A numerical investigation into the crashworthiness of automotive child restraints in transport category aircraft

August 2011

Prepared by:

Adam Shrimpton

Approved by:

Professor Graham Clark Associate Professor Cees Bil

School of Aerospace, Mechanical and Manufacturing Engineering

RMIT University

Melbourne, Australia

Executive Summary

A research project was undertaken with the objective of developing a better understanding of the crashworthiness of automotive child restraint systems (CRS) in transport category aircraft under emergency landing dynamic conditions. Three different CRS installation methods were considered: the aircraft seat lap belt, the European ISOFIX system, and the North American LATCH system. Typical airline economy class seating configurations involving forward-facing CRS installed by each of these methods were evaluated in terms of the level of protection offered to the CRS occupant, the injury potential for a passenger seated directly aft of the CRS, and the effect of the CRS on aircraft seat loading and dynamic behaviour. For each of the three CRS installation methods, the effectiveness of a top tether was assessed in terms of its influence on CRS motion and CRS occupant protection.

A recent research project carried out by the Australian Civil Aviation Safety Authority (CASA) was used as the basis for the development of a computer model. The model was validated against the results of the CASA project and used to carry out experiments in a virtual environment. This method allowed many seat configuration parameters to be analysed simultaneously and also allowed the analysis of some parameters which were unable to be measured by physical testing.

For the configurations tested, the lap belt, ISOFIX and LATCH CRS installation methods each limited the motion of a forward-facing CRS to a level that allowed the CRS to be effectively restrained on the aircraft seat without the use of a top tether. The CRS rebound motion associated with the lap belt and LATCH methods was more significant than with the ISOFIX method. The combined small forwards displacement and small forwards rotation observed in the LATCH case had the effect of restricting the forward rotation of the seatback to a much greater extent than the lap belt and ISOFIX cases.

CRS installed by each of the three methods provided an adequate level of protection to the CRS occupant. Each installation method resulted in an insignificant level of contact between the child's legs and the forward seatback. There was no significant trend in child head injury levels between the three installation methods; head injury criterion (HIC) values were generally highest for the LATCH case and lowest for the lap belt case. All three CRS installation methods resulted in child neck injury scores close to the critical level according to US motor vehicle safety standards.

The use of a top tether did not prevent the child's legs from making contact with the forward seatback for any case tested. The top tether was found to be only slightly effective in decreasing CRS motion, and only for the lap belt and ISOFIX CRS installation methods in conjunction with a modification to prevent seatback break-over. The reduced CRS rotation associated with top tether use for these cases had the corresponding effect of increasing child head and neck injury. This was most pronounced for the lap belt case, where an increase in child head and neck injury criteria of 30% and 16%, respectively, was attributed to the use of a top tether.

All tests involving an adult passenger seated in the second row of the configuration, including the 'baseline' configuration with an empty forward seat, resulted in aft passenger head injury above the critical level specified in FAR 25.562. At a typical airline economy class pitch of 30", the increase in head injury due to the presence of a CRS installed by the lap belt and ISOFIX was not substantial. The lap belt and ISOFIX methods resulted in a HIC score approximately 17% above the baseline configuration, while for the LATCH case the increase was 35%.

The effect of CRS installation method on aft passenger neck injury was difficult to determine due to the interaction between the aft passenger elbows and the forward seat armrests. However, experiment results generally indicate that the presence of a CRS in the forward seat serves to lessen the severity of aft passenger neck injury. Aft passenger femur compression results for all configurations were well within the limit prescribed by airworthiness regulations. The upper tibia bending load was found to be severe enough in all configurations, including the baseline configuration where no modification had been made to the forward seat, to potentially cause bone fracture.

Aft passenger head and neck injury levels were lowest for all CRS attachment methods in the range of seat pitches from 31-33". Certain configurations may in fact serve to reduce both head and neck injury to the aft passenger.

In the lap belt and LATCH cases the absence of a CRS occupant was found to significantly increase aft passenger head injury, while a decrease in head injury was observed in the corresponding ISOFIX case. The effect of the absence of the CRS occupant on aft passenger neck injury was found to be largely insignificant for all CRS installation methods.

Model experiments indicated that, by comparison with a baseline configuration without a passenger seated behind, the presence of a large adult passenger seated directly aft of a CRS installed by ISOFIX and LATCH causes an increase in CRS anchor load. For the configuration

tested, the presence of a 95th percentile male ATD caused increases in peak anchor load magnitude of 17% and 28% in the ISOFIX and LATCH cases, respectively.

Acknowledgements

This report details a research project conducted at RMIT University which was funded entirely by a grant from the Civil Aviation Safety Authority of Australia (CASA). The work described here is based on prior research conducted by CASA.

The author gratefully acknowledges the guidance offered by the following:

Mr Mark Bathie, CASA

Mr David Moorcroft and Mr Rick DeWeese, FAA CAMI

Professor Graham Clark and Associate Professor Cees Bil, RMIT University

Dr Prasannakumar Bhonge, Cessna Aircraft Company

Mr Ryan Adams, ADVEA Engineering

Table of Contents

E	xecutiv	e Summary	.i
A	cknowl	edgements	iv
T	able of	Figuresv	'ii
1	Intr	oduction	.1
	1.1	Objective	1
	1.2	Method	2
	1.3	Scope	2
	1.4	Review: The carriage of children in transport category aircraft	2
	1.4.1	Regulatory situation in Australia	3
	1.4.2	? Operational situation in Australia	3
	1.4.3	<i>Safety of the lap-held child</i>	4
	1.4.4	Installation of CRS in aircraft	5
	1.4.5	5 Dynamic performance of CRS in aircraft	6
	1.4.0	5 ISOFIX and LATCH CRS	7
	1.4.7	7 Relevant standards and regulations	8
2	Met	hod	10
	2.1	Injury mechanisms 1	0
	2.1.1	Head injury	11
	2.1.2	? Neck injury	11
	2.1.3	B Leg injury	12
	2.1.4	Thoracic injury	12
	2.2	Physical sled tests	13
	2.2.1	Overview	13
	2.2.2	Seat configuration	13
	2.2.3	B Load case	14
	2.2.4	Aircraft seats	15
	2.2.5	Child restraint systems	16
	2.2.0	Anthropomorphic test devices	17
	2.3	Numerical model development1	17
	2.3.1	Overview.	17
	2.3.2	? Model design and assembly	18
	2.4	Model verification and validation	28
	2.4.1	Sources of error	<u>29</u>
	2.4.2	? Numerical ATD validation	29
	2.4.3	Validation metrics	29
	2.4.4	Validation parameters	32
	2.4.4	Validation configurations and load cases	- 33
	240	Validation results	33
3	Ana	lysis and results	41
Ū	3.1	Overview	41
	3.1.1	U Load case	41
	312	P Basic configuration 2	12
	31	B Model execution	- 12
	32	Effect of CRS installation method on CRS and seatback motion	12
	321	Description of analysis	 42
	320	P Results and discussion 2	_ 13
	33	Effect of CRS installation method on child injury	50
	331	Direct of one instantation method on enne injury	50
	2.2.1	= ···· provide of an angle of a state of the	~

	3.3.2	Results and discussion	
	3.4 Eff	ect of CRS installation method on aft passenger injury	
	3.4.1	Description of analysis	54
	3.4.2	Results and discussion	54
	3.5 Eff	ect of empty CRS on aft passenger injury	
	3.5.1	Description of analysis	
	3.5.2	Results and discussion	
	3.6 Eff	ect of seat pitch on aft passenger injury	66
	3.6.1	Description of analysis	
	3.6.2	Results and discussion	
	3.7 Eff	ect of top tether on CRS motion and child injury	69
	3.7.1	Description of analysis	69
	3.7.2	Results and discussion	69
	3.8 Eff	ect of aft passenger on child injury	73
	3.8.1	Description of analysis	<i>73</i>
	3.8.2	Results and discussion	<i>73</i>
	3.9 Eff	ect of aft passenger on ISOFIX and LATCH CRS anchor loads	76
	3.9.1	Description of analysis	
	3.9.2	Results and discussion	
4	Conclu	sions	78
5	Recom	mendations	82
6	Referen	1ces	83
7	7 Glossary		
8	Append	dix A: Signal validation examples	86
9	Append	dix B: ISOFIX and LATCH CRS anchor loads	89

Table of Figures

Figure 1-1: Frame of high-speed footage from CASA study[2]. The head of the 50 th percentile adult ATD impacts the head of the 18-month-old child ATD, which impacts the forward seatback
Figure 1-2: Frame of high-speed footage from CASA study[1]. The 3-year-old child ATD occupant of an Australian CRS installed with a top tether makes glancing contact with the forward seatback
Figure 2-1: Example of aft passenger configuration[2]14
Figure 2-2: Comparison of typical sled deceleration pulse from physical testing and minimum allowable pulse under FAR 25.562
Figure 2-3: Lower anchorage points added to the aircraft seats as part of the CASA investigation[2]
Figure 2-4: L-R: Britax Duo Plus CRS, ISOFIX links, CRS installed using LATCH strap[2] 17
Figure 2-5: Left: Seatback frame prepared for geometry scanning. Right: Finite element model of seatback frame
Figure 2-6: Left: Physical test of foam material. Right: Test replicated in MADYMO 20
Figure 2-7: Graphical comparison of foam material model behaviour in loading, physical material test and MADYMO simulation. LRGR45 foam specimen, 100 mm thickness, 500 mm min ⁻¹ loading rate
Figure 2-8: Two views of aircraft seat model, base cushion and armrests removed for clarity 21
Figure 2-9: Seatback energy absorber test apparatus
Figure 2-10: Seatback energy absorber loading characteristic
Figure 2-11: Two views of CRS model
Figure 2-12: Hybrid III 50th percentile male numerical ATD positioned in aircraft seat25
Figure 2-13: TNO P3 3-year-old child numerical ATD and CRS positioned in aircraft seat 26
Figure 2-14: Variation in aft passenger initial knee angle
Figure 2-15: CRS initial postions relative to seat base cushion. L-R: lap belt, ISOFIX and LATCH cases
Figure 2-16: Aft passenger head acceleration signals for LATCH and ISOFIX CRS configurations
Figure 2-17: Overlaid position of aft passenger head at time of peak acceleration in LATCH configuration
Figure 3-1: Sled longitudinal deceleration pulse applied in all model experiments
Figure 3-2: CRS reference points
Figure 3-3: Effect of CRS installation method on CRS forward translation
Figure 3-4: Comparison of CRS translational motion associated with lap belt, ISOFIX and LATCH installation methods
Figure 3-5: Effect of installation method on maximum CRS forward rotation 46

Figure 3-6: CRS upper reference point forward displacement4
Figure 3-7: Forward rotational displacement of seatback (measured at free hinge) 49
Figure 3-8: Child lower leg contact with forward seat, lap belt CRS
Figure 3-9: Child HIC results for lap belt, ISOFIX and LATCH CRS installation methods 5
Figure 3-10: Child neck injury results for lap belt, ISOFIX and LATCH CRS installation methods
Figure 3-11: Child thorax acceleration (3 ms clip) results for lap belt, ISOFIX and LATCH CRS installation methods
Figure 3-12: Aft passenger head injury for lap belt, ISOFIX and LATCH CRS installation methods
Figure 3-13: Fractions of critical values of upper neck axial force (A') and moment (M')
Figure 3-14: Aft passenger elbow impact with forward armrest, $t = 80 \text{ ms}$
Figure 3-15: Effect of elbow-forward armrest contact on neck upper moment
Figure 3-16: Aft passenger neck injury results
Figure 3-17: Aft passenger maximum femur compressive force results
Figure 3-18: Aft passenger upper tibia maximum resultant bending moment for lap belt, ISOFIX and LATCH CRS installation methods
Figure 3-19: Effect of the absence of the CRS occupant on seatback rotation, lap belt method. 62
Figure 3-20: Effect of the absence of the CRS occupant on aft passenger head injury
Figure 3-21: Effect of the absence of the CRS occupant on aft passenger neck injury 69
Figure 3-22: Effect of seat pitch on aft passenger head injury6
Figure 3-23: Effect of seat pitch on aft passenger neck injury
Figure 3-24: Model representation of a typical top tether arrangement
Figure 3-25: Effect of top tether on maximum forward translation of CRS lower reference poin
Figure 3-26: Effect of top tether on maximum forward rotation of CRS
Figure 3-27: Effect of top tether on child head injury72
Figure 3-28: Effect of top tether on child neck injury72
Figure 3-29: Effect of aft passenger on child head injury7
Figure 3-30: Effect of aft passenger on child neck injury74
Figure 3-31: Effect of aft passenger on child head acceleration7
Figure 3-32: Peak net force exerted on the lower anchorage by ISOFIX and LATCH CRS with and without 95 th percentile male ATDs seated aft70
Figure 8-1: Aft passenger head resultant acceleration, lap belt CRS case
Figure 8-2: Aft passenger upper neck axial force, ISOFIX CRS case
Figure 8-3: Aft passenger right femur axial force, baseline case
Figure 9-1: ISOFIX baseline configuration, physical test

Figure 9-2: ISOFIX baseline configuration, model result.	90
Figure 9-3: ISOFIX aft 50th percentile ATD configuration, model result.	90
Figure 9-4: ISOFIX aft 95th percentile ATD configuration, model result.	91
Figure 9-5: LATCH baseline configuration, physical test	91
Figure 9-6: LATCH baseline configuration, model result.	92
Figure 9-7: LATCH aft 50th percentile ATD configuration, model result.	92
Figure 9-8: LATCH aft 95th percentile ATD configuration, model result.	93

1 Introduction

In recent years, several studies carried out in Australia and overseas have focussed on the safety of young children in aircraft under emergency landing conditions. The most common practice of restraining a child under the age of two years, whereby the child is seated on the lap of an adult, has been found to be inadequate in providing protection to the child; an incident which is severe but survivable for an adult is potentially fatal for a 'lap-held' child. Modern automotive child restraint systems (CRS) have been found to be capable of providing young child passengers with an appropriate level of protection[1-3].

