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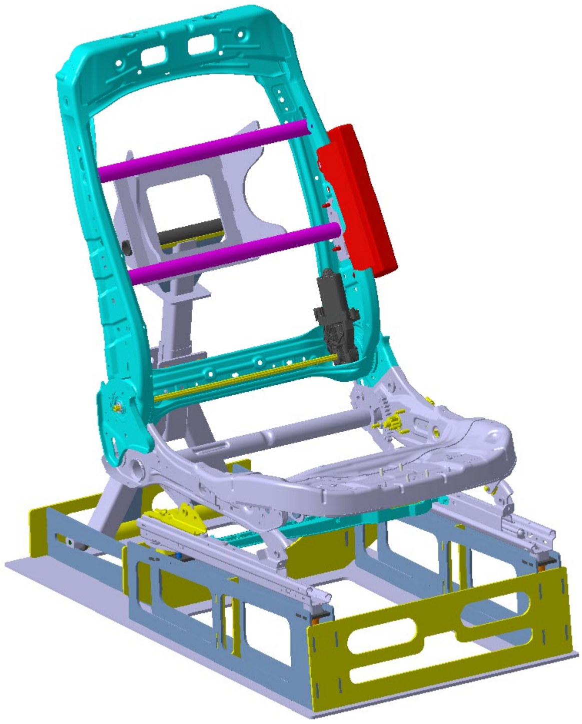

Development of a Reusable Front Seat Rig for Enhancing Sustainability in Airbag Testing

A product development project to reduce the number of seats consumed in side airbag testing

Master's thesis in Product Development

Johannes Lindholm
Jonathan Viktorsson

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
www.chalmers.se

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JOHANNES LINDHOLM
JONATHAN VIKTORSSON

Chalmers supervisor: Mohammad Arjomandi Rad, Industrial and Materials Science
Volvo Cars supervisors: John Eriksson & Robert Landholm, Airbags & Steering Wheels
Examiner: Ola Isaksson, Industrial and Materials Science

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Department of Industrial and Materials Science
Division of Product Development
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: 3D model of proposed rig concept.

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Abstract

Physical testing is a necessity in the development of cars today. Regarding safety systems such as the side airbag mounted in the front seat, the test material is currently only used for one test, despite only parts of it being damaged. The quantitative testing performed is thus wasteful. With increased global development and front loading of development projects, the problem is increasingly important.

This master thesis covers the development of a front seat rig for airbag testing. The goal was to reduce material waste and thus improve testing activities in terms of cost and sustainability. This report details the process of customer needs elicitation, concept development and design, and evaluation of the proposed rig. To confine the design space, testing of design variable effects on dummy responses was performed and showed that breakthrough material and seat stiffness did not impact dummy results to a large extent.

The concept development combined traditional product development methods with model-based methods, such as finite element analysis and topology optimisation. Various solutions were ideated and subsequently screened down to a final solution. After a concept was agreed upon, the detailed design work was performed in iterations with input from senior design and design optimisations performed in Optistruct. The result is a design that fulfils the requirements of durability while being able to cover the full range of motion of the seat, also called a travel box, in an easy manner. The proposed rig could cut testing costs by 86% and reduce the CO_2 emissions by 90% measured over 100 tests compared to the current way of testing.

Keywords: Airbag, testing, repetitive, re-usable, rig, occupant safety, SAB, seats, OOP, Out of position

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We, the authors of this thesis, would like to express our deepest gratitude to our supervisors, John Eriksson and Robert Landholm, at the Airbags & Steering Wheels team at Volvo Cars. This project would not have been possible without you. Thank you, John; you have been at the centre of this project, provided guidance and support throughout, and connected us with knowledgeable people across Volvo Cars. Thank you, Robert, for your patience and wisdom, providing us with invaluable input for the design and ways of working. We would also like to extend our gratitude to the rest of our colleagues at Airbags & Steering Wheels not only for all of your help and input and for making our time at Volvo Cars pleasant. Furthermore, thanks to all of you at Seats, Safety Centre, Crash Test Lab and Weight Reduction at Volvo Cars who have been involved in this project.

Finally, we express our gratitude to our supervisor, Mohammad Arjomandi Rad, and our examiner, Ola Isaksson, from Chalmers. Your assistance in defining the project and your guidance throughout the thesis have been invaluable. Your input was particularly crucial in shaping the report, and we are grateful for your contributions.

