato in simulazioni di impatto contro barriere di sicurezza di tipo rigido e deformabile.

0.2 Stato dell’arte

Il modello numerico di manichino utilizzato consiste in una elaborazione dell’Hybrid III originariamente distribuito dalla Livermore Software Technology Corp (LSTC). Le modifiche al modello, antecedenti al lavoro qui presentato, consistono principalmente nell’aggiunta di dettaglio alla modellazione di alcune parti, come la modellazione geometrica della parte in gomma del collo dell’Hybrid III, la modifica del rivestimento esterno del tratto lombare e l’aggiunta di dettaglio alle mani del manichino.

Il modello preso in carico consisteva in una versione datata del manichino rispetto all’ultima sviluppata in azienda durante altri progetti di tirocinio. Negli anni le differenti modifiche, non tutte documentate, avevano condotto ad un modello che tentava, con scarsi risultati, di riprodurre la reale articolazione del corpo umano, producendo risultati non comparabili con le prove sperimentali che si desiderava replicare.
Avendo come obbiettivo quello di realizzare un modello fedele il più possibile al comportamento del dispositivo realmente usato nelle prove di crash si è convenuto nel partire da un modello precedente (Figura 0.1).

![Figura 0.1: modelli di manichino: distribuito da LSTC (sinistra) e manichino di GDTech (destra)](image)

### 0.3 Prove sperimentali

Le prove sperimentali sulle quali ci si è basati nella fase di validazione dei modelli numerici possono essere suddivise in due tipologie.

La prima parte comprende delle prove di caduta libera effettuate presso il LaST del Politecnico di Milano. In queste prove la testa del manichino antropomorfo è stata separata dal resto del corpo e, una volta strumentata, è stata lasciata cadere a terra da altezza variabile in condizione spoglia e con casco di protezione indossato (Figura 0.2).
Diverse configurazioni sono state riprodotte nel test di caduta, come la variazione di velocità di impatto ottenuta variando l’altezza iniziale di caduta, e la variazione di calettamento relativo tra testa e casco, in modo da qualificare la sensibilità dell’accelerazione alla modalità di calzatura del casco di protezione (Figura 0.3).
I grafici temporali di accelerazione ottenuti sono stati inizialmente utilizzati per un confronto con gli stessi dati provenienti dalle simulazioni numeriche, e successivamente utilizzati come base statistica per un confronto di metriche tramite il programma Roadside Safety Verification and Validation Program (RSVVP).

La seconda parte della base sperimentale utilizzata in questo lavoro di tesi è rappresentata dai risultati di prove, svolte precedentemente sul modello intero di manichino antropomorfo, che ricostruiscono differenti scenari di impatto contro barriere di sicurezza. In particolare sono stati utilizzati i risultati contenuti nei report ufficiali di prova di un impatto contro un modello di barriera di tipo new-jersey in cemento e di due configurazioni di impatto contro una tipica barriera deformabile in acciaio che supporta un sistema di protezione per motociclisti.

*Figura 0.4: Modello di barriera di tipo new-jersey (sinistra) e contatto tra manichino e barriera (destra)*

*Figura 0.5: Istanti di una prova di impatto a metà della baia tra due pali di sostegno della barriera di protezione motociclisti*
I dati a disposizione dalle prove di impatto con l’intero manichino antropomorfo non sono completi di tutti i valori raccolti durante le acquisizioni, ma i grafici e le tabelle riassuntive dei parametri di classificazione della barriera di sicurezza presenti nei report ufficiali sono stati sufficienti per una comparazione qualitativa.

0.4 Simulazioni numeriche

Le simulazioni numeriche, realizzate mediante il codice LS-DYNA, sono state dapprima effettuate sul modello della testa, con l’obiettivo di calibrare il modello numerico utilizzando i risultati ottenuti durante le prove sperimentali di caduta libera. Durante questa fase diverse modifiche sono state introdotte a livello geometrico, a livello di modelli di materiale e di definizione di contatti affinché si giungesse ad un modello che produsse risultati comparabili con le prove di caduta svolte. Raggiunto un livello soddisfacente di correlazione per la sola testa, si è simulata la condizione di caduta libera della stessa inserita nel casco di protezione. I problemi di compenetrazione ed elevata deformazione che caratterizzavano il modello, per la maggior parte dovuti alle componenti del casco in polistirene espanso, sono stati risolti ed il risultato ottenuto è stato utilizzato per un confronto di metriche mediante il programma RSVVP. La curva di accelerazione in output è stata confrontata con la curva media delle storie temporali di accelerazione nella testa acquisite durante le prove sperimentali.
Successivamente alla revisione dei modelli numerici di barriera di sicurezza utilizzati sperimentalmente, si è proceduto alla riproduzione delle condizioni di impatto con il modello intero di manichino. L’impatto contro la barriera in cemento di tipo new-jersey è stato riprodotto testando la capacità del manichino a sostenere il carico risultante dalla condizione più gravosa rappresentata dal modello rigido di barriera. Successivamente sono stati simulati i due scenari citati nella normativa EN 1317-8 con la barriera deformabile di protezione motociclisti. L’analisi del comportamento del manichino antropomorfo è stata eseguita con un modello completo del sistema di ritenuta in acciaio e su un modello semplificato realizzato per ridurre l’elevato costo computazionale dovuto all’esagerato numero di elementi ed alla modellazione dettagliata dei collegamenti nella barriera.
0.5 Risultati e sviluppi futuri

La versione finale del manichino antropomorfo realizzata e fornita all’azienda ospitante risulta in grado di fornire con accettabile accuratezza il valore di HIC (Head Injury Criterion) delle prove riprodotte in ambiente numerico. Sono stati evidenziati ancora problemi a livello di predizione delle forze scambiate tra testa e collo del manichino antropomorfo. Affinché il modello prodotto sia in grado di fornire delle letture di forza e momento compatibili con le reali acquisite durante le prove sperimentali si consiglia una calibrazione del modello di collo del manichino mediante la prova sperimentale del pendolo.

Il modello numerico di manichino antropomorfo conseguito a GDTech S.A. risponde in maniera compatibile al reale durante le condizioni di impatto riprodotte.

<table>
<thead>
<tr>
<th></th>
<th>HIC_{36} sperimentale</th>
<th>HIC_{36} numerico</th>
<th>Errore percentuale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impatto new-jersey</td>
<td>1289</td>
<td>1174</td>
<td>-8.9%</td>
</tr>
<tr>
<td>Impatto sul palo CMPS</td>
<td>317</td>
<td>308.2</td>
<td>-2.77%</td>
</tr>
<tr>
<td>Impatto a metà baia CMPS</td>
<td>267</td>
<td>227</td>
<td>-14.9%</td>
</tr>
</tbody>
</table>

*Tabella 1: Riassunto del risultato ottenuto in termini di HIC per le simulazioni svolte*

Possibili sviluppi futuri possono comprendere, assieme alle prove di calibrazione del collo, lo svolgimento delle altre prove di taratura effettuate sul manichino antropomorfo reale, seguite da una loro riproduzione in numerico. Per far fronte all’occorrenza talvolta riscontrata della rottura di determinate componenti del manichino è possibile intervenire a livello dei giunti cinematici del modello numerico, in modo da rendere possibile la loro rottura sopra determinati valori di sollecitazione.
CHAPTER 1
INTRODUCTION

In this first chapter the main topic will be shortly described, starting with a panoramic presentation of the road safety domain and on the issues related to the absorption of energy in case of motorcyclist impact. The role of the anthropomorphic test device will be investigated and there will be presented the part of the European standard that sets the testing procedures when treating two-wheeler riders impact. In the last part the objectives of the work will be presented together with the thesis structure.

1.1 Road safety in motorcyclist domain

In a report reviewed on May 2016 concerning road traffic injuries, the World Health Organization states that the traffic crashes make 1.25 million deaths each year. This shocking data is accompanied with the first place, for traffic crashes, between the causes of death for young people, aged 15-29 years. For more, around 20 and 50 million is the number of people that suffer non-fatal injuries from road accidents and many of them incurs into disabilities.
The almost totality of these death on roads is registered in low- and middle-income countries, where no sufficient effort is spent in education of road safety and the investment in reliable infrastructures is not adequate. Even within high-income countries, people with a lower socioeconomic background seems to be more likely to be involved in road traffic crashes. Inevitably low- and middle-income countries are the ones called to sustain higher costs of injury, estimated to be around 5% of their gross national product, in treatment costs, from rehabilitation to incident investigation, and in reduction or even loss of productivity for victims or their families [1].

Figure 1.1: Road traffic deaths by type of road user, by WHO region [1]

The same report attributes half of these deaths (Figure 1.1) to crashes involving vulnerable road users as pedestrian, cyclist and motorcyclist. Road safety for powered two-wheeler (PTW) riders, for long time neglected, receives nowadays a call for attention. Governments are called to take action on multiple sectors, from reinforcement of police control to safety education.
In order to reduce the risk of death and injuries from motorcyclist road traffic impacts, an effective intervention is represented by the design of safer infrastructures also referred to as *biker-friendly*. This is the real problem for motorcyclists with the common safety barriers that are usually at the sides of the roads: they are incompatibles with the relative softness of a human body.

Steel made common barriers accomplish an excellent work restraining vehicles, that for any reason leave the carriageway. The barrier absorbs part of the high kinetic energy carried by the vehicles during the impacts. On the other hand, this kind of protections represent an excessive hazard for motorcyclists. The common structure of a single-beam safety barrier consists on a continuous beam of steel sustained by steel posts (Figure 1.2).

![Figure 1.2: Example of single beam safety barrier](image)

It’s evident that a sliding motorcyclist, even wearing appropriate suit and helmet, has low chance to survive to a high speed impact with the post of the barrier, and a higher chance to undergo to severe injuries at lower speeds.

The European Parliament, in a report in response to a Commission Communication [2] describes standard guardrails as death trap for motorcyclists. For that reason, nowadays different solutions are studied to ensure a better protection for the two-wheeler riders from such aggressive barrier elements. Lots of motorcyclist protection systems are already in use on European roads. They have been installed in zones where
the probability to have a bike fall is significant, as along accentuated turns, or where passing through the barrier represent a real hazard for rider’s life.

With motorcyclist barriers come different levels of protection according to their structure and purpose. It’s possible to distinguish two main groups for these protection structures (Figure 1.3):

- Discontinuous Motorcyclist Protection Systems (DMPS), locally placed around potentially aggressive elements at the side of the road with the purpose of reducing the severity of a direct impact;
- Continuous Motorcyclist Protection Systems (CMPS), situated along a barrier, or a section of it, with the aim of reducing the severity of an impact with posts or anchorages and also retaining and redirecting the fallen rider.

A motorcycle protection system, either continuous or discontinuous, is defined integrated (Figure 1.4) when it forms an integral part of a barrier design, rather than being a separate add-on fitted to an existing barrier.
1.2 The role of the ATD

Inside passive safety domain the use of a device that represent a surrogate of human beings in crash testing is essential. The development of such instrument started around the ‘70s with the need to find an option to the employment of volunteers, animals and post mortem human subjects (PMHS). The reason was not only ethical: all vehicle occupants used until that moment presented relative problems when passive safety investigation started to largely develop.

Volunteers, that were initially the first occupants used in experiments, were employed in tests where the acceleration/deceleration level did not exceed the human’s acceleration tolerability. Among the pioneers of the development of anthropomorphic test devices, a special mention has to be made on the Colonel of US Air Force John Paul Stapp. He began a study program on crashes to test the efficacy of seatbelts and of dashboards equipped with energy-absorbing padding in aircraft accidents. Different times he putted himself into dangerous acceleration/deceleration events. The contribution of Col. Stapp was crucial in the development of safety tests and procedures also in automotive industry. If employing humans as occupants meant to have the possibility to directly investigate the effects on them caused by crashing occurrences, the risk of death, or major injuries
that volunteers underwent to, obviously limited their employment until their complete decommission in favour of their inanimate surrogate.

During passive safety evolution some animals, like chimpanzee and pigs, took service in the role of vehicle occupants. They were mostly used to investigate occurrences as the tearing of flesh or breaking of bones because of some similarities that there are between them and human beings in certain anatomical tissues. The use of animals in the place of vehicles occupants begun to be reduced when the survivability to collision and tolerability to injuries become one of the main studied aspects. The history of passive safety also passed through the adoption of cadavers to represent the occupant of a vehicle during a crash. The problem related to the use of PMHS was the possibility to inspect the behaviour only of natural dead humans, old people for the most, because of the need of having integer bodies. The use of cadavers into crashes, as also the employment of soldiers from US army, suffered the main limit of not being repeatable, and so comparable and classifiable. Particular categories of human beings are not representative of the entire population that is involved in accidents.