The rate of CRS use in air transport remains low despite their use being recommended by aviation regulators. In Australia, only two of the four major domestic airlines allow the use of Australian-designed CRS aboard their aircraft. The primary difficulty associated with CRS use in air transport is that some CRS models are geometrically incompatible with the aircraft seat and lap belt. In Australia, a further difficulty exists due to the regulatory requirement for CRS to be installed using a 'top tether', the efficacy of which has been called into question.

Studies have found that two novel CRS installation methods, ISOFIX and LATCH, present a means of overcoming some of the difficulties associated with installing CRS in aircraft[1-3]. While these installation methods are generally capable of controlling CRS motion effectively, the exact nature of the behaviour of CRS installed by these methods and their potential effect on the safety of other passengers is not well understood.

A review of literature on the use of automotive child restraints in air transport led to the formulation of several research questions. Several experiments were designed with the aim of developing answers to these questions. Using recent a research project conducted by the Australian Civil Aviation Safety Authority (CASA) as a basis, a computer model of a typical economy class airline seating configuration was developed and validated. The experiments were carried using this model and the results were used to answer the research questions.

1.1 Objective

The objective of this project was to gain further insight into the answers to the following research questions relating to behaviour of forward-facing automotive child restraints in transport category aircraft under emergency landing conditions:

- What are the dynamic performance characteristics of CRS and what is the corresponding effect on the behaviour of the aircraft seat?
- What is the injury potential for a child restrained in a CRS?
- Are current practices of top tether use effective in controlling CRS motion?
- What is the injury potential for an adult seated directly aft of a CRS and how does this vary with seat pitch, CRS installation method and CRS occupant size?
- What are the loads imparted on the aircraft seat by ISOFIX and LATCH CRS and how are they affected by a passenger seated directly aft?

1.2 Scope

This research considered forward-facing automotive child restraint systems in terms of their behaviour and performance under emergency landing dynamic conditions when installed in typical economy class airline seats. Other loading conditions such as turbulence were not considered. The aspects of CRS performance considered were CRS occupant protection, interaction between the CRS and the aircraft seat in which it is installed, and the effect of the CRS on injury to a passenger seated directly aft.

The modelling phase of this study did not consider the case of rear-facing CRS. Prior studies have found that forward-facing CRS represent the critical case in terms of CRS occupant injury[4], CRS anchor loads[2], and potential injury to a passenger seated directly aft[2].

Where a particular CRS installation method required a modification to the aircraft seat, the only modification assessed by the modelling phase of this study was that used in CASA physical testing[2].

1.3 Review: The carriage of children in transport category aircraft

In a 1962 report, Dr Stanley R. Mohler, then the director of what is now the FAA Civil Aeromedical Institute, wrote:

"A particular need exists for proper infant protective equipment (in many cases at present the mother must hold her infant during the take-off and landing of an airliner)..."[5]

Since that time, the safety of children in aircraft has been the topic of several studies in Australia and around the world. While an exhaustive review of the various practices, regulations and research pertaining to the carriage of children in aircraft in different parts of the world is beyond the scope of this report, some relevant topics are discussed below.

1.3.1 Regulatory situation in Australia

Australian aviation regulations[6] require that all passengers, regardless of age, be restrained by a harness or seat belt during:

- takeoff,
- landing,
- instrument approach,
- flight less than 1000 feet above terrain, and
- turbulence.

During these times, all passengers must occupy a seat. An exception is made for children aged less than three years, who may alternatively be:

- held in the lap of an adult passenger,
- carried in a suitably-restrained bassinet, or
- seated in an approved and suitably-restrained 'infant seat'.

This provision does not except any passenger from the requirement that all passengers be restrained. CASA advisory material[7] states that a 'supplementary loop belt' is the "only known device" which provides acceptable restraint for a child held on the lap of an adult. Currently, no bassinet devices are approved for use as a restraint in Australian transport category aircraft.

1.3.2 Operational situation in Australia

Individual airlines set their own policies regarding the carriage of children within the scope of the regulations. Of the four major Australian domestic carriers, each allows children up to the age of 24 months to be restrained on the lap of an adult[8-11]. Two carriers allow the use of CRS meeting Australian design standards[9, 10]. One carrier specifically prohibits the use of CRS meeting Australian design standards[11], and another prohibits the use of CRS entirely[8]. Of the two carriers allowing the use of Australian CRS, one carrier's policy is that rear-facing restraints will only be approved for use if a member of the child's travelling party sits in the seat forward of the CRS due to potential difficulties in reclining that seat[10].

In the United States, aviation regulations require that airlines allow the use of aviation-approved CRS when a ticket has been purchased[12].

1.3.3 Safety of the lap-held child

Aviation regulations around the world require the implementation of one of two different conditions for lap-held children:

- 1. The child must be restrained by a supplementary loop belt, as is the case in jurisdictions including Australia, the United Kingdom and Europe (except Germany).
- 2. The child is unrestrained, as is the case in jurisdictions including the United States, Canada and Germany. The use of a supplementary loop belt is prohibited.

CASA advisory material^[7] states that, during a severe but potentially-survivable crash, a lap-held child restrained by a supplementary loop belt is not provided a level of safety equivalent to a separately-seated adult.

Several research programs have assessed the potential for injury of a child carried on the lap of an adult aircraft passenger during rapid forward deceleration[2, 4, 13, 14]. In each of these studies, aircraft seats were mounted on a deceleration sled and occupied by anthropomorphic test devices (ATDs, or 'crash test dummies'). Differences in ATD type, applied acceleration pulse and aircraft seat type and configuration preclude direct comparison of results; however, the finding of each study was generally the same.

- A study by Hardy[14] assessed the case of an unrestrained lap-held child, finding that this method "is likely to promote fatalities and injuries to these children during impact situations."
- A 1994 report by Gowdy and DeWeese[4] at the FAA Civil Aeromedical Institute assessed the case of a lap-held child ATD restrained by a supplementary loop belt. The authors reported that dynamic testing confirmed "[t]he impossibility of protecting a small child, by any means, sitting on the lap of an adult restrained by seat belts..."
- A 2006 report[13] by Gibson, Thai and Lumley detailed the results of dynamic testing of a lap-held child ATD restrained by a supplementary loop belt. It was found that "the forward motion of the adult dummy in a lap belt trapped and crushed the infant in the space between the front row seat back, the head and torso and the knees of the adult."
- A 2009 report by Bathie[2] concluded that, for the case of a child restrained by a supplementary loop belt on the lap of an adult, child ATD injury measurements indicated "excessive head and neck trauma". It was noted that there was no available means of measuring child injury parameters such as compression of the head, chest and abdomen.



Figure 1-1: Frame of high-speed footage from CASA study[2]. The head of the 50th percentile adult ATD impacts the head of the 18-month-old child ATD, which impacts the forward seatback.

1.3.4 Installation of CRS in aircraft

CASA advisory material[7] states that a CRS is able to provide a child with an equivalent level of safety to that of a separately-seated adult during a severe but survivable crash. However, acceptance of CRS use by Australian airlines is not widespread. This may be attributed to two major factors: the requirement for the use of a 'top tether' and geometrical incompatibility between CRS and aircraft seats.

1.3.4.1 Top tether requirement

Australian CRS design standards[15] require the use of a 'top tether' – a webbing strap between the CRS and the vehicle structure intended to prevent fore-aft rotation of the CRS. CASA advisory material[7] states that a CRS "must be secured to the aircraft seat in accordance with the child seat manufacturer's instructions or an approved alternate method". The combination of these two requirements effectively mandates the use of a top tether in the installation of Australian-designed CRS in aircraft.

The Australian carriers noted in section 1.3.2 as accepting Australian-designed CRS satisfy the top tether requirement by having a limited number of 'anchor straps' available for top tether attachment. The webbing anchor strap is attached to the aircraft seat leg structure; the top tether is passed over the seatback and attached to the anchor strap. This arrangement has been shown to be largely ineffective in controlling CRS rotation when installed on a seat with seatback break-over capability[1, 13]. Additionally, this arrangement would prevent the use of the tray table by the passenger seated directly aft of the CRS[1]. Gibson, Thai and Lumley recommended in their

2006 report[13] that the effectiveness of a top tether arrangement as outlined above be investigated for cases where seatback break-over is prevented from occurring. Bathie[1] suggested that "limited benefit" may be provided by increased seatback break-over stiffness in this arrangement.

1.3.4.2 Alternative to top tether

The development of an 'approved alternate method' of CRS installation which avoids the need for a top tether is potentially complicated due to the different CRS configurations available (i.e., forward-facing, rear-facing and convertible), and geometrical variations between CRS models of a given configuration.

Research by Bathie[1] included a brief assessment of the effectiveness of an alternative method of installing a forward-facing CRS. This method used the lap belt to restrain the CRS, but replaced the top tether with a loop of webbing passed through the CRS aft belt path and horizontally around the seatback of a typical economy class airline seat with seatback break-over capability. It was found that the dynamic performance of a CRS installed using this alternative method was "slightly improved" over that of the same type of CRS installed on the same type of seat using the top tether.

1.3.4.3 Geometrical incompatibility

Geometrical factors affecting the compatibility of CRS with aircraft seats are twofold. Studies have found that the geometry of some CRS models prevents them from physically fitting into the aircraft seat[4, 13]. Additionally, some CRS geometries prevent the proper tensioning of the lap belt and operation of the lap belt buckle when the lap belt is passed through the CRS[4, 13].

1.3.5 Dynamic performance of CRS in aircraft

Through a dynamic test program involving mostly American convertible and aft-facing CRS, Gowdy and DeWeese[4] found that the use of a CRS, while preferable to restraint by a lap belt only, does not necessarily ensure the safety of the child. The dynamic performance of aft-facing CRS was found to be satisfactory; however that of forward-facing convertible CRS was generally not. The principal reason given for this was excessive forward motion of the CRS during deceleration.

The issue of excessive motion was also apparent in dynamic testing of 11 Australian forwardand aft-facing CRS by Gibson, Thai and Lumley[13]. It was found that all tested CRS "exhibited significant forward motion, rotation and rebound motion." Some of the reasons given for this were that the path of the lap belt was too vertical and that the top tether was not effective or absent. Despite this, however, the authors concluded that children aboard aircraft are "far safer" when restrained in a CRS than if they were lap-held or restrained only by the aircraft seat lap belt.

An extended investigation by Bathie[1, 2] included dynamic testing of forward- and aft-facing Australian CRS in aircraft seats. It was found that, while the lack of an effective top tether arrangement led to an issue with CRS motion, the CRS tested performed adequately and afforded the child occupant a good level of protection[1, 2].



Figure 1-2: Frame of high-speed footage from CASA study[1]. The 3-year-old child ATD occupant of an Australian CRS installed with a top tether makes glancing contact with the forward seatback.

1.3.6 ISOFIX and LATCH CRS

Gibson, Thai and Lumley[13] in their 2006 report recommended an investigation into the use in aircraft of CRS designed to be installed by two new attachment methods: ISOFIX and LATCH. The ISOFIX and LATCH CRS attachment methods do not make use of the vehicle seatbelt for the primary connection between the CRS and the vehicle. Instead, the CRS attaches directly to hard points in the vehicle structure at point where the seat back meets the seat base. In the case of the European ISOFIX standard this is achieved through rigid links, while in the case of the North American LATCH standard this is achieved through one or more webbing straps.

In a 2007 report[3], Olivares and Amesar detailed the results of dynamic testing of CRS installed in transport category business jet seats using ISOFIX and LATCH. That study found that both of these attachment methods provide the CRS occupant with an appropriate level of safety, while overcoming the issue of excessive CRS motion associated with installation using the aircraft seat lap belt. The authors concluded that further research was required on several aspects regarding ISOFIX and LATCH CRS, including:

- the effect of seatback break-over on CRS performance,
- interaction with the occupant of a seat directly aft of the CRS, and
- CRS anchor loads.

An extended investigation by Bathie assessed the dynamic performance of CRS installed in aircraft seats using the ISOFIX[1, 2] and LATCH[2] methods as well as the aircraft lap belt[1, 2]. It was found that each of these CRS installation methods afforded the child CRS occupant a good level of protection and that the ISOFIX and LATCH methods reduce the potential for the problem of CRS motion associated with installation using the aircraft seat lap belt[2]. The investigation resulted in the recommendation of further research into the following aspects of CRS use in aircraft[2]:

- The potential for neck injury to an adult seated behind a CRS.
- The potential for tibia injury to an adult seated behind a seat which has been modified to accept ISOFIX and LATCH CRS.
- The effects of seat pitch, CRS installation stiffness, occupant size, and seat structural variations on CRS performance and injury to both the CRS occupant and an adult passenger seated directly aft of the CRS.