Johannes Lindholm, Jonathan Viktorsson, Gothenburg, June 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ATD	Anthropomorphic test device
CAB	Curtain Airbag
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CFC	Channel Frequency Class
CO_2	Carbon Dioxide
FSAB	Far-Side Airbag
IIHS	Insurance Institute for Highway Safety
LCA	Life Cycle Assessment
OOP	Out Of Position
SAB	Side Airbag
SIPS	Side Impact Protection System
SPC	Single Point Constraint
TWG	Technical Working Group (Side Airbag OOP Injury)
VCC	Volvo Car Corporation

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables that have been used throughout this thesis.

Indices

$A - surface$	Surface, that has design intent, that is either seen, touched, or both
$RBE3-element$	A rigid element type used in Optistruct to connect one or multiple independent nodes to a single dependent node without contributing to stiffness
Recliner	The advanced joint in the seat structure that allows for seat-back angle adjustment
Substructure	The structure that connects the seat to the floor
$TIE - element$	A element type used in Optistruct that enforces zero relative motion between two surfaces
$Tophat$	Vehicle interior
t	Index for time step
travelbox	A 2D visualisation of all possible positions of the seat pan
$Xdirection$	The direction of front and backwards travel, relative to the driver
$Ydirection$	The direction of sidewards travel, relative to the driver
$Zdirection$	The direction of up and down travel, relative to the driver

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1
Introduction

The current method for the development and implementation of airbags at Volvo Car Corporation (VCC) requires extensive physical testing to guarantee correct behaviour and is, because of this, resource-intensive in terms of time, cost and material resources.

1.1 Background

Airbags are normally integrated into the vehicle interior, breaking through their cover upon deployment [1]. For seat airbags, this means that at least part of the seat is destroyed during testing as the airbag breaks through its cover. Today, a completely new seat is used for each test to maintain the setup. For the particular case of Out Of Position (OOP) testing, which is done to ensure the safety of the side airbag for smaller occupants such as children and in particular when said children sit incorrectly or "out of (normal) position". Physical testing is required for the OOP evaluation even in early development phases due to insufficient maturity of the digital models [2]. All in all, hundreds of seats can be consumed during development of a new vehicle platform [2].

In 1994, Volvo Cars introduced a side airbag integrated into the seat's backrest to protect the occupant in the case of a lateral collision [3]. Side airbags have since proven to be an effective way of reducing injuries and casualties [4][5][6]. However, due to the rapid inflation that occurs during airbag deployment, in the range of 8-10 ms for side airbags (SABs), it is also possible to sustain injuries from the airbag deployment itself [7]. To mitigate this, guidelines for testing and evaluating occupant injury risk have been developed [8]. This type of testing is normally called Out of Position (OOP), as the dummies sit in unconventional positions with no safety belts.

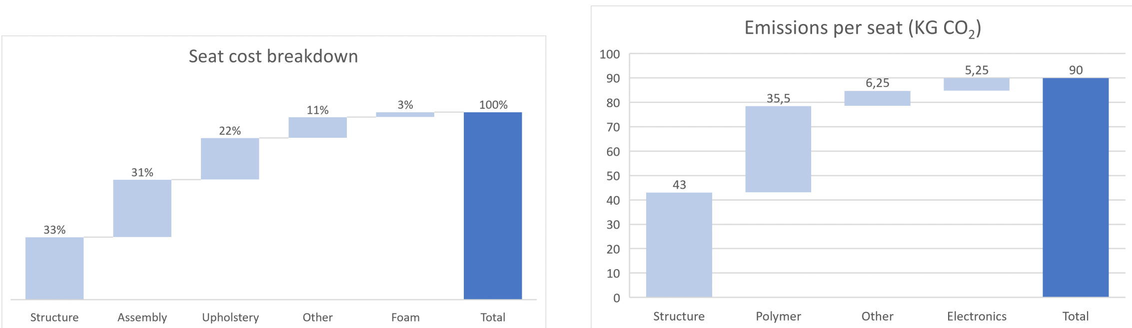
A manufacturer's agreement as part of an alliance based in the USA is in place [9], making the OOP testing an in-explicit requirement for all car producers with plans to sell in the US-market [2]. This means that testing and evaluating OOP is essential to developing seat airbags. A figure from the Technical Working Group (TWG) procedures [8] can be seen in *Figure* 1.1.

(a) OOP position 3.3.3.5 **(b)** OOP position 3.3.3.6

Figure 1.1: OOP positions example (from [8])

A seat is a complex product containing many components that may not affect the airbag's deployment (e.g., electric adjustment and massage functions). The material and production of seats during prototyping are extremely expensive. However, purchasing custom bare-bone seat structures from suppliers for VCC can be even more costly than buying the complete seat. An increase in global development means that the seats may also have to be shipped long distances, worsening the cost and emissions problem. A cost and emission breakdown of a prototype seat can be seen in *Figure* 1.2.