The need of a repeatable surrogate, that could have permitted to compare different occurrences, represents one of the main reason that led to the development of the anthropomorphic test device as we know it today. The important lesson learned from the work of passive safety’s pioneers is nowadays reflected in the connection between engineering measurements and human tolerability and the severity of injuries. The standardized ATD aims at making repeatable the experimental tests for what concerns the human behaviour reproduction in crash occurrences.
1.3 Reference regulation standard

The theme of regulation documents for the safety barriers, designed to reduce the severity of the impact of a rider of a powered two-wheeler (PTW), has become recently a very important aspect in road safety standardization. Transport safety organizations from all over the globe ask for the production and recognition of standardized norms that have to be followed for the design and production of protection systems fitted to barriers or barriers that have an inherent PTW rider protection or risk reduction capability. The regulation that has been kept as reference for the development of this thesis work is the EN 1317-8, a part of the entire restraint system norm that assess the vehicles restraint capabilities of barriers and the risk that they represent to the occupants of impacting cars. The technical specifications expressed in EN 1317-8 define performance classes taking into account rider speed classes, impact severity and the working width of the system with respect to the rider impacts.

In this sub-paragraph there will be shortly resumed the requirements expressed into the EN 1317-8. The first part of the standard summarizes and explains the technical terms used into the document. The biomechanical indices for assessing the impact severity of a PTW rider impact against a motorcyclist protection system are illustrated. The Head Injury Criterion (HIC) acceleration based criterion is presented with his defining formula:

\[ HIC = \max \left\{ \frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} a \cdot dt \right\}^{2.5} \cdot (t_2 - t_1) \]

where the a is the resultant acceleration at the centre of gravity of the head, expressed in units of gravity, and \( t_1 \) and \( t_2 \) are time instant of the acceleration time history defining a calculation interval that can’t be greater than 36 ms for the HIC\(_{36} \) value definition.
Before the detailed description of the test methods and procedures, the text of the norm states the forces and moments that have to be acquired from the ATD to evaluate the performance indices that characterize the barrier. The requested data are the forces and moments at the load cell between the head and the neck.

The testing area and the ATD clothing and equipment are described in detail. The impact conditions and the launching configuration are there presented specifying three configurations that have to be reproduced. The ATD has to be posed in supine position with its vertical axis (from head to feet) inclined of 30 degrees from the line of the barrier before to reproduce the post centred, the post offset and the mid-span impact configuration. Boundary conditions and their tolerances are stated together with the photographic coverage requested for the tests.

The severity levels for the motorcyclist protection system (MPS) are presented in terms of maximum allowable values (Figure 1.5).

The assignment of a severity level to the safety barrier basing on the force lectures from the load cell between head and neck is made by the evaluations of their time at level. The time at level graph is simply computed posing on the horizontal axis the cumulative time that the ATD’s load cell undergoes the force value expressed on the vertical axis.

An example of time at level graph for the $F_z$ compressive force is reported in Figure 1.6, where the zone identified with the number 1 means pass the criteria and at the contrary zone 2 means the failure and attribution to upper level when present.
1.4 Objectives of the work

The aim of this thesis work is to improve the FE model of an anthropomorphic test device to make it produce realistic results during a headfirst impact simulation against a roadside safety barrier. The interest is to obtain a reliable model of the anthropomorphic test device, in order to use it during the design process of motorcyclist protections systems, reducing testing costs and optimizing the improvement of such protections.

Starting from the numerical ATD model commonly used in car crash tests and pedestrian involved accidents, the objective is to put the Hybrid III FE model in condition to simulate an impact against a barrier from a supine sliding initial configuration, obtaining the same severity levels of real tests performed with different barriers.

The scenario that the simulation aims to reply is the impact of a powered two-wheeler rider against a restraint system after he has fallen from his vehicle sliding on the ground in supine position. In order to obtain a reliable model several steps have been undertaken.

The helmet role and his interaction with the head were investigated in order to calibrate their numerical model.

Figure 1.6: Severity level for $F_z$ compressive neck force: level I (left) level II (right)
Once the correlation of the head and helmet has been judged satisfactory, the head model was integrated into the complete model and several full scale simulations were carried out with the purpose of obtaining the same severity indices measured from experimental crash tests against rigid and semi-rigid safety barriers. Different restraint system and different impact configurations were used to prove the validity of the model of the anthropomorphic test device.

Under the effect of a confidential agreement signed with the internship hosting society, in this thesis work each modification made on the FE models of ATD, helmet and safety barriers cannot be described in detail.

1.5 Structure of the thesis work

This thesis is divided in 6 parts:

**CHAPTER 1: Introduction**
**CHAPTER 2: State of the art**
**CHAPTER 3: Experimental tests**
**CHAPTER 4: Numerical models**
**CHAPTER 5: Numerical – experimental correlation**
**CHAPTER 6: Conclusions and future developments**
In this chapter the Hybrid III ATD and its numerical model will be shown. The Hybrid III category will be presented and the possible numerical models will be shortly described in order to identify the FE model to work on.

2.1 Hybrid III test device

Since their first appearance in 1949 with the Sierra Sam model, developed at Alderson Research Labs to test aircraft ejection seats, aviation helmets and pilot restraint belts, the anthropomorphic test devices experienced a rapid development to the present day. This progression, guided by the needs to develop a reliable and durable device, has seen the birth of the Hybrid family. The Hybrid I model, realized in 1971, was also called 50th percentile male dummy, since it modelled an average male in height, mass and proportion. However, as it was for Sierra Sam or other models like Sierra Stan or the VIP-50 series from General Motors, the Hybrid I dummy was based on the anthropometric database from U.S. Air Force soldiers.

In 1972 the Hybrid II was introduced with improved shoulder, spine, and knee responses with respect to the previous model, together with a more rigorous
documentation that made him the first device to comply the American Federal Motor Vehicle Safety Standard (FMVSS).

Even if the Hybrid II represented a great improvement respect to the previous version, it was still very rough and its use was limited to the developing and testing seat belt designs.

The needing of a device that would allow to explore injury-reduction strategies pushed, in 1976, the General Motors researchers to develop the current Hybrid line: the Hybrid III crash test devices (Figure 2.1).

![Figure 2.1: 50th percentile Hybrid III device entire model (left) and sectioned (right)](image)

The modification of neck’s structure represents one of the main improvements on the Hybrid III model. The segmented rubber and aluminium construction with a central cable accurately simulates the human dynamic moment/rotation flexion and extension response. The insertion of a curved lumbar spine better simulates the human-like automotive seated condition, and also the shoulders, chest and knees design was improved.

The Hybrid III-50th percentile male crash test device is the most widely used crash test dummy in the world, mainly for the evaluation of frontal crash testing, and it’s
considered to have excellent bio fidelity. The extremely large measurement capability of the Hybrid III represents a great improvement respect to the previous models. In order to inspect the behaviour of a larger scenario of different occupant typology involved in a crash test, the Hybrid III is furnished also in other different sizes (Table 2.1), where the total mass data can vary according to the presence or not of the complete instrumentation.

<table>
<thead>
<tr>
<th>Hybrid III model</th>
<th>Anthropometric data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass [kg]</td>
<td>Height [m]</td>
</tr>
<tr>
<td>50th adult male</td>
<td>77.70</td>
<td>1.7458</td>
</tr>
<tr>
<td>95th adult male</td>
<td>101.15</td>
<td>1.8502</td>
</tr>
<tr>
<td>5th adult female</td>
<td>49</td>
<td>1.4986</td>
</tr>
<tr>
<td>3-year-old child</td>
<td>16.17</td>
<td>0.9448</td>
</tr>
<tr>
<td>6-year-old child</td>
<td>23.4</td>
<td>1.1405</td>
</tr>
<tr>
<td>10-year-old child</td>
<td>35.2</td>
<td>1.2014</td>
</tr>
</tbody>
</table>

*Table 2.1: Anthropometric data for the Hybrid III family*

The Hybrid III 50th percentile is characterized by a greater measurement capacity in comparison with his predecessors. While the Hybrid II was capable to furnish only 9 acceleration acquisitions (three for head, thorax and pelvis) and 5 force measurements (three for lumbar spine and one for each femur), the Hybrid III device is capable to give back more than 40 response measurements all-over its body. To be more specific, when fully equipped, the Hybrid III can provide acceleration readings in head, thorax and pelvis parts, and it can give force measurements in upper and lower neck, clavicle, humerus, thorax, lumbar spine, pelvis, femur, knee, lower leg, ankle and toe.

Among this extremely high capacity, only two parts and their relative measurements were used in this work (Table 2.2).
<table>
<thead>
<tr>
<th>Measurement</th>
<th>Data channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head accelerometers</td>
<td>Ax, Ay, Az</td>
</tr>
<tr>
<td>Upper neck load cell</td>
<td>Fx, Fy, Fz; Mx, My, Mz</td>
</tr>
</tbody>
</table>

*Table 2.2: Measurement capacity of Hybrid III in head and neck parts.*

### 2.2 Numerical models for ATD

Numerical models of human beings, be it multibody or finite element model, represent nowadays essential instruments for designers that are called to face the problems related to human safety. The complete reproduction of such a complex structure and systems would be extremely difficult. From the last decade of the ‘90s new numerical models have been developed to reproduce directly the human being, modelling skeleton, muscles, organs and other internal structures. Numerical models as the Total Human Model for Safety (THUMS) aim to simulate human body kinematics and injury responses in particular car crashes. The effort that should be spent trying to replicate the entire human body with all its organs and tissues would not be worth for the use of which road transport safety serves itself in barriers testing for motorcyclist users. For this purpose, the design and development of a numerical model of human body has to follow the same philosophy that led to the introduction of the real ATDs. The repeatability of a numerical test is crucial together with the inspected behaviour’s fidelity, so the numerical model has to reproduce as well as possible the behaviour of the ATD that’s used in experimental tests.

Numerical models have become largely applicable to transportation safety environment, thanks to the increased reliability of numerical simulations and the enormous advantage they represent in terms of costs and time on the whole design process. Considering the elevated costs of experimental campaigns, and the
consequent possible damaging of experimental devices, the use of a suitable FE model into a numerical simulation reduces the number of experimental tests to the standard requirements. Moreover, during the design phases, the numerical model allows an easiest optimization of the protection system, shooting off the costs of attempt experimental tests.

The first part of this work has been spent analysing two Hybrid III 50\textsuperscript{th} percentile adult FE models, both based on the numerical dummy used in frontal automotive impact simulations, finding out which one was the best candidate to the adaptation to a motorcyclist impact configuration. The two starting models were the standing version of Hybrid III 50\textsuperscript{th} percentile downloaded from the Livermore Software Technology Corp (LSTC) official website, and a previous version of the same model already elaborated by GDTeach S.A. Substantially coming from the same model architecture, in the next sub-paragraphs the main differences encountered between the two reference models will be exposed.

2.2.1 LSTC standing Hybrid 50\textsuperscript{th} percentile

The Hybrid III version downloaded from the LSTC models database is an elaboration made on the seated automotive configuration of the same ATD. The modifications introduced are obviously the repositioning of lower limbs and the adaptation of the lumbar parts of the dummy to fit the standing configuration (Figure 2.2).
Even if the LSTC standing model of ATD doesn’t represent the most detailed Hybrid III numerical model allowable from software’s developers, it is anyway modelled with 143 parts for a total of 4299 elements, divided in 2644 solids, 1606 shells, 3 beams and 46 between mass, discrete and numerical accelerometers elements. The structure of the ATD is represented by rigid modelled parts, that reply the internal steel frame of the real device, assembled together with kinematical joints of type spherical, revolution or translational. These internal rigid parts are modelled using *PART_INERTIA card, so their inertial properties are manually determined and they overwrite the automatic computation made by the FE solver. Deformable parts are attached to the rigid frame, somewhere sharing structural nodes with them and somewhere else defining appropriate contact card between parts. A focus is made on head and neck internal structure because these parts present the main differences with the numerical ATD elaborated by GDTech S.A.
Differently from the real ATD, the neck’s structure is reproduced with several rigid disks connected with spherical joints at midpoint distances between them (Figure 2.3). The rubber part is reproduced, in terms of mass, with a discrete nodal mass distribution, and in terms of behaviour by specifying different momentum/angle and damping momentum/rate of rotation curves in the joint stiffness definition.