1.3.7 Relevant standards and regulations

1.3.7.1 Aircraft seating and restraint crashworthiness

The Australian Civil Aviation Safety Regulations define safety standards for transport category aircraft seating and restraint systems under emergency landing dynamic conditions by reference to the United States Federal Aviation Regulations (FAR) Part 25.562. This regulation places allowable limits on specific occupant injury criteria under given loading conditions. The dynamic tests prescribed by this regulation include only adult seat occupants.

1.3.7.2 Automotive child restraint systems

All automotive child restraint systems available in Australia must meet the design and performance standards set out in Australian Standard AS/NZS 1754[15]. This standard requires CRS to be installed with an upper anchorage strap, also known as a 'top tether'. This standard sets out simple allowable occupant injury limits in the form of peak head acceleration values for forward-facing CRS.

2 Method

A dynamic finite element model was created in order to allow experiments to be conducted in a virtual environment. This experimental method was chosen over further physical tests for benefits such as low cost, a high level of adaptability, and the ability to measure any variable of interest. The finite element model was based on the physical test configuration used by CASA[2] to allow validation of model output.

The model was used to analyse the crashworthiness of seating configurations involving automotive CRS in terms of CRS motion, CRS occupant injury potential, injury potential of an adult seated directly aft of a CRS, and structural loads. The seating configuration parameters assessed were seat pitch, CRS installation method and CRS occupant size.

Experiment results were compared with results from physical tests where appropriate. ATD sensor data was used to evaluate particular occupant injury mechanisms in terms of criteria and allowable limits established in relevant regulations and literature. In this way, experiment results were used to identify potential injury to human occupants.

2.1 Injury mechanisms

The injury mechanisms considered by this study were:

- 1. Head acceleration (adult and child)
- 2. Neck axial force and fore-aft bending (adult and child)
- 3. Femur compression (adult)
- 4. Upper tibia bending (adult)
- 5. Thorax acceleration (child)

Of these, only adult head acceleration and femur compression are used in the certification of transport category aircraft seats[16]. For the remaining injury mechanisms, criteria and allowable limits were drawn from other relevant regulations and literature. Regulations generally define injury limits in terms of an acceptable level measured by a given ATD model under a given loading condition. Differences in loading condition severity between regulations and in biofidelity between ATD models mean that this approach introduces a degree of arbitrariness to the determination of whether a particular injury level is acceptable.

2.1.1 Head injury

The head injury criterion (HIC) is used in FAR 25.562[16] to evaluate head injury resulting from inertial loading. It is defined as[16]:

$$HIC = \left[(t_2 - t_1) \left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right)^{2.5} \right]_{max}$$
(2-1)

where t_1 and t_2 define the beginning and end of an arbitrary time window, respectively, and a(t) is the time history of ATD head c.g. acceleration expressed in multiples of g. The unit of time is seconds.

FAR 25.562 does not place an upper limit on the length of the time window but stipulates that a(t) is only defined over the period of a 'head strike'. Adult head injury was evaluated according to this method; however, a different method was required for the case of child head injury due to the child's head generally not making contact with surrounding structure

US Federal Motor Vehicle Safety Standard (FMVSS) 213[17] defines occupant protection standards for child restraint devices used in motor vehicles and aircraft. This standard uses the same formula for HIC as FAR 25.562. Head acceleration a(t) is defined over the entire test period; however, an upper limit of 36 ms is placed on time window length (referred to as 'HIC36'). Child head injury was evaluated according to this method.

FAR 25.562 specifies a maximum allowable HIC value of 1000 units for a 50th percentile adult male ATD occupant. This is the only occupant size for which HIC is evaluated under FAR 25.562.

FMVSS 213 specifies a maximum allowable HIC36 value of 1000 units for a variety of child ATDs representing ages from newborn to six years.

2.1.2 Neck injury

FMVSS 208[18] defines occupant protection standards for automobiles in the United States. Neck injury potential is assessed using the neck injury criteria, Nij.

$$Nij = \frac{F_z}{F_{zc}} + \frac{M_y}{M_{yc}}$$

where F_{z} and F_{z} are the measured and critical upper neck axial forces, respectively, and M_{y} and M_{y} are the measured and critical upper neck fore-aft bending moments, respectively, at a given time during the experiment.

The standard defines critical axial forces for both the tensile and compressive cases, while critical moments are defined for both the flexion (chin down) and extension (chin up) cases. Four combinations must therefore be considered in order to find the critical Nij case: tension-flexion, tension-extension, compression-flexion and compression-extension.

FMVSS 208 specifies a maximum allowable Nij value of 1.0. The critical force and moment values required for calculation of Nij are defined in FMVSS 208 for a range of occupant sizes, both child and adult. The values relevant to this research are given below.

Table 2-1: FMVSS 208 critical neck axial forces and moments for child and adult ATDs[18]

Occupant size	Tension (N)	Compression (N)	Flexion (Nm)	Extension (Nm)
3-year-old	2120	2120	68	27
50th percentile adult	6806	6160	310	135

2.1.3 Leg injury

FAR 25.562 specifies a maximum allowable axial compressive load of 2250 lbf (10.0 kN) in each femur. This is the only leg injury criterion included in FAR 25.562.

Research by Bathie[2] identified tibia bending as a potential injury mechanism for a passenger seated directly aft of a seat which has been modified to accept ISOFIX and LATCH CRS. Kerrigan et al.[19] carried out dynamic testing of cadaveric tibias, reporting fracture initiation moments in the range of 250 - 350 Nm. Kerrigan et al. concluded that these values were consistent with contemporary biomechanics literature. In lieu of a widely-recognised relevant injury criterion, this range of fracture initiation moment was used to evaluate tibia injury potential.

2.1.4 Thoracic injury

FMVSS 213 specifies a maximum allowable thorax acceleration for a CRS occupant of 60 g over a cumulative period of 3 ms.

2.2 Physical sled tests

2.2.1 Overview

The physical sled test data referred to by and presented in this report were provided by CASA. Results were provided in the form of raw data and technical reports detailing the CASA investigation [1, 2].

The numerical model developed in this project was based on the physical experiments of the second phase of an extended investigation into the use of CRS in transport category aircraft undertaken by CASA[2]. That investigation assessed the dynamic performance of a variety of CRS types and their potential to affect on the level of injury sustained by an adult passenger seated directly aft under emergency landing conditions. In addition, the cases of a lap-held child restrained by a supplementary loop belt and a child restrained in the aircraft seat solely by the lap belt were briefly assessed.

Aspects of the CASA investigation that are relevant to this particular research project are described below.

2.2.2 Seat configuration

The seat configuration implemented by CASA in physical experiments was similar to that found in a typical airline economy class seating configuration. Two rows of seats at a pitch of 30 inches were installed on a deceleration sled in a two-abreast arrangement. Two distinct occupant arrangements were used:

- 1. In arrangements designed to assess CRS performance, a CRS with a child ATD occupant was installed in an aft seat with an empty seat in front.
- 2. In arrangements designed to assess adult injury potential, a CRS with a child ATD occupant was installed in a forward seat with an adult ATD seated behind.

A third arrangement was used in a limited number of tests to assess the cases of a lap-held child and a child restrained by the lap belt only. A baseline adult injury arrangement was also used, whereby an adult occupant was seated in the aft row and the forward row was empty.

In accordance with FAR 25.562, adult occupants were placed in a normal upright sitting position. At the time that the physical tests were being carried out, future modelling was not a consideration. As a result, some important parameters such as ATD initial position, CRS initial position and lap belt initial tension were not measured.



Figure 2-1: Example of aft passenger configuration[2].

2.2.3 Load case

FAR 25.562 specifies longitudinal and vertical load cases for the dynamic testing of aircraft seats and restraint systems. The longitudinal load case includes the requirement for a minimum peak floor deceleration of 16 g to be achieved no more than 90 ms after impact and a minimum forward velocity change of at least 44 ft·s⁻¹ (13.4 m·s⁻¹). The same load case is referred to by FAA Technical Standard Order (TSO) C100b, which defines minimum performance standards for CRS approved for use on aircraft in the United States.

Limitations of the deceleration sled system used in the CASA test program prevented the application of the ideal pulse specified in FAR 25.562. The load case applied in the CASA tests typically resulted in a 21 g peak floor deceleration 50 ms after impact, exceeding the corresponding requirements of FAR 25.562. Most tests achieved a forward velocity change of approximately 14.5 m·s⁻¹, though some fell slightly below the value of 13.4 m·s⁻¹ required by FAR 25.562.



Figure 2-2: Comparison of typical sled deceleration pulse from physical testing and minimum allowable pulse under FAR 25.562.

The velocity change of approximately 14.5 m·s⁻¹ achieved in most CASA tests resulted in the magnitude of kinetic energy dissipated during the test being 17% greater than the minimum allowable under FAR 25.562. Assuming a final sled velocity of zero:

$$E_k = \frac{1}{2}mv^2$$
$$\frac{E_{k,CASA}}{E_{k,min}} = \frac{v_{CASA}^2}{v_{min}^2}$$
$$= \frac{14.5^2}{13.4^2}$$
$$= 1.17$$

Some of this additional energy would have been transferred through and dissipated by the ATDs, CRs and seat structure, leading to injury results, CRS motion and loads greater than would have been achieved with the minimum pulse.

2.2.4 Aircraft seats

The seats used in physical testing were typical economy class airline seats which had been removed from service. They were labelled as meeting the standards of FAA TSO-C39b, Type I, which does not include dynamic performance or occupant protection criteria. The seat design incorporated an energy-absorbing device to control the forward rotation of the seatback; this

device was fitted to one seatback hinge of each seat position, with the other hinge being 'free'. The energy-absorbing device was found to have only subtle design differences to those installed on seats meeting TSO-C127a, which specifies occupant protection criteria by reference to FAR 26.562. The seat base cushions were a non-flotation type, comprised of a laminate of three different polyurethane foams.

Lower anchorage points compatible with the ISOFIX and LATCH systems were added to the aircraft seats. The anchorages were small loops of 6 mm round steel bar welded to a length of 20 mm diameter, 2 mm thick circular steel tube. This tube spanned the width of both seat places and was fastened to the aft edge of each of the three spreaders at a height of 395 mm above the floor.



Figure 2-3: Lower anchorage points added to the aircraft seats as part of the CASA investigation[2].

2.2.5 Child restraint systems

The CASA investigation considered forward- and aft-facing CRS models as well as three different CRS installation methods: the lap belt, ISOFIX and LATCH. High-speed footage of the physical tests revealed that forward-facing restraints affect the dynamic behaviour of the aircraft seat to a greater extent than aft-facing models. Of the forward-facing models tested, one CRS was able to be attached to the aircraft seat by each of the three installation methods. That model, the Britax Duo Plus, is fitted with ISOFIX rigid linkages and also has a traditional belt path which provides for installation using the aircraft seat lap belt or a separate LATCH webbing strap. This CRS has a mass of approximately 8.5 kg and an allowable occupant mass range of 9 to 18 kg.



Figure 2-4: L-R: Britax Duo Plus CRS, ISOFIX links, CRS installed using LATCH strap[2].

2.2.6 Anthropomorphic test devices

Also known as 'crash test dummies', anthropomorphic test devices (ATDs) are full-scale human models with geometry, mass distribution and joint articulation representative of a human body. Accelerometers, load cells and other sensors may be fitted to an ATD to enable the measurement of variables used to determine injury potential. The adult ATDs used in the CASA research project were Hybrid III 5th percentile female, 50th percentile male, and 95th percentile male. The child ATDs used were the TNO P3 three-year-old, P1.5 18-month-old, and P3/4 nine-month-old.

2.3 Numerical model development

2.3.1 Overview

The numerical model development process required the following steps:

- 1. Measurement and discretisation of system geometry.
- 2. Measurement and definition of system stiffness, damping and mass properties.
- 3. Definition of connectivity and contact interaction between components.
- 4. Numerical evaluation of the equations describing the system.
- 5. Verification of model behaviour and validation of model output.

Two modelling methods are applicable to the type of model required by this project: the multibody method and the finite element method. The principal difference between these methods is in their treatment of geometry discretisation, with different treatments of mass discretisation, contact interaction, component connectivity and component deformability as a consequence.

2.3.1.1 The multibody method

In general, a multibody model is simpler to define and less computationally-intensive than a finite element model. The geometry of a structure is represented in a multibody model by discrete ellipsoidal, cylindrical and planar surfaces. These surfaces are attached to rigid bodies, essentially point masses with specified inertial properties. Equations define the allowable motion of the rigid bodies relative to each other and to the environment (the 'reference space'), thus creating joints between parts. Multibody surfaces are non-deformable; contact interaction behaviour between multibody parts is generally modelled using a known characteristic describing contact force relative to a given penetration of one surface by another. Multibody models are not well suited to representing complex geometries and are unsuitable for use in modelling large-scale deformation as they are unable to capture the corresponding changes in geometry.

2.3.1.2 The finite element method

Using the finite element method, the geometry of a structure is defined at finite points called nodes. Nodes are connected to one another to form elements; multiple connected elements form a part. By assigning a material property to an element, the nodes are given a mass and the stiffness and damping relationship between the nodes is defined. The behaviour of contact interactions between elements may be determined by nodal kinematic behaviour. Joints may be modelled by defining relative motion between nodes with an equation or through contact between elements. The finite element method is able to model large-scale deformation and structural failure.

2.3.2 Model design and assembly

The model was designed to be as simple and modular as possible while maintaining fidelity in critical areas, maximising computational efficiency while allowing simple reconfiguration of the model.

The MADYMO software package was selected for its emphasis on vehicle occupant safety analysis and its large library of numerical ATDs. The MADYMO solver is a combined finite element and multibody solver, enabling the user to maximise computational efficiency by using the multibody method to represent parts of the model as appropriate.