These things make deployment testing of seat airbags costly, wasteful, and unsustainable. Thus, VCC recognises the need for a test rig that acts similarly to real seats in airbag testing but can last more than one deployment. It would save substantial amounts of time and money, as well as reduce material waste, increasing the sustainability of the development phase.



(a) Cost breakdown of a seat **(b)** Current emissions per seat

Figure 1.2: Current costs & emissions breakdown of one seat, figures from *Chapter 4.10*

1.2 Goal & Purpose

The thesis aims to, during the spring semester of 2024, develop and design a generic reusable seat rig for out-of-position side airbag testing. To reduce the number of pre-production seats consumed in airbag testing, thereby reducing costs and environmental impact in development.

1.3 Problem Formulation

The rig should, in some way, be more durable than a normal seat and last for many airbag deployments. Durability should be improved by altering and simplifying the existing seat structure and components. The influence of the various parts of the seats must be understood to define the design and solution space for the rig. At a high level, the seat may be divided into: ***Seat frame structure***, ***Foam Padding***, and ***Upholstery***(fabric or leather cover). All these parts may affect the testing results, but precisely how and to what extent is not currently known. Some key research questions to be answered at the end of the project are:

RQ1: What prevents the seats from being reused in testing?

RQ2: What impact do the main components of structure, foam and upholstery have on the test results?

RQ3: What would a rig for testing side airbags without consuming a full seat for every deployment look like?

RQ4: What impact in terms of emissions and economy could a "rig" solution have compared to the current method?

1.4 Scope

The expected result is a proposed design for a front-seat rig. If possible, within the given time constraints, a prototype will be constructed. The final rig design will only consist of the seat rig, which can then be placed in existing car interior environment rigs.

1.5 Delimitations

- The rig will not be completely generic in the sense that it could be used for any car. The rig will be developed for one product platform and is intended to be used for development projects using that platform.

- To comply with confidentiality agreements the development work will be based on a seat already installed in Volvo Car products rather than current development projects.

- The rig will be developed for airbag testing. Other use cases, such as testing of upholstery concepts and their effect on airbag deployment, will not be developed. However, if possible, input from different stakeholders will be considered to simplify future work adapting the rig to other use cases.

- Currently, only OOP testing of the SAB is considered. Other SIPS components that require OOP testing (FSAB, CAB) will not be considered.

- Only the influence of the various parts of the seats will be examined. Other factors that might affect the testing, such as surrounding support surfaces, will not be examined.

2

Frame of Reference

This chapter presents an overview of topics discussed in this thesis. Topics include airbags, seats, and their testing, as well as product development methodologies.

2.1 Airbags

Airbags are used in cars to protect occupants by providing an energy-absorbing surface between the occupants and the car's interior or objects outside the car in the event of a collision [10]. Airbags can be implemented in many ways to account for different crash conditions [1].

The moment car sensors detect a crash, the crash's speed and direction are calculated. Depending on the direction and how quickly the impact happens, some airbag inflators may get an ignition signal that activates a gas generator, which pressurises the airbag with gas within milliseconds [1].

Side airbags are implemented to act in side crashes and spread the load of impact forces that might come from contacting the head and ribs into the car's interior [1]. Since the occupant sits very close to the side of the vehicle, the side-acting airbags must inflate extremely fast and are usually fully deployed before 20 milliseconds [1].

Torso-acting side airbags are placed in the side of the seat and inflate between the door panel and the occupant. This type of airbag reduces chest injuries by about 25% [11]. In a study of American data from real side crashes between 1999 and 2004, the car driver death risk was reduced by 26 percent by torso-only side airbags [4].

In the first generations of airbags, the force of deployment was very high and could, in poor circumstances, such as the driver sitting too close to the steering wheel, be a cause of injury [1]. The problem has been a target of improvement for many years, and the OOP testing being done today is to avoid these kinds of injuries [8].

2.2 (Front) Seats

The front seat in a modern car is a relatively complex product containing hundreds of components. A simple high-level breakdown can be seen in *Figure* 2.1 & *Table* 2.1.