The steel skull of the Hybrid III is not geometrically reproduced but its weight and inertial properties are defined in a small solid cube positioned in the centre of the head. The internal nodes of the vinyl skin are constrained as rigid external nodes of the skull model.

2.2.2 GDTech standing Hybrid 50th percentile

The Hybrid III model elaborated by GDTech S.A. represents the result of different modifications made on a previous seated configuration model developed by Livermore Software Technology Corporation. It presents, for the most, the same modelling decisions made from LSTC developers on the standing version presented before. Some parts, that were previously defined, were deleted and some other added following the decisions made by engineers in GDTech. As a result, the ATD model
consist in 103 parts and 5529 elements divided in 4004 solids, 1483 shells, 26 beams and 16 between discrete and numerical accelerometer elements.

As it was for the LSTC model, the lumbar parts of the Hybrid III was modified to restore the standing configuration after the repositioning of the lower limbs.

Some of the main differences with the LSTC model are the deletion of the *MAT_NULL defined shell used to set the reference coordinate systems for the steel frame parts, a different modelling choice for lumbar external parts and a more detailed modelling for the neck-head assembly.

The neck structure is still modelled by rigid disks, but here they are connected to a single rubber part defined by solid elements and viscoelastic material formulation. Along the axis of the neck, a cylindrical part, modelled by solids, is defined to simulate the presence of the cable that brings together the real ATD’s neck disks. In this model

Figure 2.4: GD Tech ATD entire lateral (left), and neck-head parts (right): lateral (up) and sectioned isometric (down)
the steel skull is physically represented by a solid part that shares his external nodes with the internal ones of the rubber cover.

### 2.3 Models comparison and reference ATD identification

The final scope was to have a numerical model of Hybrid III capable to give back from simulations a HIC value comparable to the one registered in different experimental tests.

From previous work conducted on the GDTech ATD’s model some issues were identified. Apart from providing an inconsistent HIC value in head front impact simulations, this ATD was found to have a global behaviour excessively different from the experimental results, together with the incapacity of extending its neck under the gravity load.

A preliminary analysis was carried on the two FE models to find the differences in the modelling architecture, constraints and formulations that would have justified a change for the reference model.

Originally coming from the same model, the two compared ATDs share the modelling structure, but the organization of the GDTech model was found to be less complex than the other as a result of the decisions made by previous work done on the numerical model. In particular, the definition of coordinate reference systems and the imposition of constraints between parts were modelled in more intuitive way.

The absence of a furnished database and results reports for carried simulations didn’t benefit the initial use of the new downloaded LSTC model.

The ability in extending the neck under the gravity load was inspected for the LSTC model, and the same simulation was set up for the GDTech developed one. A dynamic relaxation was conducted on the supine configuration with only the gravity load acting. The body load was initialized with a ramp from zero to the regime value, then maintained till the ATDs equilibrium. While the LSTC model exhibited a credible extension of the neck assembly, the GDTech version seemed to be unmoving. Even if
the dynamic relaxation behaviour of the new downloaded model resulted to be more realistic than the one showed by the GDTech elaborated model, the choice was reverted on this last one.

The lack of complete information on the neck rubber characterization suggested that the calibration of this model would have been more difficult in presence of stiffening curves for neck’s internal joints than with a viscoelastic defined part, that automatically give its stiffness in the three directions according to the material model used.
CHAPTER 3
EXPERIMENTAL TESTS

The Hybrid III anthropomorphic test device is the most common human surrogate that is used for dynamic tests in passive safety domain. In this chapter there will be presented the experimental tests which results are used in this thesis as base of the validation of the numerical models. The drop tests used for the head-helmet model validation were performed at the LaST laboratories of Politecnico di Milano. The full scale tests, of which the results were available, were performed, part in LaST labs and part by a society that works in the transport passive safety domain.

3.1 Experimental tests introduction

The presentation of these experimental tests is structured in two main parts. The first section will present the drop test campaign realized at the Laboratory of Transport Safety (LaST) in Politecnico di Milano with the aim to obtain a statistical basis to be used for the validation process of the FE models of head and helmet. LaST Laboratories uses both the Hybrid II and Hybrid III for his experimental tests, depending on the nature and needing of each test, but during the period of this thesis work the Hybrid III encountered its calibration stop so it was allowable only for the
first part of the experimental work. It was possible to make only few tests with the head of the Hybrid III, with and without helmet, but they resulted to be sufficient to understand the differences with the head of the Hybrid II that has been used as reference for the numerical helmet calibration.

The second part will deal with the presentation of the results of different full scale tests performed before the start of this thesis work. These full scale tests reproduce two head front impact scenarios in sliding configuration, one realized at LaST laboratories with a concrete new-jersey barrier, and the other carried out in another crash laboratory where a steel CMPS was tested. The results in terms of official reports have been used to validate the full scale simulation of the two conditions.

### 3.2 Drop tests

The drop tests were conducted isolating the head parts from the entire device and letting it fall freely, with and without the helmet, under different initial conditions, represented by the falling height and the initial orientation of the head, both in absolute orientation respect to the ground and in relative position between head and helmet.

All the drop tests were executed on a planar surface represented by the ground of the LaST laboratories. In order to reproduce a wide scenario, the variation in initial orientation for the tested device meant to reproduce the possibly differences in test set up that different laboratories may have in test reproductions.

The ATD’s head was hung upside down, from the holes that allows his connection with the rest of the body, and the falling height has been taken from the lowest part of the device till the ground. A quick release mechanism gave the start to every drop test and the data acquisition.
3.2 Drop tests

3.2.1 Testing procedures

The head of the ATD was separated from the rest of the device just under the skull connection with the upper neck part. This means that, for the Hybrid II the two screws that connect the steel cranium to the neck block were removed, and for the Hybrid III the plug that connect the head to the first neck’s disk has been took off. An aluminium machined block that carried a set of three accelerometers was placed in the internal part of the steel cranium, where it’s assumed to be the CG of the part. The direction of lecture of the accelerometers matches the standard orientations specified in EN 1317 part 8 as in Figure 3.1.

![Figure 3.1: Accelerometers, experimental configuration (left) and positive reading (right)](#)

The testing device was weighted and so hung in upside down position on the ground surface and a quick release hook was used to give the start to the drops and the acquisition. The impact area was always restricted around the symmetry plane of the head, moving from frontal to parietal zone according to the different initial orientation previewed for the drop.

The characteristics of the accelerometers used for the drop tests are resumed in Table 3.1.
Experimental tests

<table>
<thead>
<tr>
<th>Model EGCS-S425-250</th>
<th>Direction I</th>
<th>Direction II</th>
<th>Direction III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>250 g</td>
<td>250 g</td>
<td>250 g</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.57 mV/g</td>
<td>0.546 mV/g</td>
<td>0.566 mV/g</td>
</tr>
</tbody>
</table>

Table 3.1: Accelerometers characteristics [4]

The data were recorded with an acquisition system connected to a personal computer in order to set the acquisition configuration for each test and save the measurements in ascii format.

Acquisitions were realized with a sampling frequency of 12.5 kHz and for an observation time of few seconds.

No physical filtering was applied directly on measurements.

A regular camera was used to collect some photos of the test set and a slow motion function was used to record some videos of the phenomena.

3.2.2 Drop tests of the head

With the aim to characterize the behaviour of the ATD’s head under impact without any protection, drop tests were conducted on the isolated head part, both for the Hybrid II and Hybrid III device.

Even if the two entire ATD’s versions present lots of differences between them, in this case, where the only part tested is represented by the head, they can be considered comparable in terms of behaviour and response.
The head of the two ATD’s version consists in a casted steel cranium and a steel removable back cap, both recovered by a vinyl rubber layer that reproduces the skin characteristics under impact (Figure 3.2). Exception made for the vinyl skin extension on the lower part of the head, the Hybrid II and the Hybrid III heads are similar in structure and weight (Table 3.2) and presumably not very different in terms of inertial properties.

### Table 3.2: Mass comparison between the head of Hybrid II and III

<table>
<thead>
<tr>
<th>ATD</th>
<th>Weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid II head</td>
<td>4.60</td>
</tr>
<tr>
<td>Hybrid III head</td>
<td>4.47</td>
</tr>
</tbody>
</table>
The availability of a ATD’s head for the drop test campaign was restricted to the Hybrid II device, but the behaviour of the head of the Hybrid III was anyway inspected to prove substantial differences.

**Hybrid II head drop tests**

The response of the head of the Hybrid II was inspected with different drop tests, realized from different initial heights. To not compromise the integrity of the ATD’s part and looking for the response of the head in an energy range not necessarily characteristic of a motorcyclist crash test, it was decided to not exceed the height of 200 mm from the ground (Table 3.3).

<table>
<thead>
<tr>
<th>Initial height</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 mm</td>
<td>4</td>
</tr>
<tr>
<td>150 mm</td>
<td>3</td>
</tr>
<tr>
<td>200 mm</td>
<td>2</td>
</tr>
</tbody>
</table>

*Table 3.3: Number of experimental tests with the Hybrid II head*

*Figure 3.4: Initial configuration for drop test of Hybrid II’s head*
The acquired data were digitally processed in a Matlab routine with a Butterworth 4th order filter equivalent to the CFC 1000 specified by standard.

Figure 3.5: Acceleration data from Hybrid II drop test (left) and focus on first rebound (right)
Dropped from different tested initial heights, the head of the Hybrid II exhibited three rebounds before remaining completely still on the ground (Figure 3.5). The shape of the acceleration profile, that the head part undergoes to, remained exactly the same. Obviously, the rise of the falling height led to an increase in the maximum acceleration value reached by the head part.

The maximum acceleration peak and the head injury criterion (HIC) were computed for each head impact. The mean peak of acceleration for each initial configuration was used to compare the results obtained from the numerical simulations.

The HIC\(_{36}\) values were computed elaborating the acceleration data collected by the acquisition system (Table 3.4).

<table>
<thead>
<tr>
<th>Initial height [mm]</th>
<th>Test</th>
<th>Acceleration peak [g]</th>
<th>HIC(_{36})</th>
<th>Average HIC(_{36})</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1</td>
<td>157.25</td>
<td>198.67</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>188.13</td>
<td>283.62</td>
<td>229.92</td>
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<td></td>
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<td>173.45</td>
<td>240.79</td>
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<td>157.45</td>
<td>196.62</td>
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<td>150</td>
<td>1</td>
<td>242.38</td>
<td>466.03</td>
<td>422.34</td>
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<td></td>
<td>2</td>
<td>228.34</td>
<td>428.14</td>
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</tr>
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<td></td>
<td>3</td>
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<td>2</td>
<td>316.07</td>
<td>798.89</td>
<td></td>
</tr>
</tbody>
</table>

*Table 3.4: Acceleration peaks and HIC\(_{36}\) values for drop test of Hybrid II’s head*

In terms of acceleration peak, even for the same initial height, each experimental test shows a certain difference respect to their mean value. This variation
goes from 12±19 g for the 100 mm drop, from 15±16 g for the 150 mm and about 11 g for the 200 mm drop.

As the injury criterion is computed on the same first rebound, this variability in values is reflected also on the HIC$_{36}$.

The tests made on the head of the Hybrid II show a good repeatability in terms of global behaviour. For the acceleration peak, a maximum weighted variation of 11% between the acquired value and the mean one for the 100 mm drop, 7% for the 150 mm and 3% for the 200 mm drop test was measured.

In terms of injury criterion, the variation between the obtained values represent the 23% of relative deviation with the mean value for the 100 mm, 11% for the 150 mm and the 4% for the 200 mm drop.

**Hybrid III head drop tests**

Even if it was decided to use the previous version of anthropomorphic test device for the calibration tests, the response of the head of the Hybrid III was however inspected. A series of drop tests from the initial height of 150 mm were conducted with the isolated head of the ATD.

The behaviour of the Hybrid III’s head was not largely observed, at the contrary of the inspection of the head of the Hybrid II, because it has been searched the possible differences that the last version of ATD’s head could have respect to his previous version.

As it was for the 2$^{\text{nd}}$ version of Hybrid ATD, the head of the Hybrid III was hung and then let fall from the same initial heights.

The same configuration of measurement system was used to acquire the acceleration data from the inside of the head (Figure 3.6).