2.3.2.1 Geometry and material data

Aircraft seat and CRS geometry and material properties were measured in a process of 'reverse engineering'. In addition to traditional methods, geometry measurements were made using an

articulated-arm coordinate measurement machine and, in the case of complex geometry such as the aircraft seat back frame, three-dimensional optical scanning.



Figure 2-5: Left: Seatback frame prepared for geometry scanning. Right: Finite element model of seatback frame.

Material properties were either gathered from literature or measured by physical testing. The most problematic materials in this regard were the three foams comprising the aircraft seat base and back cushions. Specimens provided by the cushion manufacturer were tested at three quasi-static loading rates using a method derived from ASTM D3574[20]. Square foam samples of side length 380 mm and varying thickness were compressed on a solid surface by a solid round anvil of 200 mm diameter.



Figure 2-6: Left: Physical test of foam material. Right: Test replicated in MADYMO.

Testing revealed that all three foam materials exhibited rate-dependent behaviour; however, the maximum tested loading rate of 500 mm·min⁻¹ was deemed to be significantly below that experienced by the material in sled testing. An assessment of similar materials in quasi-static and dynamic loading by Bhonge[21] provided the basis for a rate-dependent stress scaling characteristic. The physical material test was replicated in MADYMO for verification.



Figure 2-7: Graphical comparison of foam material model behaviour in loading, physical material test and MADYMO simulation. LRGR45 foam specimen, 100 mm thickness, 500 mm·min⁻¹ loading rate.

2.3.2.2 Aircraft seat model

To reduce model complexity and maximise computational efficiency, only the left-hand seat position of the two-abreast configuration was modelled. A symmetry condition was imposed at the centre spreader so that correct structural behaviour was maintained. The aircraft seat model is fully deformable with the exception of the legs and longitudinal spreaders. These components were found not to deform significantly during physical testing so were modelled as rigid parts to maximise computational efficiency. The aircraft seat model included a simplified representation of the lower anchorage modification made as part of the CASA investigation (see section 2.2.4).



Figure 2-8: Two views of aircraft seat model, base cushion and armrests removed for clarity.

All joints were modelled by rigidly attaching the nodes of each side of a joint to a rigid body, then defining a numerical joint between the corresponding rigid bodies. This method avoided computationally-intensive contact evaluations while enabling precise control over joint behaviour. A particular example of this approach is the modelling of the energy-absorbing device fitted to one seatback hinge of each seat position. This device comprises two steel plates which plastically deform as the seatback rotates forward. A basic test rig (Figure 2-9) was manufactured to enable the resistance torque caused by the buckling plates to be measured as a function of seatback angular displacement.



Figure 2-9: Seatback energy absorber test apparatus.

The resulting characteristic curve (Figure 2-10) was used to define a restraint on the motion of the left-side seatback hinge. Hysteresis was applied in order to account for energy dissipation due to plastic deformation.



Figure 2-10: Seatback energy absorber loading characteristic.

2.3.2.3 CRS model

The only CRS implemented in the numerical model was the forward-facing CRS described in section 2.2.5. A review of the high-speed sled test footage and a post-test inspection of the CRS revealed that it does not undergo significant deformation during the deceleration sequence. With the exception of its five-point harness, the CRS was modelled as a non-deformable part.



Figure 2-11: Two views of CRS model.

The geometry of the CRS is defined by two separate parts. The nodes of both parts are rigidly supported on a single rigid body which is located at the CRS centre of gravity. The rigid body is assigned a mass of 8.5 kg, the total mass of the physical CRS. The thin foam padding that covers the CRS seating surface was represented by a contact characteristic assigned to the seating surface.

2.3.2.4 Belt models

Two methods of modelling webbing belts are available: multibody and finite element. The aircraft seat lap belt is modelled using the multibody method; one-dimensional belt segments with a defined force-strain characteristic connect the belt anchor points to the ATD or CRS, avoiding the requirement for computationally-intensive contact calculations associated with finite element belts. The multibody method is useful in this situation, as the belt path through the CRS and across the pelvis of the ATD is simple and remains constant during physical tests. A multibody belt is visible in Figure 2-12.

Finite element belts are required in the case of the CRS 5-point harness, where belt geometry and interaction with the ATD are more complex than in the case of the lap belt. Belt elements are

assigned a material characteristic, and contact is defined between the belt elements and the ATD. Finite element belt models are visible in Figure 2-13.

2.3.2.5 ATD models

The numerical ATDs used were multibody representations of the ATDs used in physical testing. In addition to geometrical features, numerical ATDs have pre-assigned contact characteristics and joint stiffness characteristics closely matching the physical ATD they represent. The numerical ATDs implemented in the model were included in the MADYMO package, and some validation data was provided by the software vendor (see section 2.4.2).

2.3.2.6 Model assembly

Once the general arrangement of the model components was complete, a dynamic positioning process was used to position the ATDs and CRS in the aircraft seats. This 'pre-simulation' is necessary in cases where, at the beginning of the test, some elements have non-zero strain or contact exists between parts which have a defined contact interaction. It ensures that these contacts behave correctly and that elements in components such as cushions are appropriately deformed, with corresponding strain values, at the beginning of the test.



Figure 2-12: Hybrid III 50th percentile male numerical ATD positioned in aircraft seat.

A pre-simulation phase was necessary, as the adult ATD and CRS both cause initial deformation of the aircraft seat base and back cushions and the initial contact forces between the child ATD and the CRS seating surface must be correct. As it was critical to replicate the physical test initial positions of the ATDs and CRS, prescribed motion was used to 'install' them in the aircraft seat. An alternative process using applied force to carry out positioning would not be appropriate in this instance due to the hysteresis behaviour of the cushion foams.

After positioning by prescribed motion, the ATDs and CRS were 'released' with gravity as the only applied force. This was done to ensure an equilibrium condition in ATD and CRS contact with the aircraft seat and also to allow joints such as those comprising the ATD spinal column to reach equilibrium under gravity.





2.3.2.7 Note on aft passenger initial position

Video footage of the physical tests indicated that there was generally little variation in adult ATD initial position between tests. However, a small variation in knee angle was noted in one case (see Figure 2-14). The effect of this was assessed using the model and was found to be significant: as the ATD slides forward on the seat, the tibias make contact with the lower anchorage bar, where present, or with the forward seat's aft lateral tube. The tibias are thereby loaded in three-point bending, the three points being: the aircraft floor, the lower anchorage bar or the aft lateral tube of the forward seat, and the knees which are moving forwards at the time of contact. As this loading effectively 'jams' the tibias between the forward seat and the floor, the upper leg and upper body then pivot about the knee. A variation in initial knee angle was found to change this pivoting behaviour and consequently the location of head impact.


Figure 2-14: Variation in aft passenger initial knee angle.

The aft passenger knee angle used in the model validation process resembled the corresponding physical test as closely as possible. For all analyses, however, the more-common knee angle depicted in the upper image of Figure 2-14 was used.

2.3.2.8 Note on CRS initial position

Video footage of the physical tests revealed that for each of the three CRS installation methods tested the initial compression of the aircraft seat base cushion was slightly different (see Figure 2-15). While seemingly insignificant, these differences were found to noticeably affect the model's prediction of CRS behaviour. These CRS initial positions were treated as a property of the associated installation method and so were maintained in the model.



Figure 2-15: CRS initial postions relative to seat base cushion. L-R: lap belt, ISOFIX and LATCH cases.

2.4 Model verification and validation

In the context of the development of a model using an established numerical code, which itself has already been subjected to a process of verification and validation by its developer, model verification is the process of ensuring that the correct input variables (such as geometry and material properties) and model configuration parameters (such as joint and contact definitions) are being implemented[22]. A continual cycle of verification was implemented during model development at the material, component and system levels.

Validation is the process of comparing model output with physical test data in order to determine the degree to which the output from a numerical model represents reality[23]. Data used in validation may be in the form of single numerical values, sensor signals or visual images.

A numerical model generally cannot be considered to be 'validated' in an absolute sense. Instead, a finite number of output parameters of the model are validated for one or more load cases. A satisfactory level of validation in one output parameter does not imply fidelity in another, even if the two are closely related. The end use of a particular model output parameter must be appropriate to the level of validation of that parameter.

The model described here was developed for use as a tool in a parametric study, with an emphasis on finding results in a timely manner while being modular in design to facilitate reconfiguration. As such, an extremely high level of validation across many output parameters is neither required nor realistically possible. While model development required an iterative process of verification and validation, it should be noted that this does not imply 'calibration' of input variables to achieve the desired output. Instead, modelling approximations in the initial model were progressively removed until an acceptable level of validation was attained. In this way, a model was achieved which was both simple in design and also able to produce results with a useful level of validity.

All output signals from both physical testing and the numerical model were filtered according to SAE J211-1[24] prior to validation.

2.4.1 Sources of error

As each physical test in the CASA program was run only once, there is no data available describing the real-world variability of output parameters. It is therefore necessary to assume for the purpose of model validation that the results of the physical test are 100% reproducible. In reality, this is not the case due to the existence of error sources such as:

- 1. Test setup errors. E.g., variations in belt pretension, ATD initial position, CRS initial position.
- 2. *Structural failure*. Structural failure was witnessed in a small number of physical tests. This can be attributed to some aircraft seats being used in multiple tests. The numerical model does not account for structural failure.
- 3. *Measurement errors.* In any physical test there is a degree of random error associated with measurement. This is especially true of the types of sensors used in sled testing; signals from accelerometers and load cells are noisy in nature and are prone to 'drift'.
- 4. *Calibration errors.* Sensors used in physical tests must be calibrated to ensure their output is within accuracy tolerances. In addition, the joint stiffness properties of an ATD must also be kept in calibration to ensure that its kinematic response is accurate.

2.4.2 Numerical ATD validation

The ATDs implemented in the numerical model were developed and subjected to a validation process by the software vendor. The validation reports provided by the software vendor were used to determine the maximum level of validation that may be expected of individual numerical ATD output parameters when implemented in the model. Validation data is made available to users of the software but is considered proprietary information and cannot be reproduced here.

2.4.3 Validation metrics

2.4.3.1 Single values

Where single numerical values are compared (e.g., signal peak values), their difference is expressed as a percentage of the physical test value. A positive difference indicates that the model gives an over-prediction of magnitude, while a negative difference indicates an underprediction of magnitude.

2.4.3.2 Time-history signals

The comparison of two transient time-history signals is a complex task. Signal properties such as the time and magnitude of the peak value are useful but only consider a single point in time. While there is no single best method for comparing transient time-history signals, the Sprague and Geers error metric[25] has been identified as being both appropriate to this type of application[26] and in good agreement with subjective assessments by experts[27]. This metric individually assesses the phase and magnitude error between two signals over a given period. These two error values are then combined into a single comprehensive error factor. The bases of the metric are the time integrals of a benchmark (physical test) signal b(t) and a candidate (numerical model) signal c(t) over a time period $t_1 < t < t_2$:

$$\vartheta_{bb} = (t_2 - t_1)^{-1} \int_{t_1}^{t_2} b^2(t) dt \qquad (2-2) [25]$$

$$\vartheta_{cc} = (t_2 - t_1)^{-1} \int_{t_1}^{t_2} c^2(t) dt \qquad (2-3) [25]$$

$$\vartheta_{cb} = (t_2 - t_1)^{-1} \int_{t_1}^{t_2} c(t)b(t)dt \qquad (2-4) [25]$$

The magnitude error factor M_{SG} and phase error factor P are given by:

$$M_{SG} = \sqrt{\frac{\vartheta_{cc}}{\vartheta_{bb}}} - 1 \tag{2-5} [25]$$

$$P = 1 - \frac{\vartheta_{cb}}{\sqrt{\vartheta_{cc}\vartheta_{bb}}} \tag{2-6}$$

These values are combined to give the comprehensive error factor, C:

$$C = \sqrt{M_{SG}^2 + P^2} \tag{2-7}$$

This error factor was used to quantify the overall level of agreement between numerical model and physical test time-history signals. It is presented in the form of a percentage for convenience. While a particular value of C does not have any generally-applicable meaning, a value of 0% indicates an excellent match between signals, while a value of 100% (1.00) would indicate a poor match. The upper limit of C is essentially unbounded.

The comprehensive error factor C does not directly take into account the difference between peak signal values. Peak values, both positive and negative, are particularly important properties of force and moment signals. Physical test and numerical model signal peak values were compared by expressing their difference as a percentage of the physical test value. Where a positive peak exists in the physical test signal, the magnitude error between the positive peak values is given by:

$$M_{pos} = \left(1 - \frac{Peak_{model,pos}}{Peak_{test,pos}}\right) \times 100$$
(2-8)

Similarly, where a negative peak exists in the physical test signal, the magnitude error between the negative peak values in is given by:

$$M_{neg} = \left(1 - \frac{Peak_{model,neg}}{Peak_{test,neg}}\right) \times 100$$
(2-9)

Where signals exhibit both positive and negative peaks, weighting factors were used to determine the relative importance of each peak according to the physical test. These factors take into account the magnitude of the positive and negative peaks as a proportion of the total amplitude of the physical test signal and are given by:

$$W_{pos} = \frac{Peak_{test,pos}}{Peak_{test,pos} - Peak_{test,neg}} \times 100$$
(2-10)

$$W_{neg} = \frac{Peak_{test,neg}}{Peak_{test,pos} - Peak_{test,neg}} \times 100$$
(2-11)

A low value of W (i.e., close to zero) indicates that a peak is relatively insignificant, a high value of W (i.e., close to 1) indicates that a peak is significant, while a value of W close to 0.5 indicates

that the positive and negative peaks are of equal significance. This weighting does not take into account whether a positive or negative peak is more significant in terms of injury potential.