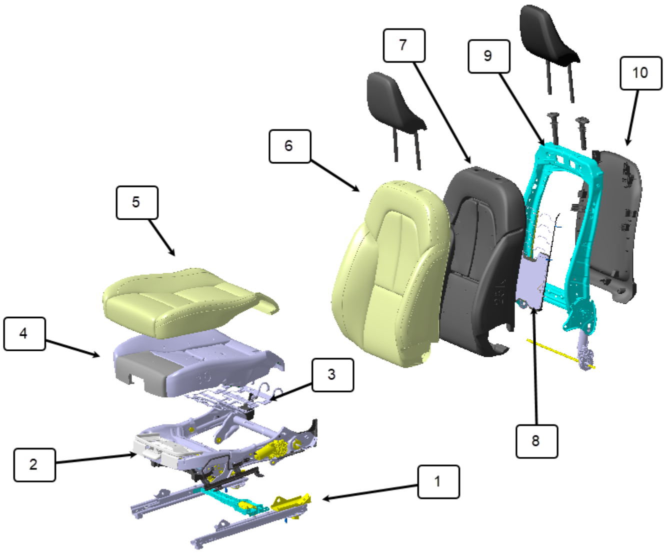


Figure 2.1: Exploded view of a front seat

No	Part
1	Rail
2	Seat pan
3	Suspension mat
4	Cushion padding
5	Cushion upholstery
6	Backrest upholsery
7	Backrest padding
8	Suspension mat
9	Seat back frame
10	Hardback

Table 2.1: Simplified bill of material for front seat

The main purpose of the seat is to provide seating for the occupant. The seat shown in particular is the seat from a Volvo XC40. This seat has adjustments for length, height, tilt and recline. The travel box is an imaginary visualisation of the seat pans' complete range of motion, which can be seen in red in *Figure* 2.2.

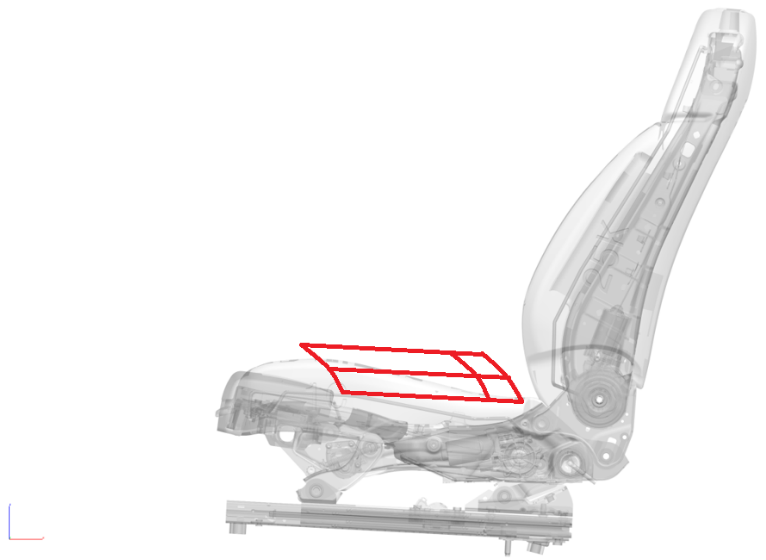
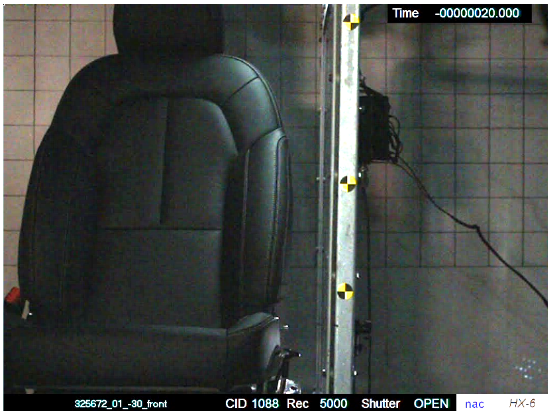
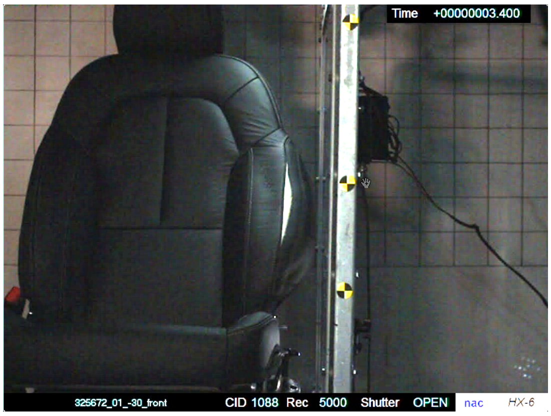


Figure 2.2: Seat travel box (In red)