The acceleration data were not filtered during the acquisition but they were processed with a digital 4$^{\text{th}}$ order Butterworth filter in a Matlab routine.
Experimental tests

The head of the tested Hybrid III device presented three main rebounds after which some of the test performed showed further minor oscillations for the acceleration profile. The level of the acceleration graphs is almost identical for the first rebound and shows a little shift in time and maximum acceleration reached level in the following rebounds.

The maximum acceleration peaks were computed for each head impact and the $HIC_{36}$ values were computed elaborating the acceleration data collected by the acquisition system (Table 3.5).
### 3.2 Drop tests

#### Table 3.5: Acceleration peaks and $HIC_{36}$ values for drop test of Hybrid III’s head

<table>
<thead>
<tr>
<th>Initial height [mm]</th>
<th>Test</th>
<th>Acceleration peak [g]</th>
<th>$HIC_{36}$</th>
<th>Average $HIC_{36}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>1</td>
<td>127.34</td>
<td>195.51</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>131.07</td>
<td>200.91</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>127.92</td>
<td>192.94</td>
<td>198.26</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>128.31</td>
<td>195.26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>132.94</td>
<td>206.69</td>
<td></td>
</tr>
</tbody>
</table>

The data obtained from the drop tests of the head of the Hybrid II and the Hybrid III are not comparable. This sensible difference has been attributed to the different thickness of the vinyl layer that covers the steel monolithic skull for both the Hybrid versions.

During the impact the different thickness of the ATD’s skin produces different deformation that could explain such a different level in maximum acceleration reached for the drop tests executed with both the head of the Hybrid II and Hybrid III.

The thickness of the vinyl layer around the head impacting area has been measured for both the ATD’s versions using an analogical micrometer (Table 3.6).

#### Table 3.6: Vinyl layer thickness comparison between the head of Hybrid II and Hybrid III

<table>
<thead>
<tr>
<th>ATD’s version</th>
<th>Thickness of vinyl layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid II</td>
<td>5.5 mm</td>
</tr>
<tr>
<td>Hybrid III</td>
<td>12.3 mm</td>
</tr>
</tbody>
</table>

The difference in the maximum value of acceleration reached in the 150 mm drop test from the Hybrid II and Hybrid III head has been subsequently proved with numerical simulations.
3.2.3 Drop tests with helmet

The same procedure used for the head drop tests was followed to experimentally observe the behaviour of the head of the anthropomorphic test device with the helmet worn. The head was hung upside down with the same trigger mechanism used for the head drop tests.

The full face helmet

The head protection used for the drop tests campaign was a city road full face helmet produced by the NZI Helmets. The Activity model (Figure 3.7) is a standard protective helmet composed by an outer shell in thermoplastic resin material and a protective expanded polystyrene (EPS) closed cell foam as inner layer.

![Activity Helmet from NZI](image)

As the protection attached documentation asserts, the NZI helmets are designed to comply the United Nations ESE R22.05 homologation standard, also applicable in all European countries. For five prescribed impacting points on the helmet this standard imposes to check the acceleration value reached from the head and compare it to limit values.

The Table 3.7 resumes the characteristics of the helmet used.
### Activity NZI helmet

<table>
<thead>
<tr>
<th>Head circumference</th>
<th>570 ÷ 590 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>1.4 ± 0.05 Kg</td>
</tr>
<tr>
<td>Max longitudinal dimension</td>
<td>~ 325 mm</td>
</tr>
<tr>
<td>Max lateral dimension</td>
<td>~ 242 mm</td>
</tr>
</tbody>
</table>

*Table 3.7: Physical properties of the helmet*

### Fixed height Hybrid II helmet drop tests

As it was for the head drop tests, the availability for this kind of tests was restricted to the Hybrid II’s head. A first series of tests was conducted to find out if the acquired data had presented the repeatability characteristic in front of slightly different initial configuration for the drop (Table 3.8). A reference initial height has been set to 450 mm for every drop test (Figure 3.8).

<table>
<thead>
<tr>
<th>Number of the test</th>
<th>Initial configuration description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2-9-10</td>
<td>Head inserted into the helmet in neutral position</td>
</tr>
<tr>
<td>3-4-11-12</td>
<td>Safety strap unfastened and neutral fit</td>
</tr>
<tr>
<td>5-6-13-14</td>
<td>Head slightly rotated around y-axis into helmet (nose to chest configuration)</td>
</tr>
<tr>
<td>7-8-15-16</td>
<td>Head slightly rotated around x-axis into the helmet (left ear to left shoulder configuration)</td>
</tr>
</tbody>
</table>

*Table 3.8: Number of experimental Hybrid II drop tests with helmet*
The acquired data were processed via Matlab routine with a Butterworth 4\textsuperscript{th} order filter equivalent to the CFC 1000 specified by standard. Than the signals were re-phased positioning at the same time the impacting moment for each acceleration spectrum (Figure 3.9).
3.2
Drop tests

The results show substantially a dual peak profile for the acceleration history in drop test with helmet. Some cases present also a third peak instead of the secondary dynamic behaviour after the first two main peaks. Even considering the same initial height, the response of the impacting head seems to vary a lot, even between the same scenarios. The HIC values, that were computed for each profile processing the acquired data, are reported in Table 3.9.

<table>
<thead>
<tr>
<th>Test</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIC</td>
<td>111.19</td>
<td>101.30</td>
<td>99.94</td>
<td>133.99</td>
<td>65.86</td>
<td>133.25</td>
<td>96.54</td>
<td>66.43</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIC</td>
<td>119.36</td>
<td>106.24</td>
<td>128.70</td>
<td>75.78</td>
<td>184.64</td>
<td>98.02</td>
<td>142.57</td>
<td>93.72</td>
</tr>
</tbody>
</table>

Table 3.9: Head injury criterion values for Hybrid II 450 mm drop test with helmet
The obtained results led to think about a statistical way for the comparison between experimental tests and numerical simulations.

**Fixed height Hybrid III helmet drop tests**

Differently from the case of the head drop tests, for the helmet worn condition not sensible differences were attended between the tests made with the head of the Hybrid II and the Hybrid III. The work of absorbing the impacting energy in the helmet worn scenario is executed mainly by the protection wearing, that deforms itself preserving the anthropomorphic device’s head.

However, the Hybrid III head have been used in some tests to estimate the degree of accordance of his behaviour with respect to the one of the Hybrid II. The same height of 450 mm from the ground was chosen as reference.

The same procedure used for the head of the Hybrid II was adopted for the test with the head of the Hybrid III. Acquired acceleration data were filtered and re-phased for representation.

![Acceleration data for drop test with helmet using Hybrid III head](image)

*Figure 3.10: Acceleration data for drop test with helmet using Hybrid III head*
The profile of the acceleration graph obtained from the drops using the Hybrid III’s head presents, for the first rebound, two main peaks followed from a different secondary dynamic that in a case led to at the creation of a third peak.

As expected the profile and the acceleration levels did not move sensibly from the ones obtained using the Hybrid II’s head.

In Figure 3.11 is possible to see the superposition of the results obtained in the two cases for a 450 mm drop.

Given the availability of the devices in LaST laboratories and saw that the head of the different versions of ATD doesn’t sensibly affect the results, the head of the Hybrid II was used for the following study of drop tests with helmet.

![Figure 3.11: Superposition of acquired acceleration data from drop test with helmet](image)

**Drop tests with helmet**

A series of drop tests have been conducted with the head of the Hybrid II and the helmet in order to obtain an experimental comparison base for the numerical simulations and validate the head protection. As it was for the isolated head, the initial conditions of the drop have been varied. It has been decided to test the head into the helmet in a free fall from four different heights (Table 3.10). The maximum initial
Experimental tests

height was set to 600 mm to not significantly damage the head protection looking for a repeatable event during each drop with the same initial condition.

<table>
<thead>
<tr>
<th>Initial height</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 mm</td>
<td>3</td>
</tr>
<tr>
<td>300 mm</td>
<td>3</td>
</tr>
<tr>
<td>450 mm</td>
<td>3</td>
</tr>
<tr>
<td>600 mm</td>
<td>3</td>
</tr>
</tbody>
</table>

*Table 3.10: Number of experimental tests with the head of the Hybrid II and the helmet*

The acquired data were digitally processed (Figure 3.12). The corresponding injury criterion (HIC) value have been computed and presented in Table 3.11 together with the maximum acceleration values reached during the first rebound of the helmet onto the ground.
3.2 Drop tests

Figure 3.12: Acceleration data from Hybrid II drop test with helmet (left) and focus on first rebound (right)
<table>
<thead>
<tr>
<th>Initial height [mm]</th>
<th>Test</th>
<th>Acceleration peak [g]</th>
<th>HIC$\textsubscript{36}$</th>
<th>Average HIC$\textsubscript{36}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>1</td>
<td>32.82</td>
<td>36.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>37.17</td>
<td>44.62</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>36.04</td>
<td>42.79</td>
<td>41.16</td>
</tr>
<tr>
<td>300</td>
<td>1</td>
<td>55.62</td>
<td>120.39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>47.62</td>
<td>82.76</td>
<td>97.95</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>50.17</td>
<td>90.71</td>
<td></td>
</tr>
<tr>
<td>450</td>
<td>1</td>
<td>70.88</td>
<td>170.51</td>
<td>170.99</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>74.06</td>
<td>170.26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>75.26</td>
<td>172.21</td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>1</td>
<td>93.90</td>
<td>293.33</td>
<td>242</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>94.17</td>
<td>252.68</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>79.02</td>
<td>179.98</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.11: Acceleration peaks and HIC$\textsubscript{36}$ values for drop test of Hybrid II’s head and helmet

The presented curves show a good level of repeatability, together with an increase in acceleration peak values and in the HIC values responding to the initial height variation.

The profiles of the acceleration remain substantially bi-modal for all the four impact configurations, but the predominance of one peak on the other seems to reduce at lower heights and lower initial velocities.
3.3 Full scale experimental tests

As a term of comparison for the elaborated numerical models the acquired data collected during experimental campaigns conducted previously of the start of this work has been used.

The main goal of this work is to obtain a numerical model of anthropomorphic test device capable to reproduce correctly an impact scenario against a safety barrier. The numerical ATD involved in a head front impact from a sliding supine configuration, had to be able to give back a head injury criterion value placed in the same range of the one obtained from experimental tests, in order to classify the motorcyclist protection system that GDTech S.A. has interest to work with. Among the large database of GDTech S.A. two typology of safety barrier have been chosen to test the numerical ATD’s behaviour against them. In this paragraph first the experimental impact of an anthropomorphic test device against a concrete barrier will be presented, and then an impact against a deformable steel CMPS.

3.3.1 Testing procedures

The experimental test procedures are stated in European standard [5] that has been already presented in the introduction to this work. The acquired data from the ATD are the three acceleration lectures from inside the skull and the lecture of forces and momentum on three axes from the load cell between head and neck parts. The sampling frequency is set to 12.5 kHz and the collected data have been processed, as requested by the norm, with physical filters of characteristics reported in Table 3.12.
Experimental tests

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Channel Frequency Class (CFC)</th>
<th>Channel Amplitude Class (CAC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ax, Ay, Az</td>
<td>1000</td>
<td>500 [g]</td>
</tr>
<tr>
<td>Fx, Fy</td>
<td>1000</td>
<td>9000 [N]</td>
</tr>
<tr>
<td>Fz</td>
<td>1000</td>
<td>14000 [N]</td>
</tr>
<tr>
<td>Mx, My, Mz</td>
<td>600</td>
<td>290 [Nm]</td>
</tr>
</tbody>
</table>

Table 3.12: Characteristics for filters used in full scale tests [5]

The ATD, equipped with regular suit and helmet, is thrown in supine position with 60 km/h velocity toward the restraining system with a trajectory angled 30° from the safety barrier line. The ATD, equipped with a homologated polycarbonate full face helmet, is positioned on a wood axe rigidly constrained to a cable moved by a compressed air cylinder. The trimming of alimentation pressure allows the control of the speed of impact. The axe is arrested at a distance of 2 meters from the impact and inertial forces drive the ATD against the barrier.