2.4.4 Validation parameters

Only the model output parameters for which physical test data was available were able to be validated. Of these, several are relevant to the end use of the model. These are:

- 1. ATD head acceleration (aft passenger and child)
 - o Signal comprehensive error factor
 - Signal peak value(s)
 - Head injury criterion (derived)
- 2. ATD upper neck forces moments in the longitudinal vertical plane (aft passenger)
 - o Signal comprehensive error factor
 - Signal peak value(s)
- 3. ATD femur axial force (aft passenger)
 - Signal comprehensive error factor
 - Signal peak value(s)
- 4. ATD thorax acceleration (child)
 - Signal comprehensive error factor
 - Signal peak value(s)
- 5. CRS anchor loads (lap belt tension, ISOFIX and LATCH lower anchorage forces)
 - Signal comprehensive error factor
 - Signal peak value(s)

For model configurations with an adult seated behind a CRS, the level of validation of the aft adult head acceleration signal gives an indication of the fidelity of the global response of the model. This is due to the high level of validation of this parameter in the numerical ATD model and also its sensitivity to an assortment of input variables:

- Aft ATD kinematics
- Aft lap belt properties
- Tray table material properties
- Seat-base and seatback cushion material properties
- Seatback break-over behaviour
- CRS anchor properties

For model configurations designed to measure the baseline performance of the CRS (i.e. with no aft passenger), the child ATD head acceleration and CRS anchor load signals are equally useful in assessing the global response of the model.

The time period used for all signal validation was the full 150 ms numerical model test period. This method gives a good indication of the overall match between physical test and model output data; however, it also dilutes the effect of shape mismatch between signals during important short-duration events such as head impact. To overcome this to some extent, the head injury criterion (HIC) was used as a validation parameter. HIC is useful in this regard as it is highly sensitive to the head acceleration signal magnitude over a relatively small time period. In the case of the aft passenger, the HIC36 value was used in validation to allow direct comparison with results in the CASA report[2]. However, this is largely inconsequential as the HIC 'unlimited' time period was seldom greater than 20 ms and never greater than 36 ms.

2.4.5 Validation configurations and load cases

Seven of the configurations used in CASA physical testing were replicated. These were:

- Three CRS baseline configurations, where a CRS installed aft of an empty seat using the lap belt, ISOFIX and LATCH methods.
- Three aft passenger configurations, where a Hybrid III 50th percentile male ATD was seated behind a CRS installed using the lap belt, ISOFIX and LATCH methods.
- An aft passenger baseline configuration, where a Hybrid III 50th percentile male ATD was seated directly aft of an empty seat.

In each configuration, the seat pitch was 30 inches (0.762 m). Where a CRS was present, it was installed in its fully upright position and occupied by a TNO P3 three-year-old child ATD.

The acceleration pulse applied in each case was the sled acceleration signal from the associated CASA physical test.

2.4.6 Validation results

The results of the numerical model signal validation process are presented below. Two graphical examples are given in Appendix A.

The parameters exhibiting the highest level of validation are the ATD head acceleration signals for both the child and aft passenger, with a comprehensive error factor of less than 15% in all cases. Aft passenger upper neck force and moment validation results were quite spread out, with

comprehensive error factors of between 16% and 48%. The level of validation in the aft passenger femur axial force signals was generally very low. In each case (head, neck and femur) the level of validation seen in the numerical model is consistent with the results of numerical ATD validation and is therefore as high as can reasonably be expected.

The CRS anchor load signals generally exhibit a good level of validation.

2.4.6.1 CRS baseline configuration – Lap belt CRS

The CRS was installed using the aircraft seat lap belt only and occupied by a 3-year-old child ATD. The child head acceleration signal and the derived HIC36 value matched well with physical test data. The thorax acceleration signal matched test data to a reasonable degree; however, a spike in the model output resulted in the peak acceleration being over-predicted by 181%. The model under-predicted peak lap belt tension by 25%.

Table 2-2: CRS baseline configuration – Lap belt CRS signal validation results

Signal	C %	M _{pos} %	W _{pos} %	M _{neg} %	W _{neg} %
Child head acceleration	10.8	-6.9	100.0	N/A	N/A
Child thorax acceleration	28.4	181.1	100.0	N/A	N/A
Lap belt tension	28.8	-25.1	98.9	-100.0	1.1

Table 2-3: CRS baseline configuration - Lap belt CRS HIC validation results

Injury Parameter	Model	Physical test	Error
Child HIC36	494	475	3.9%

2.4.6.2 CRS baseline configuration – ISOFIX CRS

The CRS was installed using the ISOFIX method and occupied by a 3-year-old child ATD. The child head acceleration signal and the derived HIC36 value matched well with physical test data. The thorax acceleration signal matched well with test data. The peak lower anchorage peak horizontal force was under-predicted by 6%, while the peak vertical force was over-predicted by 60%.

Signal	C %	M _{pos} %	W _{pos} %	M _{neg} %	W _{neg} %
Child head acceleration	5.2	-32.6	100.0	N/A	N/A
Child thorax acceleration	15.7	13.6	100.0	N/A	N/A
Lower anchorage net horizontal force	18.5	448.8	7.2	-5.9	92.8
Lower anchorage net vertical force	12.2	60.2	80.8	46.39	19.2

Table 2-4: CRS baseline configuration - ISOFIX CRS signal validation results

Table 2-5: CRS baseline configuration – ISOFIX CRS HIC validation results

Injury Parameter	Model	Physical test	Error
Child HIC36	440	528	-16.7%

2.4.6.3 CRS baseline configuration – LATCH CRS

The CRS was installed using the LATCH method and occupied by a 3-year-old child ATD. The child head acceleration signal and the derived HIC36 value did not agree as well with test data as in the lap belt and ISOFIX cases. The thorax acceleration signal matched well with test data. The lower anchorage net force was under-predicted by 27%.

Table 2-6: CRS baseline configuration – LATCH CRS signal validation results

Signal	C %	M _{pos} %	W _{pos} %	M _{neg} %	W _{neg} %
Child head acceleration	14.2	-7.0	100.0	N/A	N/A
Child thorax acceleration	23.3	0.2	100.0	N/A	N/A
Lower anchorage net horizontal force	25.3	-25.7	96.9	-92.8	3.1
Lower anchorage net vertical force	29.5	-34.3	97.6	-70.9	2.4

Table 2-7: CRS baseline configuration - LATCH CRS HIC validation results

Injury Parameter	Model	Physical test	Error
Child HIC36	368	557	-33.9%

2.4.6.4 Aft passenger configuration – Lap belt CRS

A Hybrid III 50th percentile male ATD was seated behind a CRS which was installed using the lap belt and occupied by a 3-year-old child ATD. The child head acceleration signal did not match physical test data as closely as in the corresponding CRS baseline configuration, with HIC36 being over-predicted by 55%. The aft passenger head acceleration signal exhibited a close match with physical test data. Upper neck signals gave mixed results; the fore-aft moment signal matched well with test data, while axial and shear forces did not. Femur axial force signals

generally did not match well with test data; however, peak femur compression values were predicted well.

Signal	C %	M _{pos} %	W _{pos} %	M _{neg} %	W _{neg} %
Child head acceleration	19.2	-1.7	100.0	N/A	N/A
Aft passenger head acceleration	3.3	-4.6	100.0	N/A	N/A
Aft passenger upper neck axial force	43.8	-26.3	53.2	-45.6	46.8
Aft passenger upper neck longitudinal shear force	32.9	34.8	36.8	-17.1	63.2
Aft passenger upper neck fore-aft moment	22.5	100.6	5.8	-9.9	94.2
Aft passenger femur axial force, left	107.5	175.2	38.9	11.3	61.1
Aft passenger femur axial force, right	142.5	211.6	38.7	-1.5	61.3
CRS anchor lap belt tension	28.1	-32.4	100.0	N/A	N/A

Table 2-8: Aft passenger configuration - Lap belt CRS signal validation results

Table 2-9: Aft passenger configuration - Lap belt CRS HIC validation results

Injury Parameter	Model	Physical test	Error
Child HIC36	404	261	54.8%
Aft passenger HIC36	1720	1714	0.4%

2.4.6.5 Aft passenger configuration – ISOFIX CRS

A Hybrid III 50th percentile male ATD was seated behind a CRS which was installed using the ISOFIX method and occupied by a 3-year-old child ATD. The child head acceleration signal matched physical test data quite well; however, HIC36 was over-predicted by 23%. The aft passenger head acceleration signal matched very closely with test data. Upper neck force and moment signals matched reasonably well with test data, while femur axial force signals did not. The physical test signal for the aft passenger left femur axial force in this configuration exhibited an anomaly early in the test. The time period used in the validation of this parameter was adjusted to exclude the anomaly; however, the general fidelity of the physical test signal is questionable.

Table 2-10: Aft passenger configuration - ISOFIX CRS signal validation results

Signal	C %	M _{pos} %	W _{pos} %	M _{neg} %	W _{neg} %
Child head acceleration	12.9	4.4	100.0	N/A	N/A
Aft passenger head acceleration	5.3	2.4	100.0	N/A	N/A
Aft passenger upper neck axial force		-23.9	62.3	-0.6	37.7
Aft passenger upper neck longitudinal shear force	22.0	61.0	23.6	-34.0	76.4
Aft passenger upper neck fore-aft moment	15.5	3.7	7.8	-18.4	92.2

Aft passenger femur axial force, left	67.8	-86.5	45.6	-76.6	54.4
Aft passenger femur axial force, right	49.1	5.3	32.2	-37.7	67.8

Table 2-11: Aft passenger configuration - ISOFIX CRS HIC validation results

Injury Parameter	Model	Physical test	Error
Child HIC36	422	344	22.7%
Aft Passenger HIC36	1653	1651	0.1%

2.4.6.6 Aft passenger configuration – LATCH CRS

A Hybrid III 50th percentile male ATD was seated behind a CRS which was installed using the LATCH method and occupied by a 3-year-old child ATD. The child head acceleration signal matched physical test data reasonably well; however, HIC36 was over-predicted by 43%.

The aft passenger head acceleration signal and HIC36 score exhibited a lower level of agreement with test data than in the lap belt and ISOFIX CRS aft passenger configurations. In physical testing, the aft passenger head acceleration signal for this configuration exhibits a sharp peak (indicated by the arrow in Figure 2-16) approximately 6 ms after the initial peak resulting from contact with the tray table.



Figure 2-16: Aft passenger head acceleration signals for LATCH and ISOFIX CRS configurations

Review of the film footage of this test suggests that this secondary peak, which is present in the model but to a smaller degree, is likely to be due to the tray table penetrating the seat back and making contact with the CRS. This idea is supported by the image below in which the position of the aft passenger head is overlaid at the time of this secondary peak.



Figure 2-17: Overlaid position of aft passenger head at time of peak acceleration in LATCH configuration

Upper neck force and moment signals generally did not match well with physical test data, with the exception of the peak extension moment. The femur axial force signals did not match well with test data.

Signal	C %	M _{pos} %	W _{pos} %	M _{neg} %	W _{neg} %
Child head acceleration	12.9	17.1	100.0	N/A	N/A
Aft passenger head acceleration	9.4	4.7	100.0	N/A	N/A
Aft passenger upper neck axial force	56.4	-27.0	50.5	24.2	49.5
Aft passenger upper neck longitudinal shear force	40.4	51.0	51.9	-21.3	48.1
Aft passenger upper neck fore-aft moment	47.7	144.8	25.5	0.4	74.5
Aft passenger femur axial force, left	61.7	-15.3	57.0	-66.9	43.0
Aft passenger femur axial force, right	124.5	226.9	34.5	-60.6	65.5

Table 2-12: Aft passenger configuration - LATCH CRS signal validation results

Injury Parameter	Model	Physical test	Error	
Child HIC36	329	230	43.0%	
Aft passenger HIC36	1779	2025	-12.2%	

Table 2-13: Aft passenger configuration - LATCH CRS HIC validation results

2.4.6.7 Aft passenger baseline configuration

A Hybrid III 50th percentile male ATD was seated behind an empty seat. The aft passenger head acceleration signal matched well with test data; however, HIC36 was over-predicted by 17%. The upper neck force and moment peak values generally matched well with test data. A low level of agreement was found in the femur axial force signals.

Table 2-14: Aft passenger baseline configuration validation results

Signal	C %	M _{pos} %	W _{pos} %	M _{neg} %	W _{neg} %
Aft passenger head acceleration	5.7	-21.3	100.0	N/A	N/A
Aft passenger upper neck axial force	11.3	161.1	3.9	-14.3	96.1
Aft passenger upper neck longitudinal shear force	31.6	-29.5	99.3	2813.1	0.7
Aft passenger upper neck fore-aft moment	41.0	542.3	5.2	3.8	94.8
Aft passenger femur axial force, left	70.7	144.2	28.7	-28.8	71.3
Aft passenger femur axial force, right	95.4	131.8	29.1	-18.9	70.9

Table 2-15: Aft passenger baseline configuration HIC validation results

Injury Parameter	Model	Physical test	Error
Aft passenger HIC36	1535	1313	16.9%

3 Analysis and results

3.1 Overview

This section details the method and results of the experiments designed to answer the research questions posed in section 1.1. Results should be read in light of the level of validation indicated in section 2.4; where no validation information exists for a particular parameter, results should be treated as being 'indicative' only.