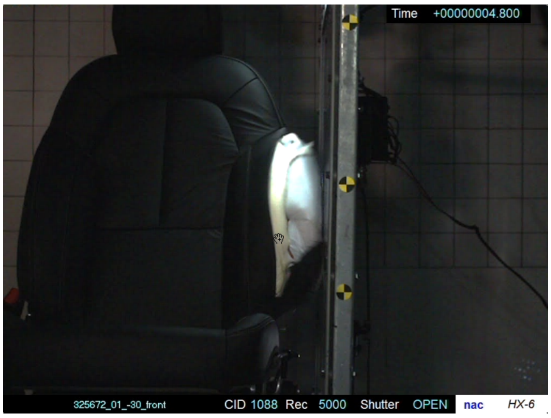
As the SAB is normally integrated into the seat, a solution must be implemented to allow it to break out of the seat. The most common way to implement this is by employing a tear or SIPS seam. The tear seam is a weakened part of the upholstery that tears open upon airbag deployment—allowing the airbag to position and function as intended. A typical sequence of events can be seen in *Figure* 2.3.



(a) Closed tear seam



(b) Tear seam beginning to rupture



(c) Tear seam nearly completely open

(d) Airbag in position

Figure 2.3: Stages of tear seam opening during airbag deployment

2.3 Testing in Development of Airbags

Product development is an iterative process of designing, building and testing. In literature, this activity is referred to as design-build-test cycles [12]. The testing activities might either be physical or utilise modelling and simulations. Airbag development, like most product development, follows a similar development process. The seat and side airbag development can utilise both physical and model-based development. For the application brought up in this thesis, side airbag OOP testing, only physical testing is used currently by Volvo Cars and its suppliers due to low maturity in CAE models for this purpose.

2.3.1 Physical Testing

Physical testing is necessary for the development of safety-critical systems such as seats and airbags [2]. Physical testing is often a requirement for authorities. Testing may either be carried out by a car manufacturer and the results sent to authorities or done by the responsible institute to ensure the data given is valid. The SAB OOP testing is carried out by the manufacturer, and data is sent to the Insurance Institute for Highway Safety (IIHS) upon request. However, IIHS may choose to perform their own testing as well. Virtual testing as an alternative is on the rise, and for example, the safety rating organisation Euro NCAP aims to utilise this more in the future [13]. Still, at the very least, physical testing must be used to verify and validate model-based testing. Physical testing, however, requires specialised equipment and data processing, which is covered in this subsection.

Processing of OOP Test Data

When performing physical tests, the resulting data is noisy and needs to be passed through a low-pass filter before analysis. In automotive impact tests, there are standards that determine how this should be done. ISO 6487 and SAE J211 are two such standards [14][15]. According to the standards, channel frequency class (CFC) filters are to be used. The CFC filters can be realised by a 4-channel Butterworth filter, passing the data twice: once forwards and once backwards. The combined filter has zero phase shift [15]. For which applications the different classes should be used is displaced in *Table* 2.2, adapted from [15]. These filter classes are recommended; however, specific test protocols may require different filter classes. Due to difficulties in comparing data that is filtered differently, utilising these standards is important.

Table 2.2: SAE J211, ISO 6487 Filter Classes and Application adapted from [15]

Dummy Instrumentation	Head	Accelerations	CFC1000
	Neck	Forces	CFC1000
		Moments	CFC600
	Thorax	Spine Accelerations	CFC180
		Rib Accelerations	CFC1000
		Sternum Accelerations	CFC1000
		Defelections	CFC600
	Lumbar	Forces/Moments	CFC1000
	Pelvis	Accelrations/Forces/Moments	CFC1000
	Femur/Lower Leg	Forces/Moments	CFC600
		Displacements	CFC600

2.3.2 Virtual Testing of Seats and Side Airbags

Virtual testing is done by running simulations of models representing the physical system in some way. Models can be defined as "An abstract description of the real world giving an approximate representation of more complex functions of physical systems."[16] Whereas a simulation is the process of using a model to predict the system response. In the case of airbags and seats, the models may be either numerical models or data-driven models. In this thesis, only numerical models are used.