3.3.2 Full scale test on concrete new-jersey barrier

The portion of concrete new-jersey barrier that has been used in LaST laboratories in the experimental campaign has the common step profile that presents a large base, usually funded into the ground or fixed to a basement, and a thinner vertical body that extends for about 1 m from the road level (Figure 3.13). The tested model presents, in the upper part, a steel rebar that is also used for the connection between different module of the new-jersey safety barrier.
The horizontal slide of the LaST laboratories has been used to throw the ATD against a new-jersey concrete barrier. The restraint system has been positioned in an angled position respect to the speeding up trajectory of the anthropomorphic test device. Mass values for the test are resumed in Table 3.13.

<table>
<thead>
<tr>
<th></th>
<th>Weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male 50th percentile Hybrid III</td>
<td>77</td>
</tr>
<tr>
<td>Protective suit</td>
<td>3.5</td>
</tr>
<tr>
<td>Full face helmet</td>
<td>1.45</td>
</tr>
<tr>
<td>Total mass</td>
<td>81.95</td>
</tr>
</tbody>
</table>

*Table 3.13: Mass values for the tested 50th percentile Hybrid III at Politecnico di Milano*

A high speed camera has been used to record a slow motion video of the test (Figure 3.14).
Experimental tests

The collected data from the three accelerometers inside the head of the ATD were elaborated and the HIC value for the test have been computed (Table 3.14).

<table>
<thead>
<tr>
<th>Impact speed</th>
<th>61 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact angle</td>
<td>30°</td>
</tr>
<tr>
<td>HIC value</td>
<td>1289</td>
</tr>
</tbody>
</table>

Table 3.14: Impact initial conditions for the impact test against concrete new-jersey barrier
3.3 Full scale experimental tests

3.3.3 Full scale test on steel CMPS

The experimental tests on the deformable restraint system, that has been decided to reproduce, are two impact scenarios against an integrated CMPS made of steel (Table 3.15).

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Forming shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post</td>
<td>S355</td>
<td>C folded</td>
</tr>
<tr>
<td>Upper beam</td>
<td>S355</td>
<td>Omega folded</td>
</tr>
<tr>
<td>Lower Beam</td>
<td>S235</td>
<td>Planar</td>
</tr>
</tbody>
</table>

*Table 3.15: Steel CMPS main characteristics*

As requested by the standard EN 1317-8 two different impact scenarios were reproduced, the post centred and the mid-span impact.

With the same pneumatically driven mechanism the model of Hybrid III has been accelerated and let impact the barrier line with an angle of 30°. Masses for the impacting ATD for both the post centred and mid-span impact are resumed in Table 3.16 and Table 3.17

<table>
<thead>
<tr>
<th>Weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male 50th percentile Hybrid III 76.8</td>
</tr>
<tr>
<td>Protective suit, gloves and boots  7.6</td>
</tr>
<tr>
<td>Full face helmet 1.6</td>
</tr>
<tr>
<td>Total mass 86</td>
</tr>
</tbody>
</table>

*Table 3.16: Mass values for the tested 50th percentile Hybrid III during post centred impact*
Experimental tests

<table>
<thead>
<tr>
<th>Weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male 50th percentile Hybrid III</td>
</tr>
<tr>
<td>Protective suit, gloves and boots</td>
</tr>
<tr>
<td>Full face helmet</td>
</tr>
<tr>
<td>Total mass</td>
</tr>
</tbody>
</table>

Table 3.17: Mass values for the tested 50th percentile Hybrid III during mid-span impact

Different cameras have been used to record the events from the spots identified by the regulation. The acceleration data, force and momentum lectures have been elaborated to obtain the injury level used to classify the safety barrier.

In Figure 3.15 and Figure 3.16 are presented some pictures taken from the top view camera for both the post centred and the mid-span impact scenario.

Figure 3.15: Frames from the post centred impact against a CMPS
The results obtained, operating on acquisitions, were provided under form of resume table into the official report of the tests. An abstract of the resume of the experimental results is here presented in Table 3.18, where the relative HIC values obtained for the post and the mid-span impacts are reported.

<table>
<thead>
<tr>
<th></th>
<th>Post centred impact</th>
<th>Mid-span impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact velocity</td>
<td>62.1 km/h</td>
<td>60.4 km/h</td>
</tr>
<tr>
<td>Impact angle</td>
<td>30 deg</td>
<td>30 deg</td>
</tr>
<tr>
<td>HIC value</td>
<td>317</td>
<td>267</td>
</tr>
</tbody>
</table>

*Table 3.18: HIC values obtained from experimental tests on CMPS*
Figure 3.17: Permanent plastic deformations on the steel CMPS for post centred (left) and mid-span (right) impact configuration

In Figure 3.17 are reported two pictures of the restraint system after the test for both the post centred and the mid-span impact point position. The injury criterion values have been used as a comparison term for the full scale simulations to find out if the numerical model of the ATD was capable to predict a HIC value compatible with the class of the CMPS from the experimental tests.
CHAPTER 4
NUMERICAL SIMULATIONS

The Finite Element Analysis allow to predict and understand in detail a crash event reproducing it in virtual environment, reducing time and costs related to experimental campaigns. During the period of this thesis work all the simulations were conducted with LS-DYNA as solver software. Ls-PrePost was used to create and modify the models before the FEM calculations.

In this chapter of the thesis work the FE models developed during the internship in GDTech S.A will be presented. There will be described the modelling simplifications adopted, together with the modifications made on the models that was identified as reference.

4.1 The FE model of Hybrid III

The starting model for the ATD was set to be the version that was already used by GDTech S.A. in road transport related crash simulations. This version is not the most detailed model of the Hybrid III that the LSTC group provides for his customers, but the level of fidelity in the ATD’s parts reproduction, even if not optimal, makes the used model the best starting point for this type of study. The ATD’s FE model of
Hybrid III was initially downloaded from LSTC library, where models are shared for LS-DYNA users, and it has been modified by the technical office of GDTech S.A.

The model proposed for this study didn’t sensibly differed from the original downloaded version shared by LSTC, unless the variation in geometry of modelled parts or kinematical joints definition between them.

The FE model present in GDTech S.A. was already tested in motorcyclist impact simulations but without acceptable results.

During a simulation of motorcyclist impact with a safety barrier, the model of ATD directly enter in contact with the restraining structure. It was evident that without proper adaptations, the numerical model of anthropomorphic test device could not be used in a direct impact scenario if it was modelled minding the ATD as a vehicle’s occupant. The impact area and energy levels can importantly change from an inside car accident condition to a direct sliding post hitting, so also the designers’ attention changes into detail modelling some parts rather than others.

The first problem identified was the overestimation of the HIC value. In order to obtain a model of ATD reliable in two wheeler impact against safety barriers, the attention for the numerical Hybrid III was focused on the head parts.

4.1.1 General check on the entire model

Before to focus the attention on any calibration process, a first observation has been made on the entire model and his behaviour during previous simulations present in the database of GDTech S.A.

Different simulation’s reports noted some evident problems and strange behaviours of body and limbs. An immediately appreciable problem, at the supine positioning of the ATD, was the lack of extension of neck part under the action of gravity load.

The articulations between the subparts of limbs and between lumbar parts seemed to be not consistent with the movements that the real ATD could exhibit. Connections between movable parts for the real device mainly consist in joints of rotation. At the
contrary in the numerical model elbows and shoulders, together with knees and ankles, showed relative motions that were not allowed to the real device.

The ATD’s numerical model developers from LSTC decided to define the parts of the steel framework of the device as *PART_INERTIA.

This card allows the user to manually define the mass and inertial matrix of a body, overriding the normal computation, based on geometry, made by the solver. In this way these parts had not to be accurately represented, and their inertial properties could be manually assigned directly basing on the real geometry of the parts. The *PART_INERTIA card allows a double definition for CG, both by coordinates and by node identification. It resulted that several repositioning for the numerical dummy, together with the definition of CG by coordinates, led to an improper definition of centre of mass for the parts defined as *PART_INERTIA.

Even the terms of the inertial matrixes changed for limbs parts that were supposed to be symmetric respect to the vertical plane that cuts in two the ATD.

Taking the LSTC downloaded model as reference, the CG and inertial matrix of the *PART_INERTIAs were reset. In particular, for every part of the steel framework the CG position, defined by node identification, was attributed as *CONSTRAINED_EXTRA_NODE together with the definition of inertial reference coordinate systems (Figure 4.1).

![Figure 4.1: Barycentric position for *PART_INERTIAs before (left) and after reset (right)](image-url)
The numeric kinematical joints have been restored in physical positions re-orienting the revolution axis in correct position for each limb articulation. The tree-file was written, looking for future eventual repositioning of the ATD, and adapted to the moving of both the ATD and the helmet parts.

Moreover, severe problems were identified in contact behaviour between head skin and inner helmet parts. In particular, the geometry and the mesh size of the interested parts were not comparable, and these differences have been considered one of the factors that led to the wrong behaviour of the contact between the parts (Figure 4.2). Describing more in detail the modifications realized on head and helmet in the further subparagraphs, the solutions adopted to the contact definition problems between those parts will be there presented.

Figure 4.2: Vertical and horizontal sections of head and helmet parts

4.1.2 Model of the head of the Hybrid III

The head part of the numerical ATD was separated from the rest of the body at the neck connection, as it was for the real device prepared for the drop tests. The numerical model of the head is defined by four parts and it reproduces quite the exact composition of the real ATD’s head (Figure 4.3).
The mass value of the head assembly has been checked and compared to the measured mass from the experimental tests (Table 4.1), and despite the difference between the reproduced and real mass, no density value has been modified to not vary the inertial matrix of the assembly.

<table>
<thead>
<tr>
<th></th>
<th>Mass [kg]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real instrumented HIll head</td>
<td>4.47</td>
<td>-</td>
</tr>
<tr>
<td>Numerical model of head</td>
<td>4.83</td>
<td>+8.05</td>
</tr>
</tbody>
</table>

*Table 4.1: Mass comparison between experimental and numerical head*

As anticipated before, the interface between head and helmet presented contact problems due to the fact that helmet may have been designed for another ATD’s model different from the one that’s actually used. The face of the elements that during the impact enter in contact with a *SURFACE_TO_SURFACE card definition, were not ideally placed ones against the others. Moreover, some nodes of the skin part were already penetrated into the Expanded Polystyrene Styrene (EPS) inner layer of the helmet, thing that only worsened the behaviour of the contact search between the two parts.
Numerical simulations

To solve the problem, a position scaling around the centre of mass of the part was operated for those nodes that were excessively pronounced in outward direction from head’s outer surface. The solid elements from the skin part were splitted in eight, directly from LS-PrePost, and as a consequence the same procedure was adopted for the skull’s elements, that share the nodes with the vinyl cover (Figure 4.4).

![Figure 4.4: Mesh refinement for head’s outer skin and steel skull](image)

4.1.3 Head model calibration

The head was positioned to simulate the drop test. The experimental set up was reproduced so the head was placed upside down at a distance from a rigid wall equal to the initial height of the real head from the ground. Gravity loads were initialized into the numerical model and, at the starting time of the transient simulation, the head was let free to fall from an initial orientation that visually respected the one from experimental tests. The requested data in output was the resultant acceleration at the *SEATBELT_ACCELEROMETER element positioned at the CG of the head.

The first obtained results in terms of acceleration-time history was really far from the one of the experimental drop test. Also from the LS-PrePost animation, the head showed an excessive elastic behaviour during the impact with the ground. The
The FE model of Hybrid III numerical peak of acceleration was underestimating the real acquired peak for nearly the 60%. The prolongation in time of the peak of the first rebound resulted underestimated too.

It was decided to act on the *MAT_VISCOELASTIC card that defines the material properties for the head skin. A curve fitting optimization process has been set using the optimization tool of LS-DYNA named LS-OPT. The effect of a variation of the terms that define the shear relaxation behaviour into the viscoelastic card was singularly inspected, till obtaining a set of parameters that allowed a satisfying correlation between acceleration-time history (Figure 4.5) and the resulted HIC value (Table 4.2).

![Figure 4.5: comparison between experimental and numerical drop test Hybrid III’s head](image)

<table>
<thead>
<tr>
<th>Height [mm]</th>
<th>Test</th>
<th>Acceleration peak [g]</th>
<th>HIC$_{36}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>experimental</td>
<td>127.34 to 132.94</td>
<td>192.51 to 206.69</td>
</tr>
<tr>
<td></td>
<td>numerical</td>
<td>136.2</td>
<td>230.9</td>
</tr>
</tbody>
</table>

Table 4.2: Acceleration peaks and HIC$_{36}$ values comparison Hybrid III head drop

In the Appendix A the same simulations have been made with a reduced thickness for the head skin to reproduce the head of the Hybrid II. The efficacy of the calibrated
parameters is demonstrated in the comparison between the results of experimental and numerical drop test for the Hybrid II version of anthropomorphic test device.