All model output signals were filtered according to SAE J211-1[24].

3.1.1 Load case

The sled deceleration pulse applied in all model experiments was representative of a typical pulse applied in physical testing, with a peak of 21.5 g occurring at 43 ms and total velocity change of 14.5 m·s⁻¹ (see Figure 3-1). The pulse was applied as a prescribed acceleration of the joint connecting the sled to the reference space with roll, pitch and yaw values of zero. The sled floor was undeformed.



Figure 3-1: Sled longitudinal deceleration pulse applied in all model experiments

3.1.2 Basic configuration

Unless otherwise specified:

- Experiments were conducted with a row-to-row pitch of 30 in (0.762 m).
- The CRS referred to is the forward-facing CRS described in sections 2.2.5 and 2.3.2.3.
- The CRS, where present and occupied, was occupied by a TNO P3 3-year-old ATD.
- The aft passenger, where present, was a Hybrid III 50th percentile male ATD.

3.1.3 Model execution

Analyses were run on the RMIT University high-performance computing cluster. A typical analysis required approximately five hours to solve on a single node consisting of two quad-core AMD Opteron 2.3 GHz CPUs and 32 Gb RAM.

3.2 Effect of CRS installation method on CRS and seatback motion

3.2.1 Description of analysis

The purpose of this series of experiments was to analyse:

- The translation and rotation behaviour of CRS installed using the lap belt, ISOFIX and LATCH.
- The corresponding effect on seatback rotation.

The CRS were installed in the aircraft seat in their corresponding reference positions (see section 2.2.5) and occupied by a TNO P3 numerical ATD. An empty seat was placed in front at a pitch of 30 inches (0.762 m). Two reference points on the CRS body (see Figure 3-2) were used to assess translational and rotational motion. The lower point was chosen as it gives a good indication of whether the CRS base is at risk of sliding off the seat base cushion, while the upper point was chosen as it is generally the first (and sometimes only) point of contact between the CRS and the seatback.

For all tests, the rotation of the forward and aft seatbacks was controlled by the energy absorber described in 2.3.2.2. A baseline test was carried out in order to measure seatback rotation behaviour for the case of an empty seat (i.e. no CRS or other occupant present).



Figure 3-2: CRS reference points

3.2.2 Results and discussion

3.2.2.1 CRS translation

Each of the three installation methods resulted in greatly different translational motion behaviour. Figure 3-3 presents a comparison of the maximum forward translation of the CRS lower reference point for the lap belt, ISOFIX and LATCH cases.



Figure 3-3: Effect of CRS installation method on CRS forward translation

The greatest forward translation was observed in the lap belt case. By contrast, the LATCH case resulted in forward translation of approximately half of the value measured in the lap belt case. This difference is attributable to the more-favourable belt angle associated with the LATCH installation, approximately 50° above horizontal compared with the 72° belt angle associated with the lap belt installation. The effect of belt angle is also evident in Figure 3-4, which plots the path prescribed by the CRS lower reference point for each of the three configurations.

The small forward translation observed in the ISOFIX configuration is a result of the deformation of the lower anchorage bar and rigid-body rotation of the CRS about the ISOFIX loops.



Figure 3-4: Comparison of CRS translational motion associated with lap belt, ISOFIX and LATCH installation methods

3.2.2.2 CRS rotation

Each of the three installation methods resulted in different CRS rotation behaviour. The ISOFIX method effectively constrained the CRS to rotation about the ISOFIX loops, with very little vertical motion of the pivot point, resulting in the high level of forward rotation observed.



Figure 3-5: Effect of installation method on maximum CRS forward rotation

The translation allowed by the lap belt leaves less of the CRS base in contact with the base cushion; the CRS is therefore less-supported in the vertical direction and more able to rotate forwards. This effect occurs to a much lesser extent in the LATCH case, with a corresponding lower level of forward rotation.

3.2.2.3 CRS general motion

Each of the three installation methods restrained the CRS sufficiently to keep it in place on the aircraft seat base cushion. The motion of the CRS upper reference point was used to assess the combined effect of CRS translation and rotation on seatback motion. The displacement of this point in the forward direction is plotted in Figure 3-6.



Figure 3-6: CRS upper reference point forward displacement

Figure 3-6 illustrates three important points:

- 1. The LATCH installation method is associated with a substantially smaller forward displacement of the upper aft edge of the CRS than the other two methods.
- 2. The ISOFIX installation method does not result in significantly smaller displacement of the upper aft edge of the CRS than the lap belt method.
- 3. The lap belt and LATCH methods both exhibit rebound motion to a greater extent than the ISOFIX method.

While the simulation time period of the numerical model was not long enough to fully capture the rebound behaviour of the CRS, the indication in Figure 3-6 of more-severe rebound effects associated with the lap belt and LATCH methods is consistent with the findings in physical testing[2]. This indicates that the ISOFIX method is associated with better dissipation of CRS kinetic energy.

During deceleration, restraining forces are applied to the CRS by the aircraft seat. The two mechanisms for this are the direct contact between the CRS and the aircraft seat base cushion and a force transmitted through the CRS installation hardware (i.e., the lap belt, the lower anchorage, and the LATCH belt-ISOFIX bar combination). The application of this restraining force leads to:

- 1. *Compression of the seat base cushion*. At the high compressive strain rates associated with this scenario, the foam comprising the cushion exhibits hysteretic behaviour. This means that a significant amount of the CRS kinetic energy transferred to the seat base cushion is dissipated.
- 2. *Elongation of the webbing belt in the lap belt and LATCH cases.* Webbing belts generally exhibit a degree of elasticity at low strain levels, meaning that CRS kinetic energy transferred to the belt will reappear as kinetic energy (and therefore CRS motion) once the peak forwards inertial force on the CRS has passed.
- 3. Deformation of the lower anchorage bar in the ISOFIX and LATCH cases. The permanent deformation seen in the physical tests and numerical model indicates that this is partially dissipative.
- 4. Other small-scale deformation. Small-scale deformation occurs in the aircraft seat structure and sled deceleration system but is not significant to the overall motion of the CRS.

In light of the above points, the better rebound behaviour observed in the ISOFIX case may be attributed to the degree of kinetic energy dissipation inherent to that installation method as a result of:

- 1. The rigid connection to the lower anchorage bar, as opposed to the use of a webbing belt.
- 2. The plastic deformation of the lower anchorage bar.
- 3. The motion of the CRS inherent to this method leading to greater compression of the seat base cushion.

3.2.2.4 Seatback motion

CRS installed by each of the three methods limited seatback rotation to within half of the range observed in the baseline (empty seat) case. High-speed footage from the physical tests and animation from the numerical model both indicate that the location of the CRS upper reference point was generally the first, and sometimes only, point of contact between the CRS and the seatback. Comparison of time history plots of the forward displacement of this point (Figure 3-6) and seatback angular displacement measured at the 'free' hinge (i.e. without energy absorber) (Figure 3-7) for each of the three installation methods indicates that these two parameters are closely linked: greater displacement of this point allows greater seatback motion.



Figure 3-7: Forward rotational displacement of seatback (measured at free hinge)

In the LATCH case, the seatback initially rotates forward to within approximately 5° of the maximum value for the lap belt and ISOFIX cases. However, this is largely due to elastic deformation in the seatback frame. The frame returns to its normal shape after initial contact with the CRS, resulting in a forward rotation of approximately 17°, 8° less than that observed in the lap belt and ISOFIX cases.

3.3 Effect of CRS installation method on child injury

3.3.1 Description of analysis

The child head, neck and chest injury results from the experiments in section 3.2 were analysed to determine the performance of the lap belt, ISOFIX and LATCH CRS installation methods in terms of injury to the child CRS occupant. Results were compared with the injury levels observed in 'baseline' configurations of the physical test and numerical model, where a modification was made to the energy absorber of the seat in which the CRS was installed to prevent seatback break-over.

Child neck injury results from physical testing were not available as the child ATD used did not have neck instrumentation fitted.

3.3.2 Results and discussion

3.3.2.1 Contact with forward seat

For each installation method, in both the physical test and the numerical model, the CRS combined rotation and translation was enough to allow the lower part of the child's legs to make contact with the forward seatback. Though generally minor in all cases, this is most pronounced in the lap belt CRS case (below).



Figure 3-8: Child lower leg contact with forward seat, lap belt CRS

3.3.2.2 Child head injury

The average child HIC score across all tests was 450. The minimum of 368 and maximum of 557 were seen in the ISOFIX and LATCH physical tests, respectively. These values are significantly

below the allowable limit of 1000 set out in FMVSS 213[28]. The lap belt method exhibited the least spread in HIC scores and resulted in an average of 395, while the average for ISOFIX was 10% higher at 434. The average HIC for the LATCH method was 520, 32% above that for the lap belt method.





3.3.2.3 Child neck injury

Child neck injury scores were all close to the critical level according to FMVSS 208. The critical neck injury mechanism in all cases was the tension-flexion combination.





3.3.2.4 Child thoracic injury

Figure 3-11 presents a comparison of model and physical test child thoracic injury results in terms of the greatest level of thorax acceleration with a cumulative duration of 3 ms or more. As was the case in the validation process, the match between model and physical test results was poor. Physical test results for each of the CRS installation methods indicated thorax acceleration level within the 60 g limit specified by FMVSS 213. Model results exhibited a wide variation, from 25% below the allowable limit in the ISOFIX case to 46% above in the lap belt case.



Figure 3-11: Child thorax acceleration (3 ms clip) results for lap belt, ISOFIX and LATCH CRS installation methods

3.4 Effect of CRS installation method on aft passenger injury

3.4.1 Description of analysis

To assess the effect of CRS installation method on aft passenger injury potential, a 50th percentile Hybrid III numerical ATD was seated directly aft of a seat in which a CRS was installed, at a seat pitch of 30 in. (0.762 m). The CRS was occupied by a TNO P3 3-year-old numerical ATD. The CRS installation methods tested were the aircraft seat lap belt, ISOFIX and LATCH.

The results from this configuration were compared with those from a baseline configuration in which the forward seat was empty. The injury mechanisms investigated were head acceleration (HIC), neck axial force and fore-aft moment (Nij), femur compression and tibia bending. Model results for head, neck and femur injury were compared with physical test results.

It should be noted that the leg injury levels measured in the ISOFIX and LATCH cases are associated with the particular design modification made in the CASA investigation and are not necessarily inherent to the implementation of ISOFIX and LATCH lower anchorages.

3.4.2 Results and discussion

3.4.2.1 Aft passenger head injury

All CRS installation methods, as well as the baseline configuration without a CRS, resulted in aft passenger HIC scores significantly above the limit of 1000 set out in FAR 25.562.



Figure 3-12: Aft passenger head injury for lap belt, ISOFIX and LATCH CRS installation methods

In both the numerical model and physical test, the lap belt and ISOFIX methods resulted in similar HIC scores in the order of 1600-1700. The LATCH case resulted in the highest HIC score in both the numerical model and physical test, with values of 1779 and 2025 respectively. With reference to Figure 3-6, it has been shown that for the LATCH case, the CRS is in a significantly more-aft position at the time of aft passenger head impact with the tray table (approx 90-100 ms) than is observed in the lap belt and ISOFIX cases. For this reason, the tray table is effectively able to make contact with the CRS through the seatback fabric during aft passenger head impact. This contact force is transferred to the aft passenger head, resulting in the higher HIC score for the LATCH case.

3.4.2.2 Aft passenger neck injury

According to numerical model results, the critical neck injury mechanism in each case was the tension-extension combination. In the numerical model, the peak neck injury invariably occurred just prior to head impact. Upper neck moment generally became insignificant after impact, while axial force turned from tensile to compressive. In Figure 3-13, results from the ISOFIX physical test case are presented as an example. Upper neck axial force (A') and moment (M') are plotted as fractions of their critical values.



Figure 3-13: Fractions of critical values of upper neck axial force (A') and moment (M')

The 'step' observed in the neck moment signal at 80 ms is apparently an effect caused by the impact of the ATD's elbows with the forward armrests, as shown in Figure 3-14.



Figure 3-14: Aft passenger elbow impact with forward armrest, t = 80 ms

This elbow-to-armrest contact occurred for all CRS installation methods in both the numerical model and physical tests. This contact causes the ATD upper torso to be partially constrained in forward rotation prior to head impact. The effect of this on upper neck moment is evident in Figure 3-15, which compares the cases of an empty forward seat, an empty forward seat with no armrest, and the standard configuration with a CRS installed using ISOFIX. A comparison of these signals suggests that the peak in upper neck moment at approximately 90 ms is due solely to the elbow-armrest contact and is not a function of CRS installation method. It appears that the presence of a CRS in fact serves to reduce the magnitude of this peak.



Figure 3-15: Effect of elbow-forward armrest contact on neck upper moment

Numerical model neck injury scores were consistently lower than those found in physical testing. It is likely that this is an issue with the model; the validation process revealed that adult neck tensile force was consistently under-predicted by the model. Each of the physical tests resulted in a neck injury score above the critical level, including the baseline configuration with no CRS present.



Figure 3-16: Aft passenger neck injury results

3.4.2.3 Aft passenger femur compression

Neither the physical test nor numerical model data revealed any significant correlation between the presence of the lower anchorage bar (in the ISOFIX and LATCH cases) and aft passenger maximum femur compression. Each configuration resulted in a maximum femur compressive load well within the 2250 lbf (10 kN) limit set out in FAR 25.562, both in the physical test and the numerical model.