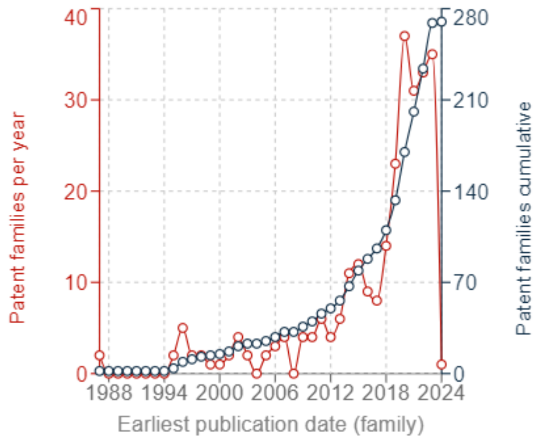
The seat and side airbags are some of the most difficult to model accurately as the SAB is one of the fastest airbags to inflate while interactions with surrounding support surfaces are high and changing throughout the event. The airbag has to pass through a relatively narrow passage while the support surfaces may deform considerably.

Recent efforts have been made to improve the accuracy of seat models' breakthrough behaviour. A 2022 technical paper discloses the development of a CAE model of the seat tear seam including validation against physical testing [17]. It shows the approximate forces and the shape of the stress-strain curve, as well as the impact of modelling SAB deployment with or without this seam implemented. Some takeaways are listed below:

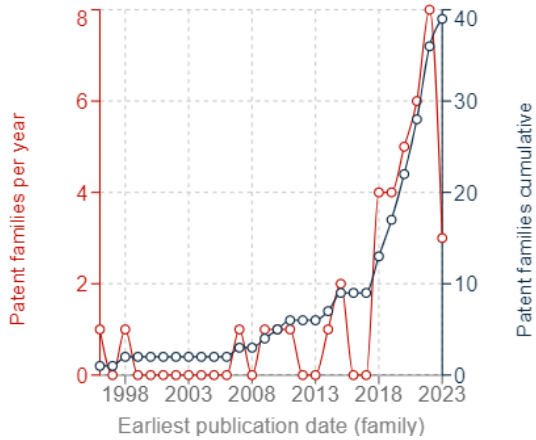
- The stress-strain relationship is linear but scales non-linearly with seam length.
- The failure is a brittle one as there is little to no plastic yield.
- The presence of the seam seems to have minimal effect on timing; however, when present, there is an early pressure spike as well as a smaller fully inflated volume.

2.3.3 Airbag Test Rigs

A patent search was done to find prior art in the area of seat airbag testing rigs. Various combinations of synonyms for this kind of product as well as classification searches were performed in the database Espacenet.



(a) Airbag Test Devices



(b) Seat Airbag Test Devices

Figure 2.4: Graphs over number of patents published per year over time

As can be seen in the graphs in *Figure* 2.4, there are numerous patents in the broader family of airbag test devices. However, the specific area of SAB test rigs yields significantly fewer results.

These results were achieved by searching for airbag (AND seat) in the title or abstract and any of the classes: G01M17/007, G01M99/00, G01M17/00 or G01M13/00. G01M is the class for "Testing static or dynamic balance of machines or structures; testing of structures or apparatus, not otherwise provided for" and the different classes here are sub-classes of G01M.

Among these patents, none claims to be such a rig that this thesis aims to develop. Among the closest contenders is the patent "CN210719725U Seat backrest quick mounting device for automobile seat airbag unfolding test"[18]. That is a rig for quickly mounting and removing complete seatbacks for airbag testing without a dummy. This solution has a high cost of consumables while not being compatible with dummy testing in its current form. This is because the entire seat back must be replaced after each test, and the interface does not include a seat cushion.

2.4 Sustainability Considerations

The United Nations has set up a blueprint for sustainable development and 17 Sustainable Development Goals [19]. Volvo Cars recognises the importance of sustainable development and has set up goals in terms of climate action, circular economy and responsible business [20]. Volvo's ambitions in short are listed below:

- Net zero greenhouse gas emissions by 2040
- Aiming towards becoming a circular business by 2040
- Improve and protect people's lives in VCC value chain and society

A framework for a circular economy has been suggested by PBL Netherlands Environmental Assessment Agency [21]. The strategies suggested are listed in *Table* 2.3.

Table 2.3: Circularity strategies within the production chain, in order of priority adapted from [21]

Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g. through sharing products, or by putting multi functional products on the market)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and it's parts	R3 Re-use	Re-use by another consumer of discarded product which is still in good condition and fulfills its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with it's original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of materials with energy recovery

The development of a test rig to be used instead of actual seats can be seen as following the circularity strategy **R1 Rethink**, as a rig is a different (but not radically different) product that could make use more intensive in terms of tests per seat.

2.5 Product Development Methodology

Product development, i.e. the process of developing products, can be imagined as a series of stages and gates. A generic PD process as imagined by Ulrich et. al. [22] is shown in *Figure 2.5*.