### 4.1.4 Neck model

The first cause of the absence of extension movement of the neck under gravity load was firstly attributed to the wrong definition of lower neck’s kinematical joint. After the check made on the entire model, the revolution axis was restored in correct position, and between the two right parts. In supine configuration, with the gravity load properly introduced and initialized, the neck part remained still in initial position.

In this condition it was impossible to use the numerical ATD into crash simulations against barriers that has a step at ground level as some new-jersey model. The miss of this first obstacle would have led to an improper reproduction of the experimental test, where the head inside the helmet founds itself close to the ground.

To figure out what was the real behaviour of the Hybrid III some pictures of the real ATD in supine position, with and without the helmet (Figure 4.6) were captured.
Figure 4.6: Supine neck’s position for the real Hybrid III

The structure of the neck of the Hybrid III allows it to slightly extend backward bringing the head’s back part to come closer to the ground. Neck’s structure was modified during previous works starting from the original LSTC model and actually it reproduces quite exactly the real ATD’s neck (Figure 4.7).

Figure 4.7: Section of the neck’s assembly for the numerical ATD

The neck assembly is composed by five disks of steel-reproducing material of different thickness, all connected to the rubber part properly shaped to allow neck’s extension and flexion. Inside this cylindrical structure there is a beam modelled by solid elements that, along its axis, shares the nodes with a cable defined beam. The
solid modelled beam is connected in lower and upper ends respectively to the neck’s back support and to the head’s end plate.

Different dynamic relaxations were computed, in which the stiffness parameters of the neck parts were one by one extremely reduced. It resulted that the solid modelled beam carried the almost totality of neck’s flexural stiffness.

It was decided to act on this part trying to reproduce into the numerical environment the real internal neck mechanism of the neck of the Hybrid III. In reality the steel cable inside the neck holds together the entire structure, and its tension has to be regulated during calibration stops to ensure the correct articulation of the assembly. All around the cable there is a protective pipe that prevents the friction between the cable and the rubber and steel disks during neck’s flexion or extension. The task of providing the axial and flexural stiffness is attributed to the external parts of the neck.

With the aim of reproduce the real condition of the neck part, and following some modelling advise from papers and reports on the argument [3] [6] [7], the internal structure of the neck was changed, together with some element formulations and material models (Figure 4.8).

![Figure 4.8: Neck’s internal structure modification](image)

The cable’s elements formulation was changed into beam from truss in *BEAM_SECTION card, and the solid modelled beam was transformed into a shell
**4.2 FE model of the full-face protective helmet**

The numerical model of the full-face helmet used in this thesis work was previously realized in Politecnico di Milano [10] and it was currently adopted for numerical simulations in GDTech S.A.

The FE model of the full-face helmet can be subdivided in three main parts. The outer layer of the helmet is modelled by shell elements that shares their nodes with the inner layer part modelled by solids. In the lower part of the helmet the safety strap is modelled by a shell string that enters in contact with the chin of the ATD. The safety strap is connected, on its ends, to the outer shell by two beam modelled cords (Figure 4.9).
The outer layer of the helmet, made in acrylonitrile butadiene styrene (ABS), is modelled using the *MAT_ELASTIC card, while the card *MAT_CRUSHABLE _FOAM is used to reproduce the expanded polystyrene of the inner layer. The choice to model the sponge part that protect the face of the ATD verted on the use of *MAT_LOW_DENSITY_FOAM. The shell modelled part of the safety strap is modelled in *MAT_ELASTIC and the cords are modelled using *MAT_SEATBELT. After the modifications made on the head’s external surface and mesh, the coupling between head and helmet was checked.

During the first simulations the head showed an excessive moving capability inside the helmet. The opposite condition was experienced during the real test set up, where the head was pushed inside the helmet that kept it well firm also without the use of the safety strap. With the intent to get closer to the experimental condition, two main modifications were applied on the helmet model. The original gap between the head and the inner layer of the helmet was reduced filling the empty space with solid elements created by offset the inner helmet surface (Figure 4.10).

The first two beam elements of the cords that connect the shell modelled safety strap to the outer shell of the helmet were converted in cable formulation in order to
4.2

FE model of the full-face protective helmet

define an axial tensioning force, capable to reproduce the experimental coupling condition between head and helmet.

The head helmet assembly was checked in mass reproduction before to simulate the drop tests (Table 4.3 and Table 4.4).

<table>
<thead>
<tr>
<th>Mass [kg]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real NZI Helmet</td>
<td>1.4</td>
</tr>
<tr>
<td>Numerical model of helmet</td>
<td>1.349</td>
</tr>
</tbody>
</table>

*Table 4.3: Reproduced and real mass for the full-face helmet*

<table>
<thead>
<tr>
<th>Mass [kg]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real ATD’s head and helmet</td>
<td>5.912</td>
</tr>
<tr>
<td>Numerical model of head and helmet</td>
<td>6.182</td>
</tr>
</tbody>
</table>

*Table 4.4: Reproduced and real mass for the model of drop test with helmet*

### 4.2.1 Helmet model calibration

As it was for the numerical head drop tests, the head and helmet model were positioned upside down at a distance from a rigid wall given by the falling height that had to be reproduced. Without any gyroscopes information the initial orientation of the assembly was set similar to the observed one from the experimental test (Figure 4.11).
Numerical simulations

Different documents from previous simulations on the ATD’s impact reported an excessive acceleration level reached by the head of the numerical anthropomorphic device respect to the ranges reached in the same experimental tests. The first simulations were found to agree with the previous reports.

Moreover, the helmet presented different contact issues between outer and inner shell and between solid elements of the same EPS inner layer during impacts. Different simulations led to the definition of *AUTOMATIC_SURFACE_TO_SURFACE contact cards between the two density polystyrene parts and the outer shell.

To avoid the error termination caused by negative element volume computation, due to the excessive deformation of the crushable foam, it was decided to insert a *CONTACT_INTERIOR card for the soft materials of the inner layer. The definition of the interior contact allows the introduction of a minimum compaction thickness, defined as percentage of initial geometry, that stop the element deformation and rise its stiffness of a prescribed percentage (Figure 4.12).

Successively to the solution of the contact problems into the model, two optimization processes on the 450 mm drop simulation were set with the objective to fit the numerical with the experimental acceleration time history. The variables of LS-OPT in this process were the Young modulus of the outer shell, the tensile stress cut-

Figure 4.11: Experimental and numerical initial condition for drop test of head and helmet
off and the damping parameter together with the scale factor for the yield stress-volumetric strain slope for the *MAT_CRUSHABLE_FOAM materials.
To set the limit values for the optimization variables some material parameters information obtained from the provider of the helmet or from reports on the modelling of similar objects were used.

![Figure 4.12: Frames from the drop test simulation with helmet](image)

The optimization processes led to the definition of two different calibrated models for the full-face helmet. They mainly differed in yielding stress-volumetric strain slope and in damping coefficient of the EPS inner layer.
In Figure 4.13 the results gave by these two models are compared to the experimental drop tests made for different falling height.
Figure 4.13: Comparison of acceleration time history for the numerical models of helmet

<table>
<thead>
<tr>
<th>Height [mm]</th>
<th>Test</th>
<th>HIC&lt;sub&gt;36&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>experimental</td>
<td>36.08 to 44.62</td>
</tr>
<tr>
<td></td>
<td>calibrated 1</td>
<td>42.56</td>
</tr>
<tr>
<td></td>
<td>calibrated 2</td>
<td>46.86</td>
</tr>
<tr>
<td>300</td>
<td>experimental</td>
<td>82.76 to 120.39</td>
</tr>
<tr>
<td></td>
<td>calibrated 1</td>
<td>107.6</td>
</tr>
<tr>
<td></td>
<td>calibrated 2</td>
<td>113.3</td>
</tr>
<tr>
<td>450</td>
<td>experimental</td>
<td>170.26 to 172.21</td>
</tr>
<tr>
<td></td>
<td>calibrated 1</td>
<td>176.9</td>
</tr>
<tr>
<td></td>
<td>calibrated 2</td>
<td>180.4</td>
</tr>
</tbody>
</table>
The first calibration result previews a model of helmet capable to accurately predict the peaks values of the acceleration time history for the 450 and 600 mm fall, and to produce HIC values comparable with the experimental acquired data for all the initial configurations. However, the first result seemed to not be capable to give back the right order of the two peaks that characterize the first rebound of the helmet on the ground. This inversion of higher and lower peak could be also linked to an inversion into the numerical model of the characteristic frequencies of the helmet, not necessarily due to the identified material parameters.

The second result obtained from the optimization process gave good results in terms of HIC value for the different initial drop heights but it failed the exact prediction of the maximum peak for the 600 mm fall. This result, at the contrary of the previous one, furnish the right order of peaks on the entire rebound.

Simulations made on the full scale impact showed no sensitive difference with the use of a set of calibrated parameters instead of the other, so the second set was adopted as reference for the further simulations. Moreover, in the following paragraph the calibration of the numerical model of helmet has been checked with the Roadside Safety Verification and Validation Program (RSVVP).

<table>
<thead>
<tr>
<th></th>
<th>experimental</th>
<th>179.98 to 293.33</th>
</tr>
</thead>
<tbody>
<tr>
<td>calibrated 1</td>
<td>246.3</td>
<td></td>
</tr>
<tr>
<td>calibrated 2</td>
<td>248.2</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.5: HIC value comparison between numerical and experimental drop with helmet
4.2.2 Head and helmet models validation with RSVVP

The Roadside Safety Verification and Validation Program it’s a routine that calculates quantitative comparison metrics used in verifying and validating roadside safety crash tests and simulations. This program has been realized at Worcester Polytechnic Institute (WPI) by the engineers Malcolm H. Ray and Mario Mongiardini [11].

Comparison metrics used in RSVVP are mathematical measures that provide an objective, quantifiable comparison of the agreement between two curves. The comparison metrics calculated by RSVVP can be used to validate computer simulation models using data obtained from experimental tests, verify a simulation with another simulation, assess the repeatability of two experimental tests or, generally speaking, perform a comparison of virtually any pair of curves.

In this work the RSVVP has been used to compare the acceleration time history obtained from the numerical simulation of drop test with helmet with the acquired acceleration data collected during the experimental test.

In detail the numerical reproduction of the 450 mm drop test has been compared with the mean curve of the experimental drop from the same height, not considering the acquisitions of the tests for which the initial configurations were too different from the one numerically reproduced.
4.3 Safety barriers model

Concerning the two types of safety barriers used in this thesis work in full-scale impact simulations, the realization and set up of the numerical models passed through different modification phases.

In the following sub-paragraph, the models of the concrete new-jersey barrier and of the steel CMPS will be presented and there will be shortly described the path of modifications that led to the final models used for the experimental – numerical correlation.
4.3.1 Model of the concrete new-jersey barrier

The modelled new-jersey barrier represents an extremely simplification of the real restraint system, in fact only the safety barrier’s profile has been accurately reproduced because of the use that was previewed in this work.

It was decided to model the material as rigid instead of a concrete material formulation. In fact, while with cars and bigger means of transport the correct calibration of the concrete model it’s crucial to succeed in correlating a numerical simulation with experimental tests, dealing with the relative low stiffness values that characterize the ATD’s structure, the rigid assumption for the material of the barrier was considered non significantly restrictive.

![Figure 4.15: FE model for the concrete new-jersey barrier](image)

The profile of the rigid safety barrier reproduces exactly the shape of the real tested barrier. The measurements on the experimental restraint system have been took directly from the same new-jersey used in impact tests conducted in the campaign at LaST laboratories.

The mechanical properties inserted into the material card were obtained from the documentation in possess of GDTech S.A. on concrete material characterization. The main physical characteristics of the reproduced new-jersey barrier are resumed in Table 4.6.
4.3 Safety barriers model

<table>
<thead>
<tr>
<th>Length [m]</th>
<th>n° of elements</th>
<th>Element type</th>
<th>Weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>3160</td>
<td>HEXA</td>
<td>3735</td>
</tr>
</tbody>
</table>

*Table 4.6: Physical properties of the FE model of new-jersey barrier*

### 4.3.2 Model of the steel CMPS

A numerical model of the used CMPS was already present in GDTech S.A. However, different modifications were expected on the existent model after the receiving of some detailed descriptions of the tested item provided by the safety barrier constructor and by the laboratory where the tests were performed. Coming from the CAE templates, the FE model of the integrated steel motorcyclist protection system was perfectly reproduced in geometry.