Figure 3-17: Aft passenger maximum femur compressive force results

3.4.2.4 Aft passenger tibia bending

Compared with the results from the lap belt case, the presence of the lower anchorage bar in the ISOFIX and LATCH cases did not appear to cause a significant increase in the maximum upper tibia bending moment. While there is no tibia injury component in FAR 25.562 or other relevant standards, tibia bending moment levels observed in all four cases (including baseline and lap belt cases, where the forward seat was unmodified) were found to be in the range of 250-350Nm where bone fracture may initiate[19].



Figure 3-18: Aft passenger upper tibia maximum resultant bending moment for lap belt, ISOFIX and LATCH CRS installation methods

3.5 Effect of empty CRS on aft passenger injury

3.5.1 Description of analysis

The mass of the TNO P3 3-year-old ATD (15 kg) is close to the maximum allowable occupant mass for the CRS (18 kg). During deceleration the CRS occupant exerts a force on the CRS in the forward direction, acting to 'pull' the CRS away from the rotating seatback. A smaller occupant would exert a smaller force being on the CRS, potentially leading to diminished seatback motion. To assess the effect of this on aft passenger injury potential, a 50th percentile male ATD was seated at 30 in. pitch directly aft of a seat containing an unoccupied CRS installed using the lap belt, ISOFIX and LATCH methods. These results were compared with the results of the analysis in section 3.4.

3.5.2 Results and discussion

3.5.2.1 Aft passenger head injury

The absence of the CRS occupant had a profound effect in all cases, leading to both increased and decreased aft passenger head injury level depending on CRS installation method. In each case, this was a result of reduced CRS motion causing a reduction in seatback rotation. The lap belt case is presented as an example in Figure 3-19, where the seatback rotation behaviour measured in this analysis is plotted with data from the baseline test described in section 3.2. For this particular case, seatback rotational displacement is approximately 5° less at the time of aft passenger impact on account of the CRS being empty.


Figure 3-19: Effect of the absence of the CRS occupant on seatback rotation, lap belt method

In the lap belt case, reduced seatback rotation resulted in the aft passenger's head impacting the very stiff structure at the top of the tray table and a corresponding extreme HIC score. This effect occurred to a lesser extent in the LATCH case, where HIC increased by approximately 50%. In the ISOFIX case, however, the reduction of the motion of the CRS and seatback was beneficial; the seatback was still rotating forward at the time of impact, and the level of rotation at this time was sufficient that the aft passenger's head impacted the relatively 'soft' centre of the tray table. This resulted in a decrease in HIC of approximately 30% compared with the case of an occupied CRS.



Figure 3-20: Effect of the absence of the CRS occupant on aft passenger head injury

3.5.2.2 Aft passenger neck injury

The effect of the absence of the CRS occupant on aft passenger neck injury was generally minor. It was most apparent in the LATCH case, where neck injury criterion was reduced by approximately 10%.



Figure 3-21: Effect of the absence of the CRS occupant on aft passenger neck injury

3.6 Effect of seat pitch on aft passenger injury

3.6.1 Description of analysis

The effect of seat pitch on aft passenger head and neck injury was investigated for configurations involving CRS installed using the aircraft lap belt, ISOFIX, and LATCH. Seven seat pitches were tested in the range of 28 - 34 inches (0.762 - 0.864 m) at intervals of 1 inch (0.0254 m). A 50^{th} percentile Hybrid III numerical ATD was placed in a seat directly aft of a seat in which a CRS was installed using one of the three aforementioned methods. The CRS was occupied by a TNO P3 3-year-old numerical ATD.

3.6.2 Results and discussion

3.6.2.1 Aft passenger head injury

In each configuration tested the aft passenger's head contacted the forward seatback, resulting in a HIC value greater than the critical value of 1000 defined in FAR 25.562. For the LATCH case at a pitch of 34", the tray table deformed to the extent that it was no longer supported by the seatback frame on one side. This resulted in a low HIC value for this configuration; however, the result is considered an anomaly. With the exception of this case, head injury was lowest in the ISOFIX case at a pitch of 31" with a HIC value of 1387. The lowest HIC value observed in the lap belt case was 1464 at a pitch of 32", while in the LATCH case the minimum of 1634 occurred at a pitch of 31".



Figure 3-22: Effect of seat pitch on aft passenger head injury

3.6.2.2 Aft passenger neck injury

Aft passenger neck injury was below the critical level for all seat pitches and all CRS installation methods except the 28" ISOFIX case. For all attachment methods, neck injury criterion values generally decreased with increased seat pitch, from approximately 0.9 at a pitch of 29" to approximately 0.7 at 33".



Figure 3-23: Effect of seat pitch on aft passenger neck injury

3.7 Effect of top tether on CRS motion and child injury

3.7.1 Description of analysis

Two series of experiments were conducted in order to determine the effect of top tether use on CRS motion and child injury. In the first series, no modification was made to the aircraft seat in which the CRS was installed (i.e., seatback break-over behaviour was controlled by the energy absorber described in section 2.3.2.2). In the second series, the energy absorber in the aft seat was made rigid to prevent the seatback from breaking over. This was done to determine whether such a modification is able to increase the effectiveness of the top tether.

In both series of experiments, the CRS was installed in the aircraft seat using the lap belt, ISOFIX and LATCH methods and occupied by a 3-year-old child ATD. The top tether routing was representative of a typical installation used in practice (see Figure 3-24 below).



Figure 3-24: Model representation of a typical top tether arrangement.

3.7.2 Results and discussion

3.7.2.1 CRS motion

In all experiments the lower part of the child's legs made minor contact with the forward seatback, as was the case in previous experiments where no top tether was used.

The implementation of a top tether was found to very slightly reduce the forward translation of the CRS lower reference point (Figure 3-2). A small further decrease in translation resulted from preventing the seatback from breaking over.



Figure 3-25: Effect of top tether on maximum forward translation of CRS lower reference point

The effect of preventing the seatback from breaking over was partially negated by the flexibility of the seatback frame; some elastic deformation of the seatback occurred due to tension in the top tether.

The implementation of a top tether resulted in a small decrease in CRS forward rotation in the lap belt and ISOFIX cases. In the LATCH case, however, the path of the top tether over the seatback head cushion led to increased CRS rotation. This behaviour was unique to the LATCH case and was an effect of the lower position of the CRS in the seat; in the lap belt and ISOFIX cases the seatback head cushion remains behind the CRS rather than above it.



Figure 3-26: Effect of top tether on maximum forward rotation of CRS

The effect of prohibiting seatback break-over was more evident in CRS rotation results, with reductions of 2-3° observed in the lap belt and ISOFIX cases. In the LATCH case, CRS rotation was reduced but still slightly greater than the result where no top tether was used.

3.7.2.2 Child injury

For the lap belt and ISOFIX cases, where the top tether served to slightly reduce CRS motion, child head injury was increased. The increase was slight for cases where the seatback was able to break over and the tether was largely ineffective. However, for the cases where seatback break-over was prohibited, HIC scores for the lap belt and ISOFIX cases increased by 30% and 17% respectively. For the LATCH case the top tether served to slightly increase CRS rotation, leading to a decrease in HIC.



Figure 3-27: Effect of top tether on child head injury

The effect of top tether use on child neck injury was minimal, except in the lap belt case with no seatback break-over where it resulted in a 16% increase in the value of the neck injury criterion. This may be attributed to the top tether decreasing CRS forward rotation by approximately 3° in this case.



Figure 3-28: Effect of top tether on child neck injury

3.8 Effect of aft passenger on child injury

3.8.1 Description of analysis

The results of the analyses described in sections 3.3 and 3.4 were compared in order to determine the effect of the aft passenger on injury to the child occupant of a CRS installed using the lap belt, ISOFIX and LATCH.

3.8.2 Results and discussion

For all three CRS installation methods, the presence of an aft passenger had the effect of decreasing child head injury. This effect was most apparent in the lap belt case, with a reduction in HIC of approximately 16%.



Figure 3-29: Effect of aft passenger on child head injury

Similarly, child neck injury was decreased in each case by the presence of an aft passenger. The greatest decrease observed was for the LATCH case, with a reduction in neck injury criterion of 17%.



Figure 3-30: Effect of aft passenger on child neck injury

Contact between the aft passenger and the forward seatback, beginning with the aft passenger's hands at approximately 70 ms, causes the forward seatback to rotate forwards and exert a force on the CRS. This in turn causes more forward rotation of the CRS than would otherwise occur and therefore a more gradual deceleration of the child's head; this effect is evident in Figure 3-31 below.



Figure 3-31: Effect of aft passenger on child head acceleration

3.9 Effect of aft passenger on ISOFIX and LATCH CRS anchor loads

3.9.1 Description of analysis

CRS anchor loads for the ISOFIX and LATCH configurations were measured by physical testing. Due to the size of the apparatus required to measure the loads, this was only possible in the CRS baseline configuration (i.e., without a passenger seated aft). The model was used to measure ISOFIX and LATCH CRS anchor loads in an aft passenger configuration with a 95th percentile male Hybrid III ATD. In all experiments, the CRS was occupied by a 3-year-old ATD and the aircraft seats were arranged at a pitch of 30". The results of these experiments were compared with physical test results and model results from the corresponding CRS baseline configurations (see section 3.2).

3.9.2 Results and discussion

By comparison with physical test results for the baseline configuration, the model peak net anchor force was lower by 15% in the ISOFIX case and 28% in the LATCH case. Compared to model baseline values, the 95th percentile male ATD caused an increase in peak net force of 17% in the ISOFIX case and 28% in the LATCH case.



Figure 3-32: Peak net force exerted on the lower anchorage by ISOFIX and LATCH CRS with and without 95th percentile male ATDs seated aft.

Plots describing the force exerted on the lower anchorage over the duration of each of the experiments described in this section are available in Appendix B.

4 Conclusions

A numerical model of a typical airline economy seating configuration involving forward-facing automotive child restraints was developed and validated against physical test data. The model was used to assess the crashworthiness of three CRS installation methods – the aircraft seat lap belt, ISOFIX and LATCH – under emergency landing dynamic conditions similar to those set out in FAR 25.562.

Conclusions are presented below as responses to the research questions posed at the beginning of the project. Numbers in parentheses refer to the specific experiment from which a particular conclusion was drawn.

4.1 What are the dynamic performance characteristics of CRS and what is the corresponding effect on the behaviour of the aircraft seat?

The lap belt, ISOFIX and LATCH CRS installation methods each limited CRS motion to a level that allowed the CRS to be effectively restrained on the aircraft seat under emergency landing dynamic conditions. The lap belt method allowed the greatest level of forward translation of the CRS. The forward translation associated with the LATCH method was approximately half of that measured in the case of the lap belt, while the forward translation associated with the ISOFIX method was insignificant. CRS forward rotation was lowest for the LATCH case, while the levels observed in the lap belt and ISOFIX cases were greater by factors of two and three respectively. The rebound motion associated with the lap belt and LATCH cases was found to be more significant than with the ISOFIX case as a result of the elastic effect of the webbing straps used in these installation methods. (3.2)

CRS installed using the lap belt, ISOFIX and LATCH methods each restricted maximum seatback rotational displacement to within half of the value observed for the case of an empty seat. The combined small forwards displacement and rotation in the LATCH case had the effect of restricting the forward rotation of the seatback to a much greater extent than the lap belt and ISOFIX cases. Seatback forward rotational displacement in the LATCH case was approximately 8° less than the value of approximately 25° measured in both the lap belt and ISOFIX cases. (3.2)

4.2 What is the injury potential for a child restrained in a CRS?

CRS installed using the lap belt, ISOFIX and LATCH methods each provided the child occupant with an adequate level of protection. Each installation method resulted in a relatively insignificant level of contact between the child's legs and the forward seatback. There was no significant trend in child head injury levels between the three installation methods; head injury criterion values were generally highest for the LATCH case and lowest for the lap belt case, with the average value for the ISOFIX case being slightly higher than that for the lap belt. (3.3)

Physical testing[2] found child thoracic acceleration levels to be within prescribed limits. Model results for child thoracic acceleration varied widely from corresponding physical test results and are considered to be unreliable. (3.3)

All three CRS installation methods tested resulted in child neck injury scores close to the critical level according to US motor vehicle safety standards. The reduced severity of CRS rebound behaviour associated with the ISOFIX method was not apparent in the peak head and neck injury levels of the child CRS occupant. (3.3)

The presence of a passenger seated directly aft of a CRS was found to cause a reduction in head and neck injury to the CRS occupant. The effect on head injury was found to be most substantial in the lap belt case, with a reduction in head injury criterion of 16%. The LATCH case resulted in the greatest effect on neck injury, with a reduction in neck injury criterion of 17%. (3.8)

4.3 Are current practices of top tether use effective in controlling CRS motion?

For the each of the three CRS installation methods tested, the use of a top tether had little or no benefit in terms of CRS motion or CRS occupant injury. The use of a top tether did not prevent the child's legs from making minor contact with the forward seatback for any case tested. The top tether was found to slightly decrease CRS motion for the lap belt and ISOFIX CRS installation methods when used in conjunction with a modification to prevent seatback break-over. The reduced CRS rotation associated with top tether use for these cases had the corresponding effect of increasing child head and neck injury; this was most pronounced for the lap belt case with an increase in head and neck injury criteria of 30% and 16% respectively. (3.7)

4.4 What is the injury potential for an adult seated directly aft of a CRS and how does this vary with seat pitch, CRS installation method and CRS occupant size?