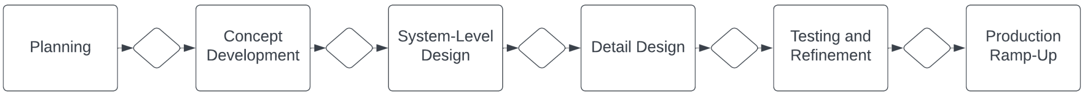


Figure 2.5: Generic PD process

A key attribute in the concept phase is breaking down the problem into smaller more manageable pieces and solving them individually and on a system level. This is a method to ensure a wider design space exploration. A method for this proposed by Ulrich et al. is function means modelling [22]. Function means modelling, essentially breaking down the product into functions and listing the means by which those functions are solved.

Once solutions have been found for the subproblems, the sub-solutions are to be combined to complete concepts. The authors present the morphological matrix as a method of managing this process. The morphological matrix is a matrix with the functions along one axis and the different solutions along the other. Picking one solution for each function will then result in a complete concept. The morphological matrix is only a tool for organising this and, as such, does not aid in creating "good" combinations. A method for taking concept balancing into account in concept creation has been suggested by Lars Almefelt [23]. This is a variation of the matrix where each sub-solution interaction with the next is judged in an attempt to catch potential synergies or, on the other hand, avoid the opposite.

The resulting output from a morphological matrix is a catalogue of complete concepts. The proposed method by the authors for finding a winning concept is a combination of set-based concurrent engineering and concept screening and then selection [22]. This approach combats the designer's paradox, i.e. as the project goes on, the design freedom decreases while the knowledge of the problem necessary for the designer increases. Set-based concurrent engineering stems from Toyota [24]. In short, this means that several concepts (a set) are developed concurrently as far as possible, delaying the decision of which concept to go with. The process in which decisions are taken is designed to complement this approach. Concepts are primarily screened rather than selected. This method keeps a larger set for longer, making it more likely to get the correct outcome.

Concept screening is normally done in several different steps with varying degrees of depth. Initial screenings can be made with concept classification trees and elimination matrices. These are methods where the concepts are organised and then eliminated or kept based largely on engineering judgement whether the concepts are promising or not. Once more knowledge of the problem and the solutions has been gathered or created, slightly more sophisticated methods can be used. The Pugh matrix is a matrix where the concepts are evaluated comparatively against each other using different screening criteria. The goal is to reduce the number of concepts to a handful that can be developed far enough to enable comparison in absolute terms rather than comparative. When there is enough knowledge about the concepts and problem to make absolute comparisons, a selection matrix such as the Kesselring matrix may be used. In the Kesselring matrix, the concept of absolute performance is evaluated and compared with weighted selection criteria. The outcome of this should be one final winning concept.

Coming up with solutions to complex problems can be facilitated by Design thinking philosophy. Design thinking is described by Katja Tschimmel as a mindset for effectively coming up with novel solutions to wicked problems. It offers models and tools to facilitate, speed up and visualise the innovative process. It's not only of interest for designers but can help connect the creative process to business and problem solving in any field or industry [25].

One way of describing design thinking revolves around types of reasoning. In an interview with professor and author in business management, Roger Martin [26], he explains the concepts of inductive, deductive and abductive reasoning and how especially business education lacks focus on abductive reasoning. Martin argues that a good designer can utilise all three kinds of reasoning throughout the creative process. Abduction generates ideas, deduction predicts the result, experimentation tests the prediction in the real world, and induction draws conclusions from the test results, which can lead to new ideas through abduction in a loop as depicted in *Figure* 2.6 reworked from [26].

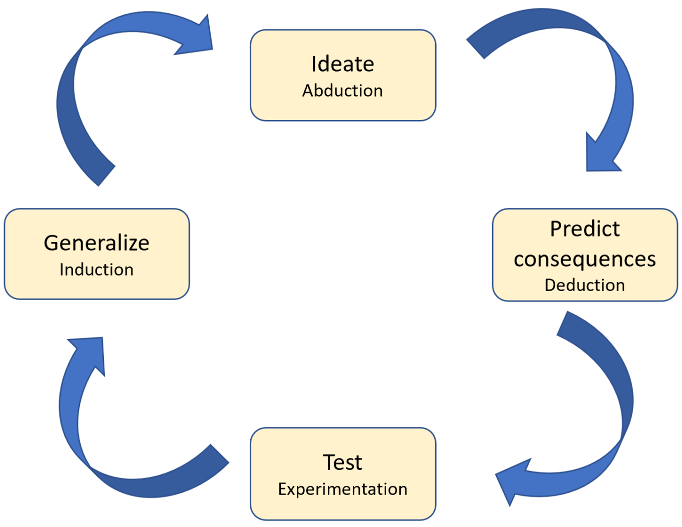


Figure 2.6: The natural process of design adopted from Roger Martin

2.6 Life Cycle Assessment

Life Cycle Assessment (LCA) is a well established method to in a structured way map out and quantify all resources consumed during a products complete lifetime, and what impact the resource use has on the environment [27]. The goal of the assessment is to consider every single step on the product life cycle in order to get an objective and comparable view [27].