The only simplification into the model was made into the connection representation. The steel bolts that connect the upper beam to the posts and to the CMPS were modelled by beams instead of being three-dimensionally modelled by solid elements.

*Figure 4.16: Profile (left) and module (right) of the integrated CMPS*

It was asked to update the FE model of the steel barrier according to the new information received on the effective configuration of the tested item. In particular, it
was requested to reposition the lower beam and so redesign the spacer parts that sustain the CMPS.

After the geometrical update, the curves that define the different steel characteristics into the material cards were derived starting from the data of the static experimental tests made directly on the restraint system components.

The obtained numerical model of the steel barrier was very finitely meshed and excessively heavy in terms of computational weight to the point where it was necessary to reduce it in order to allow the simulation of full scale impact to run in acceptable time. The CAE models of the barrier’s beams were used to extract their mid-surface on which the FE discretization has been performed. The holes on the beams that forced the excessive small size of shell elements were deleted and the entire surfaces were meshed with elements having a doubled mean size.

<table>
<thead>
<tr>
<th></th>
<th>n° of elements</th>
<th>reduction size [mm]</th>
<th>mass [kg]</th>
<th>Mass variation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>refined model</strong></td>
<td>261614</td>
<td></td>
<td>542.272</td>
<td>-</td>
</tr>
<tr>
<td>Upper beam</td>
<td>80368</td>
<td>15</td>
<td>263.083</td>
<td>-</td>
</tr>
<tr>
<td>Lower beam</td>
<td>119160</td>
<td>10</td>
<td>124.549</td>
<td>-</td>
</tr>
<tr>
<td>Posts</td>
<td>31798</td>
<td>10</td>
<td>96.699</td>
<td>-</td>
</tr>
<tr>
<td><strong>simplified model</strong></td>
<td>73239</td>
<td>-72%</td>
<td>530.683</td>
<td>-2.1%</td>
</tr>
<tr>
<td>Upper beam</td>
<td>29064</td>
<td>-63%</td>
<td>261.068</td>
<td>-0.7%</td>
</tr>
<tr>
<td>Lower beam</td>
<td>34076</td>
<td>-71%</td>
<td>125.741</td>
<td>+0.9%</td>
</tr>
<tr>
<td>Posts</td>
<td>6084</td>
<td>-80%</td>
<td>97.113</td>
<td>+0.4%</td>
</tr>
</tbody>
</table>

Table 4.7: Comparison between refined and simplified model of CMPS

The results of Table 4.7 consider also the substitution of the beam and shell modelled bolts into spotweld beams. This important simplification led to a rigid link between the parts that were connected by bolts, thing that has been considered acceptable due to the fact that during the experimental tests no failure was observed for the connection elements.
While the simplified numerical version of CMPS was adopted to calibrate the model of the ATD during full scale simulations, the refined model was used to test the effective improvement of the model in impact behaviour.

4.4 Full scale impact simulations

The numerical models just presented were included in a main launching file in order to set up the full scale impact simulations. In particular, the head, that was used to simulate the drop tests, was reconnected to the rest of the ATD’s body and also the full face helmet was placed in correct position. Depending on the type of simulation the model of concrete barrier or the steel CMPS was imported into the launch file.

The ATD model was moved to fit the standard requirement of an impacting angle of 30 degrees. As it was found, the FE model of the Hybrid III had a total weight of 81 kg, about 4 kg more than the real ATD. Previous work made on the ATD’s model led to the addition of mass to some parts of the body to take into account the presence of the protection suit, gloves and boots. The weight of the protection wearing was distributed on the ATD’s jacket, arms, lumbar cover, leg and shoes. The weight of the numerical Hybrid III was calibrated taking as reference the experimental measurements made at LaST laboratories during the new-jersey test campaign. Successively simulating the impact against the CMPS the model was not recalibrated in term of mass reproduction due to the not excessive mass loss toward the experimental measurement (Table 4.8 and Table 4.9). Moreover, the reproduced mass for the protection wearing remains in line with the mean weight of those elements as the market nowadays propose them.
Thanks to the created tree file, it was possible to reposition the ATD in its starting supine configuration. This means that the upper and lower limbs, together with the head and neck assembly, were slightly moved from the standing initial position to reduce the necessary time for those parts to reach their equilibrium configuration during the dynamic relaxation.

The gravity load had to be initialized before that the ATD was thrown with initial velocity toward the barrier.

While the axial force into the cables of the helmet was automatically inserted from the *MAT_CABLE card, it was necessary to carry a dynamic relaxation before the transient analysis to avoid the impulsive insertion of the gravity load and to mainly let the head of the ATD reach the equilibrium configuration (Figure 4.17).
4.4 Full scale impact simulations

Figure 4.17: Loading process adopted for the full-scale simulations

The dynamic relaxation was used to ramp the gravity load and after that, at the beginning of the transient analysis, the curve has been kept constant from time zero. When the ATD reached the equilibrium position under the gravity load, the launching velocity was inserted with the card *VELOCITY_GENERATION _START_TIME (Figure 4.18 and Figure 4.19).

Figure 4.18: Frames from the dynamic relaxation output
4.4.1 Impact against the new-jersey concrete barrier

To reach the final configuration of the full-scale simulation against the concrete new-jersey no long work has been done on the barrier model. At the contrary different contact type and formulation were inspected to solve all the problems that came out when the foam parts of the inner layer of the helmet were compressed between the head and the rigid barrier. The behaviour under different penalty formulation for the contact between ATD and barrier were inspected, together with the attribution of different parameters for the contact interior definition.

To completely avoid the error termination of the simulations it has been necessary to modify the yielding stress volumetric deformation graph for the EPS parts of the helmet, sensibly increasing the yield stress at high deformation levels (Figure 4.20).
Some minor issues were solved in contact definition between the barrier elements and the ATD’s jacket, upper and lower limbs.

The last obtained results from the new jersey impact showed a general behaviour of the ATD not really far from the one observed during the experimental test (Figure 4.21 and Figure 4.22).

Figure 4.20: Yielding stress volumetric deformation curve extension
Figure 4.21: Screen from downstream view new-jersey impact (respectively 0.19, 0.2, 0.22, 0.24, 0.27, 0.3, 0.33, 0.36 [s])
4.4 Full scale impact simulations

4.4.2 Impact against the steel CMPS

The setting of the simulation for the full-scale impact against the continuous motorcyclist protection system passed through different phases and modifications, for both the model of the ATD and the model of safety barrier. While the FE model of ATD encountered only minor modifications, as the insertion of a *MAT_NULL cover for the jacket and upper limbs to solve contact problems, the
model of CMPS was for long time object of changes in beams constraint, bolt initialization and interface friction properties.

The computational cost required by the CMPS models forced the important simplification to remove the model of soil from the simulations. It was tried to reproduce the action made by the soil on the post by constraining the translation of the nodes of the posts not at the soil surface but 0.15 m under the ground level.

The insertion of gravity load on the CMPS model caused different problems for the contact and connections between the steel parts. The *INITIAL_AXIAL_FORCE_BEAM is supposed to be used to ramp the load during a dynamic relaxation and simulate the clamping force present into the connection. At the beginning of the transient analysis the axial force into the beams that model the bolt bodies is intended to remain at the last value reached during the ramping load, but in reality it seems that because of a bug in LS-DYNA it decrease in modulus till the deletion of every tensioning force right after time zero.

The loss in tension force into the bolts made the beams of the barrier to change their height from the ground and inclination, respect to original position, while the ATD was still extending his neck to reach the equilibrium position.

To have the correct position of the barrier, at the moment of the ATD impact, it was tried to exclude the barrier beams from the gravity loaded bodies. This exclusion was made considering that the effect of the gravity loads on the barrier during the impact were negligible, also given the absence of failures all along the safety barrier.

The rise of friction coefficient between the connected parts had the desired effect on the phenomenon, together with the moving of the head and nut parts of the bolts in closer position to the steel beams and supports. Restoring the gravity load on the barrier it was observed that the no gravity solution for the barrier led to results that were not very far from the last solution adopted.

This issue didn’t come from the simplified model, where the bolts were substituted by spotweld rigid beams.

As expressed into the test reports the two extremities of the CMPS were connected to the external posts by the end part presented in Figure 4.23.
4.4 Full scale impact simulations

Figure 4.23: End component for the CMPS according to the CAD drawings

The photographic proofs of the failed tests of the same experimental campaign, showed different ways of connection between the CMPS beam and the posts, but in all the video and photo available the end component, that was present in the CAD drawings of the barrier, were missing.

Figure 4.24: Photographs of failed tests: CMPS and post connection (left) and ATD kept by the barrier (right)

The failed test investigation was made to explain the cause of the high working width obtained during the mid-span impact simulation with the refined barrier model. The high deformation of the CMPS beam led to the formation of a pronounced undertow where the ATD ended his run at the place of being redirected on the carriageway continuing sliding on the ground (Figure 4.24).
There was in fact the possibility that, also for the tests that succeeded, the end of the CMPS beam was first tensioned and then clamped directly on the posts at the extremities from the impacting front side. In this way the CMPS beam could have had less longitudinal free movement during the impact.

The suggested hypothesis was supported by the experience of the working team in the experimentation of safety barriers.

In order to reproduce the clamped configuration at the extremities of the CMPS, a trial model was realized. The end parts were deleted and the movement of the external nodes of the beam in longitudinal direction was forbidden by the insertion of a *BOUNDARY_SPC_SET card.

The behaviour of the ATD against this model of barrier was tested and it gave good results for the post centred impact. The mid-span configuration was not tested on the barrier with clamped extremities because this solution mismatched with the explicit drawings present on the reports of the succeeded tests. Also if the simulations could have reproduced the experimental tests in a more accurate way, the model of barrier with clamped CMPS was not spendable on any simulation report, so the solution was soon abandoned.

After different set up trials, the final versions of full scale impact simulations were run for both the refined model of the steel barrier and the simplified model with coarser mesh and spotweld beams for connections.

The results are here presented in the same order in which they were obtained, so first the results of the post centred configuration will be shown and then the mid-span scenario on the complete refined model of the barrier will be presented. The animation frames for the impact against the simplified model of CMPS are reported in Appendix B.
4.4.3 Full scale post centred impact simulation

In Figure 4.25 some captured screen from the upstream view of the output animation of LS-DYNA are presented. After the initialization performed into the dynamic relaxation and the first part of transient analysis, the ATD model was able to hit the CMPS at the desired height with the head-down initial state. The general behaviour observed from the animation during the impact shows a great improvement respect to the previous results. The ATD seems to have also reduced his trend toward taking off after the impact against the barrier, problem that was encountered into the results obtained before this thesis work. No more limiting contact issues were noticed in the post centred impact reproduction, thanks to the substitution of the master set in contact definitions. The contact role for upper body parts with the barrier was moved to the created *MAT_NULL covers, improving the contact efficacy setting it between shell and shell instead of shell on solid.
4.4.4 Full scale mid-span impact simulation

When the post centred scenario has been reproduced, the mid-span impact was simulated to prove the robustness of the realized model. The only modification made on the input file of the mid-span full scale impact simulation was the rise of the contact thickness for the barrier beams into the *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE card. Without the introduction of this modification the contour of the upper arm part excessively deformed the CMPS beam near the post, and there it was blocked leading to an excessive neck solicitation due inertial forces action on the head parts. In the simulation of the mid-span impact with the simplified model of barrier no contact problems came out probably due to the coarser mesh realized and the rigid connection between upper and lower barrier’s beams made by spotweld beams.
Figure 4.26: Screen from upstream view mid-span impact refined barrier (respectively 0.18, 0.2, 0.23, 0.26, 0.28, 0.32, 0.35, 0.40 [s])
This chapter contains the correlation between the experimental and numerical results obtained for the full scale impact scenarios. In the first part there will be presented the correlation of the results for the concrete new-jersey barrier. The second part, concerning the comparison for the steel made CMPS, is further divided in two. Before the level of accordance reached between the experimental test and numerical simulation for the post centred impact scenario will be shown, then the reproduction of the mid-span impact will be compared to the relative experimental test.