Each test of the 50th percentile male aft passenger configuration, including the baseline configuration with an empty forward seat, resulted in aft passenger head injury above the critical level specified in FAR 25.562. This is likely due to the severity of the applied test pulse being in excess of that prescribed by this regulation and also the fact that the aircraft seats tested were not compliant with this regulation. At 30" pitch, the increase in head injury due to the presence of a forward-facing CRS occupied by a three-year-old child ATD and installed using the lap belt or ISOFIX methods was not excessive. Taking the average of the numerical model and physical test results for each configuration, the lap belt and ISOFIX methods resulted in a HIC approximately 17% above that of the baseline configuration, while for the LATCH case the increase was 35%. The higher head injury level associated with the LATCH case is due to the reduced seatback motion associated with this installation method. (3.4)

The effect of CRS installation method on aft passenger neck injury was difficult to determine due to interaction between the aft passenger elbows and the forward seat armrests. However, model and physical test results generally indicate that the presence of a CRS in the forward seat serves to lessen the severity of aft passenger neck injury. An exception to this was observed in the physical test of the ISOFIX case, where aft passenger neck injury was slightly above that measured in the physical test baseline configuration. (3.4)

Aft passenger femur compression results were well within prescribed limits for all configurations. Upper tibia bending was found to be severe enough to potentially cause bone fracture in all configurations, including the baseline and lap belt configurations where no modification had been made to the forward seat. (3.4)

Aft passenger head and neck injury levels were lowest for all CRS attachment methods in the range of seat pitches from 31-33". A comparison of the results of this experiment with the model baseline (i.e. empty forward seat) results from section 3.4 suggests that certain configurations may in fact serve to reduce both head and neck injury to the aft passenger. For example, the ISOFIX configuration at 31" pitch resulted in head and neck injury criterion values 8% and 20% lower, respectively, than the baseline configuration with no CRS at 30" pitch. All but one configuration resulted in decreased neck injury, with the greatest reductions of 31% and 26% observed in the 32" LATCH and 33" ISOFIX configurations, respectively. (3.6)

Experiment results supported the idea that, in terms of CRS occupant size, the complete absence of a CRS occupant represents the worst case for aft passenger injury potential. Compared to results obtained with the CRS occupied by a three-year-old ATD, the absence of a CRS occupant was found to significantly increase aft passenger head injury in the lap belt and LATCH cases. However, a reduction in HIC of 30% was found in the ISOFIX case. In all cases, the change in the level of head injury observed was due to the CRS limiting forward seatback rotation. This was clearly detrimental in the lap belt and LATCH cases, where head impact occurred in the stiff area at the top of the tray table. It was beneficial, however, in the ISOFIX case where more-subdued CRS motion caused head impact to occur at the centre of the tray table while it was still in forward motion. The effect of the absence of the CRS occupant on aft passenger neck injury was found to be generally insignificant. (3.5)

4.5 What are the loads imparted on the aircraft seat by ISOFIX and LATCH CRS and how are they affected by a passenger seated directly aft?

Physical testing found that the peak net force exerted on the lower anchorage by the CRS was approximately 10 kN for both the ISOFIX and LATCH cases in a 'baseline' configuration with no adult passenger seated aft[2]. Corresponding model experiments indicated a lower force magnitude for both cases: 8.4 kN for the ISOFIX case and 7.2 kN for the LATCH case. According to model results, the presence of a 95th percentile male ATD seated directly aft increased lower anchorage peak net force in the ISOFIX and LATCH cases by 17% and 28%, respectively. Scaling physical test results according to the conservative assumption that the model baseline results are in error, a 95th percentile male ATD seated directly aft of CRS installed by the ISOFIX and LATCH methods may result in a peak net force on the lower anchorage of approximately 12 kN and 13 kN, respectively. (3.9)

5 Recommendations

- The use of automotive child restraint systems in air transport should be promoted as a safe alternative to seating children on the lap of an adult.
 - Introduce a regulation preventing air transport operators from prohibiting the use of approved CRS, similar to United States FAR 121.311 paragraph (c)(2).
 - To facilitate the implementation of the above recommendation, introduce a set of approval criteria designed such that compliant CRS are compatible with and perform adequately in transport category aircraft seats (see sections 1.3.4 and 1.3.5).
 - The approval criteria development process should consider removing the requirement for the use of a top tether in air transport CRS installations.
- An adult passenger should not occupy a seat directly aft of a seat in which a CRS is installed. This need not limit the number of CRS able to be used at once on a given aircraft if a 'tiered' arrangement is implemented; e.g., CRS may be installed in seats directly forward of a bulkhead, and any additional CRS are installed directly forward of other CRS.

6 References

- 1. Bathie, M 2007, An investigation of automotive child restraint installation methods in transport category aircraft, Civil Aviation Safety Authority, Canberra.
- 2. Bathie, M 2009, An Investigation of Automotive Child Restraint Installation Methods in Transport Category Aircraft - Phase II, Civil Aviation Safety Authority, Canberra.
- 3. Olivares, G & Amesar, P 2007, *Implementation of ISOFIX and LATCH equipped automotive child restraint systems in an aircraft environment*, National Institute for Aviation Research, Wichita.
- 4. Gowdy, V & DeWeese, R 1994, *The performance of child restraint devices in transport airplane passenger seats*, Federal Aviation Administration Civil Aeromedical Institute, Oklahoma City.
- 5. Mohler, S R 1962, *Civil aeromedical research: Responsibilities, aims and accomplishments*, Federal Aviation Administration Civil Aeromedical Institute, Oklahoma City.
- 6. Civil Aviation Safety Authority 2009, CAO 20.16.3: Air service operations carriage of persons, Canberra.
- 7. Civil Aviation Safety Authority 2002, CAAP 235-2: Carriage and restraint of small children in aircraft, Canberra.
- 8. Tiger Airways 2011, *Children and infants*, [cited 2011 28/5]; Available from: <u>http://www.tigerairways.com/au/en/children and infant.php</u>.
- 9. Qantas Airways n.d., Information for Children and Infants when travelling on Qantas, [cited 2011 28/5]; Available from: <u>http://www.qantas.com.au/travel/airlines/travelling-with-children-infants/global/en</u>.
- 10. Jetstar Airways 2011, *Get on board*, [cited 2011 28/5]; Available from: <u>http://www.jetstar.com/au/en/Planning-and-Booking/Travelling-with-kids/Flying-</u> <u>With-Jetstar/Get-on-board</u>.
- 11. Virgin Australia Airlines n.d., *Travelling with Infants and Children*, [cited 2011 28/5]; Available from: http://www.virginaustralia.com/Personal/Flightinfo/BeforeYouFly/ TravellingwithInfantsandChildren/index.htm.
- 12. United States of America, 14 CFR 121.311: Seats, safety belts and shoulder harnesses, Washington, DC.
- 13. Gibson, T, Thai, K & Lumley, M 2006, *Child restraint in Australian commercial aircraft*, Australian Transport Safety Bureau, Canberra.
- 14. Hardy, R N 1990, Infant and child restraint research in European Cabin Safety Conference, Gatwick, UK: Civil Aviation Authority.
- 15. Standards Australia 2010, AS/NZS 1754:2010: Child restraint systems for use in motor vehicles, Sydney.
- 16. United States of America, 14 CFR 25.562: Emergency landing dynamic conditions, Washington, DC.
- 17. United States of America, 49 CFR 571.213: Child restraint systems, Washington, DC.
- 18. United States of America, 49 CFR 571.208: Occupant crash protection, Washington, DC.

- 19. Kerrigan, J R et al. 2003, *Experiments for Establishing Pedestrian-Impact Lower Limb Injury Criteria*, 2003 SAE World Congress, Detroit.
- 20. ASTM International 2008, *Standard Test Methods for Flexible Cellular Materials Made From Olefin Polymers*, West Conshohocken.
- 21. Bhonge, P 2008, A Methodology for Aircraft Seat Certification by Dynamic Finite Element Analysis, Wichita State University, Wichita.
- 22. Oberkampf, W L & Trucano, T G 2002, *Verification and validation in computational fluid dynamics,* Progress in Aerospace Sciences, **38**(3): p. 209-272.
- 23. AIAA 1998, Guide for the verification and validation of computational fluid dynamics simulations. Vol. AIAA-G-077-1998, Reston.
- 24. SAE International 2007, Surface Vehicle Recommended Practice J211-1: Instrumentation for Impact Test Part 1 Electronic Instrumentation, Warrendale.
- 25. Sprague, M A & Geers, T L 2003, Spectral elements and field separation for an acoustic fluid subject to cavitation, Journal of Computational Physics, **184**: p. 149-162.
- 26. Oberkampf, W L & Barone, M F 2006, *Measures of agreement between computation and experiment: Validation metrics,* Journal of Computational Physics, **217**(1): p. 5-36.
- 27. Schwer, L E 2007, Validation metrics for response histories: perspectives and case studies, Engineering with Computers, (23): p. 295-309.

7 Glossary and abbreviations

ATD	Anthropomorphic test device, or 'crash test dummy'
CASA	Civil Aviation Safety Authority, Australia
CRS	Child restraint system(s)
FAA	Federal Aviation Administration, United States of America
FAR	Federal Aviation Regulations, United States of America
FMVSS	Federal Motor Vehicle Safety Standards, United States of America
ISOFIX	A European standard CRS installation method, generally comprising two rigid prongs which attach a CRS to hard points located between the back and base of a vehicle seat
LATCH	A North American standard CRS installation method, generally comprising one or two webbing straps which attach a CRS to hard points located between the back and base of a vehicle seat
Lower anchorage	Hard points located between the back and base of a vehicle seat to enable the use of CRS meeting the ISOFIX and LATCH standards
Top tether	A webbing strap connecting a CRS to an anchor point, intended to limit CRS forward rotation
Transport category aircraft	In general, an aircraft with a passenger seating capacity of 20 or more.

8 Appendix A: Signal validation examples

Three representative model validation examples are presented below with a graphical comparison of signals and also the values of the validation metrics described in section 2.4.3.



8.1 Example one

Figure 8-1: Aft passenger head resultant acceleration, lap belt CRS case.

C = 3.3%	A comprehensive error factor of 3.3% indicates a good match between signals.
$M_{pos} = -4.6\%$	The simulation positive peak is smaller in magnitude than the physical test positive peak by a value of 4.6% of the physical test positive peak.
$W_{pos} = 100.0\%$	The magnitude of the physical test positive peak is 100% of the amplitude of the physical test signal.
$M_{neg} = N/A$	No part of the physical test signal is negative.
$W_{neg} = N/A$	No part of the physical test signal is negative.

8.2 Example two



Time (s)

Figure	8-2: At	ft passen	ger uppe	er neck axi	al force,	ISOFIX	CRS	case.
		1	0 II		,			

C = 28.1%	A comprehensive error factor of 28.1% indicates a reasonable match between signals.
M _{pos} = -23.9%	The simulation positive peak is smaller in magnitude than the physical test positive peak by a value of 23.9% of the physical test positive peak.
$W_{pos} = 62.3\%$	The magnitude of the physical test positive peak is 62.3% of the amplitude of the physical test signal.
$M_{neg} = -0.6$	The simulation negative peak is smaller in magnitude than the physical test positive peak by a value of 0.6% of the physical test negative peak.
$W_{neg} = 37.7$	The magnitude of the physical test negative peak is 37.7% of the amplitude of the physical test signal.

8.3 Example three



Time (s)

Figure 8-3	3: Aft pass	enger rig	ht femur	axial force	e, baseline	case.
	···· P ····				,	

C = 95.4%	A comprehensive error factor of 95.4% indicates a poor match between signals.
M _{pos} = 131.8%	The simulation positive peak is larger in magnitude than the physical test positive peak by a value of 131.8% of the physical test positive peak.
$W_{pos} = 29.1\%$	The magnitude of the physical test positive peak is 29.1% of the amplitude of the physical test signal. The positive peak is significant, but not as significant as the negative peak.
M _{neg} = -18.9	The simulation negative peak is smaller in magnitude than the physical test positive peak by a value of 18.9% of the physical test negative peak.
$W_{neg} = 70.9$	The magnitude of the physical test negative peak is 70.9% of the amplitude of the physical test signal.

9 Appendix B: ISOFIX and LATCH CRS anchor loads

The ISOFIX and LATCH CRS anchor loads measured in the analysis detailed in section 3.9, plus some additional experiments with a 50th percentile male Hybrid III ATD, are presented below. The horizontal and vertical components of the net external force acting on the lower anchorage over the duration of the experiment are plotted as Cartesian pairs. The horizontal force is positive in the forward direction, while the vertical force is positive upwards. Four sets of results are presented for both the ISOFIX and LATCH cases: physical test baseline, model baseline, model with 50th percentile male ATD seated aft, and model with 95th percentile male ATD seated aft.



Figure 9-1: ISOFIX baseline configuration, physical test.



Figure 9-2: ISOFIX baseline configuration, model result.



Figure 9-3: ISOFIX aft 50th percentile ATD configuration, model result.



Figure 9-4: ISOFIX aft 95th percentile ATD configuration, model result.



Figure 9-5: LATCH baseline configuration, physical test.



Figure 9-6: LATCH baseline configuration, model result.



Figure 9-7: LATCH aft 50th percentile ATD configuration, model result.



Figure 9-8: LATCH aft 95th percentile ATD configuration, model result.