All the experimental results presented in this chapter are based on the official test reports prepared to resume the main data about testing procedures and safety barrier classification. Reports were the only terms of comparison available to check the numerical simulations with. The obtained numerical model for the Hybrid III anthropomorphic test device cannot be considered detailed at the point to compare, by direct overlap, the acceleration time histories from the head accelerometers or to accurately reproduce the time at level for the neck’s forces.

The comparison here proposed aims to clarify the capability of the numerical model of Hybrid III in predicting with good accuracy the behaviour of the real ATD and so also the class of the safety barrier tested.
5.1 Available terms of comparison

As introduced in the chapter preface, the only mean to assess if and in what measure the realized numerical model of ATD was reliable was the comparison with the data expressed into the reports of the experimental tests. According the standard EN 1317-8, during the testing phases of a restraint system, it is requested to collect the acceleration lectures from the in head accelerometer and to register the forces and moments history from the load cell positioned just at the base of the head. These data have to be successively elaborated and used to characterize the safety barrier. From the acceleration time history the HIC value of the test is obtained, and from the forces and moments the moments at the occipital condyle and the time at level graphs that are used to state the class level of the barrier are computed.

Into the test reports, together with a photographic documentation of the tested item and the dummy used, it is reported a summary table comprehensive of the assessed level for each verification requested by the standard. The graphs of acceleration, force and moments in function of time were used to qualitatively compare the numerical environment and the experimental values. Not having the x-y pairs of any data, it resulted complicated to use those graphs for a direct results curve correlation. Fortunately, the aim of this thesis work was to obtain a model capable to predict the level that a restraint system belongs to for each value of force, moment and acceleration. This thesis work will proceed to show the computed values of the numerical simulations requested by EN 1317-8 comparing it with the same data reported in the experimental test reports.
5.2 Results for the concrete new-jersey impact

The experimental report of the test of the concrete barrier of type new-jersey encloses the acquired data from the three accelerometers inside the head of the Hybrid III, together with the initial conditions of the test and the computed HIC value. A slow motion video registered during the experiment has been used to propose a visual comparison with the obtained numerical simulation. No data were available on the framerate used with the slow motion camera, so the image comparison proposed aims only to give a qualitative level of accordance in the behaviour of the ATD.
The global behaviour exhibited by the ATD’s model reproduces quite well the observed experimental one. Remains for the Hybrid III FEM the tendency to lift its body from the ground after the impact. This trend, that is more accentuated than for the ATD, seems to have been reduced from previous versions of the same model but it’s still present and should be investigated. Concerning the HIC value that characterize the test, it was reached a great accordance between the experimental and numerical one (Table 5.1).
5.3 Results for the steel CMPS impact

The reports of the experimental tests made on the steel continuous motorcyclist protection system allow a deeper comparison between the real and numerical environment. Also there are available photographic documentation, initial conditions and the HIC value associated to the test, but respect to the impact test against a concrete barrier there is the possibility to evaluate the capability of the numerical model in predicting the force and moment values from the upper neck load cell computing the level attributed to the barrier for the data requested in the standard EN 1317-8.

<table>
<thead>
<tr>
<th>HIC&lt;sub&gt;36&lt;/sub&gt;</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental test</td>
<td>1289</td>
</tr>
<tr>
<td>Numerical simulation</td>
<td>1174</td>
</tr>
</tbody>
</table>

*Table 5.1: Experimental numerical comparison for the HIC value in the new-jersey impact*

Again only for a qualitative evaluation the acceleration time histories collected from the head of the ATD are there compared (Figure 5.2).

![Figure 5.2: Comparison of head acceleration time history for the new-jersey impact](image-url)
5.3.1 Post centred impact correlation
In Figure 5.3 a visual comparison is realized. It shows the top view of the experimental testing area and proposes the positions of the numerical ATD during the same impact. The lecture of forces and moments from the kinematical joint at the base of the head were used to compute the moments at the occipital condyle for the numerical version of the Hybrid III. The force time histories in the three directions were also used to compute the time at level graphs. In Table 5.2 the numerical results are compared with the experimental table present into the report.
The numerical model of Hybrid III fails to predict the axial tensile force into the neck and overestimate the maximum value reached in the momentum at occipital condyle (MocX) time history.
As ulterior evaluation in Table 5.3 is reported the comparison between the working width of the barrier in experimental test and in numerical reproduction.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental working width</strong></td>
<td>0.1 m</td>
</tr>
<tr>
<td><strong>Numerical working width</strong></td>
<td>0.131 m</td>
</tr>
</tbody>
</table>

*Table 5.3: Working width comparison between experimental and numerical post centred impact*

### 5.3.2 Mid-span impact correlation

The results obtained for the mid-span full scale simulation are here presented in comparison with the data and graphs present into the experimental report.
Figure 5.5: Experimental and numerical comparison mid-span impact on CMPS
In Figure 5.5 it was tried to capture the position of the ATD from the top view video and the same view reproduced for the simulation. Table 5.4 reports the results for the mid-span impact configuration.

*Figure 5.6: Time at level graph comparison between experimental and numerical mid-span impact*
Table 5.4: Results resume for the mid-span impact with CMPS

<table>
<thead>
<tr>
<th></th>
<th>Experimental</th>
<th>level</th>
<th>Numerical</th>
<th>level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HIC</strong></td>
<td>267</td>
<td>I</td>
<td>227</td>
<td>I</td>
</tr>
<tr>
<td><strong>Fx positive</strong></td>
<td>Fig 5.6</td>
<td>I</td>
<td>Fig 5.6</td>
<td>I</td>
</tr>
<tr>
<td><strong>Fz compression</strong></td>
<td>Fig 5.6</td>
<td>II</td>
<td>Fig 5.6</td>
<td>I</td>
</tr>
<tr>
<td><strong>Fz tension</strong></td>
<td>Fig 5.6</td>
<td>I</td>
<td>Fig 5.6</td>
<td>FAIL</td>
</tr>
<tr>
<td><strong>MocX</strong></td>
<td>62.1</td>
<td>I</td>
<td>136</td>
<td>II</td>
</tr>
<tr>
<td><strong>MocY positive</strong></td>
<td>20.5</td>
<td>II</td>
<td>30.7</td>
<td>II</td>
</tr>
<tr>
<td><strong>MocY negative</strong></td>
<td>17.5</td>
<td>I</td>
<td>62.8</td>
<td>I</td>
</tr>
</tbody>
</table>

Also for the mid-span impact configuration the numerical ATD fails to predict some of the values of force and moments in the upper neck load cell. There was encountered a high overestimation for both the MocX maximum value and for the tension force into the neck, as it was for the post centred configuration. In this case the numerical Hybrid III seems to predict also a lower value of compression neck force than the one registered during the experimental campaign.

As it was for the post centred impact scenario, in Table 5.5 the comparison between the working width of the barriers are reported.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental working width</strong></td>
<td>0.32 m</td>
</tr>
<tr>
<td><strong>Numerical working width</strong></td>
<td>0.278 m</td>
</tr>
</tbody>
</table>

Table 5.5: Working width comparison between experimental and numerical mid-span impact
The work presented in this thesis was focused in obtaining a FE model of anthropomorphic test device of type Hybrid III that could have been used in motorcyclist crash simulations. The numerical model of ATD has the objective of improving and optimizing the design of motorcyclist safety barriers.

The experimental drop tests carried on the head and helmet were found to have a good repeatability in acceleration time history but the initial coupling conditions between the head and the helmet demonstrated to heavy influence the value of acceleration peak reached. The way in which the helmet is placed on the ATD’s head can importantly affect the acceleration time history of the experimental test.

Part of the work involved solving all the contact problems at the interface between the head and the foam parts of the helmet, and also between the helmet and the restraint system, in case of rigid barrier; in view of that it is reasonable to believe that those parts will have a stable behaviour even during impacts against less stiff or deformable barriers.

A limit still remains for the last version of numerical ATD and it is represented by the overestimation of some forces and moments in the upper neck load cell. In order to ensure a correct prediction of forces and moments at the neck level actions are
Conclusions and future developments

necessary in the definition of rotational stiffness and damping moment for the relatives kinematical joints.
The modifications made on the whole ATD have led to a more realistic behaviour prediction for the body and limbs.

6.1 Future developments

From the experimental campaign point of view, the Hybrid III head behaviour could be more largely characterized performing drop tests from different initial heights, different impact points and maybe on inclined surface.
The neck correlation represents the next objective of the numerical Hybrid III improvement process. As the modifications realized in this work on the neck of the Hybrid III were not supported by an experimental base, the neck model developed has to be necessarily calibrated with a pendulum test.
The possibility to exhibit a rupture of a component for the ATD has been inspected but not studied in detail. The relative simplicity of the used model of ATD, with respect to other versions available from models libraries, leads to believe that, also in view of the very coarse mesh, a reasonable reproduction of rupture would not be possible.
However, noting the most failure susceptible parts, that are shoulders and limbs, it is possible to introduce a failure criterion for the joints that connect the different parts of the ATD.


English Version, Draft.


[16] Mazdak Ghajari, Ugo Galvanetto, Imperial College London. Virtual and experimental testing of helmets. European commission DG research, deliverable n. 3.4.


In this appendix it is reported the work conducted on the head of the numerical model to fit the experimental data of the drop tests made with the head of the Hybrid II version of anthropomorphic test device.

A.1 Numerical model of the head of the Hybrid II

During the presentation of the FE model of the head of the ATD for the numerical reproduction of the drop tests, it was observed that the main difference between the head of the Hybrid II and Hybrid III, in terms of cause of the effective difference into the output acceleration time history, could be the different thickness of the vinyl layer of the skin that cover the skull. After a measuring of the actual thickness of the rubber layer for both the version of anthropomorphic test devices, the results showed that the skin of the Hybrid II around the impact zone for the drop tests was nearly a half of the thickness of the skin for the Hybrid III version.

In the description of this thesis work this difference between the versions of the ATD were retained the main cause of the different level of maximum acceleration registered into the head of those models during the drop tests.
Here it will be presented a simple and not fully detailed follow up for the geometrical adaptation made on the numerical head’s elements to fit the results obtained from the carried experimental drop tests. The simulation is presented in appendix.

The rubber layer that covers the skull of the numerical ATD was brutally deprived of one layer of elements onto its upper part in order to reproduce, in that zone, the condition of the head of the Hybrid II (Figure A.1). In this way the thickness of the skin near the drop test impacting point was set similar to the real measured rubber layer (Table A.6.1).

<table>
<thead>
<tr>
<th>Thickness [mm]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real vinyl cover</td>
<td>5.45</td>
</tr>
<tr>
<td>Numerical skin</td>
<td>5.17</td>
</tr>
<tr>
<td></td>
<td>-5.13</td>
</tr>
</tbody>
</table>

*Table A.6.1: difference in thickness reproduction in numerical environment for Hybrid II skin*

The results, produced with the same material parameters used for the Hybrid III’s head calibration, showed a good level of accordance for the Hybrid II in reproducing the maximum acceleration level reached during experimental tests.

The drop test from an initial height of 150 mm has been simulated with the modified model of the head of the ATD (Figure A.2).
The model realized is capable to well estimate the maximum acceleration value reached for the 150 mm drop test. In Table A.6.2 a comparison between the experimental and numerical obtained HIC values is resumed.

<table>
<thead>
<tr>
<th>HIC&lt;sup&gt;36&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental drop tests</strong></td>
</tr>
<tr>
<td><strong>Numerical drop test</strong></td>
</tr>
</tbody>
</table>

*Table A.6.2: HIC value comparison for the 150 mm drop test with the head of the Hybrid II*
In this appendix the animation frames for the full scale post centred and mid-span impact against the simplified model of continuous motorcyclist protection system are reported.

B.1 Post centred full scale impact simulation
Appendix B
Full scale impact simplified model of CMPS

Figure B.1: Screen from upstream view post centred impact simplified barrier (respectively 0.18, 0.2, 0.22, 0.25, 0.29, 0.32, 0.36, 0.41 [s])
Figure B.2: Screen from top view post centred impact simplified barrier (respectively 0.18, 0.2, 0.22, 0.25, 0.29, 0.32, 0.36, 0.41 [s])

B.2 Mid-span full scale impact simulation
Figure B.3: Screen from upstream view mid-span impact simplified barrier (respectively 0.18, 0.21, 0.24, 0.28, 0.32, 0.36, 0.39, 0.44 [s])
Figure B.4: Screen from top view mid-span impact simplified barrier (respectively 0.18, 0.21, 0.24, 0.28, 0.32, 0.36, 0.39, 0.44 [s])