By including every step in the life cycle, from extraction of the material resources to production, to use, to disposal of waste material or also called "cradle to grave" it is not possible to try shifting emissions from one phase to another in order to appear better in a certain area [27]. The comparability in the results make LCA an objective decision support tool when evaluating changes or alternatives in terms of sustainability [27]. LCA can help identify the emissions coming from each point in the life cycle of a product, and consequently where it makes most sense to act for improvement [28].

VCC has made and published LCA's of the XC40, EX40 and EC40 models where the emission for different car configurations and electricity supplies are compared [29]. The report shows the usefulness of LCA in real examples as the different car models emissions in all phases can be presented next to each other for a comparison. LCA is expected to be used in order to answer RQ4, "**What impact in terms of emissions and economy could a "rig" solution have compared to the current method?**" as it objectifies the potential gains of making changes to the testing procedures.

3

Methodology

To answer the research questions, qualitative and quantitative research must be carried out. To answer the research questions, physical experiments, simulations and interviews with knowledgeable employees were conducted. The focus of the qualitative studies was primarily to grasp the scope and important details of how the testing is currently carried out and what prevents it from being re-used. Whereas the experiments and simulations focus on quantitative results to guide the design with critical values that must be withstood by the solution. The methodology used throughout this project to answer the research questions is presented in this chapter and can be summarised in the flowchart *Figure 3.1*.

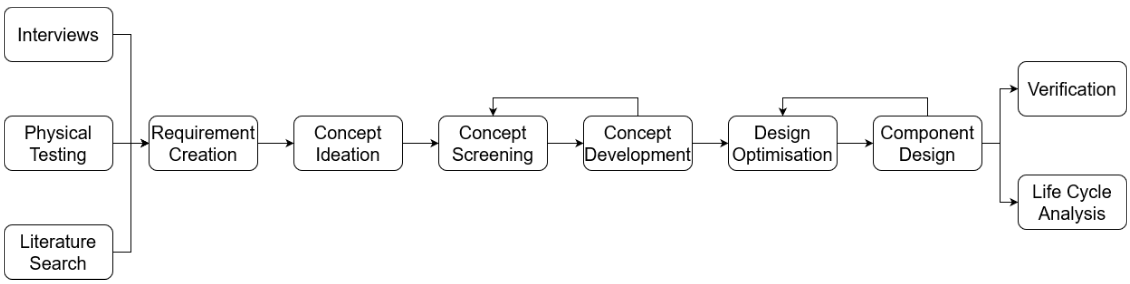


Figure 3.1: Methodology flowchart

3.1 Data Collection

Initially the problem details and solution limitations were not fully known. More information collection was thereby needed to better understand the problem and map the customer needs in a concise way. Data collection was done through four main channels, interviews with employees of VCC, physical experiments, computer aided simulations and secondary sources such as old test videos, books, reports, patents, and procedures.

3.1.1 Interviews

Since Volvo Cars is considered to be the customer due to the product being created for internal use and not to be sold, meetings or interviews were held with a variety of stakeholders from different functions at VCC. A list of the stakeholders can be seen in *Table* 3.1.

Table 3.1: List of stakeholders that were interviewed

Function	Role	Participants
Airbags & Steering Wheels	Concept Engineer	2
	Technical Expert	1
Safety Centre	Crash Analysis Engineer	1
	Information Architect	1
	Test Technician	1
Seats	CAE Engineer	2
	Design Engineer	1
	Sustainability & Material Strategy	1

The interviews were held in an informal and exploratory manner to get the persons to open up as much as possible. The unstructured interviews followed the process described in [30] by setting the goals of the study, finding suiting participants, deciding the setting and conducting the interviews. Before the meetings some key questions were planned specific to the expertise of the interviewee, sometimes sent in advance if the questions were so specific they would need to find certain information themselves. The main questions were used to guide the dialogue with discussions of the answers and follow-up questions that came up on the spot. But much of the discussions were run freely based of what the target person brought up. The questions and answers and summaries from each interview session was written down and organised chronologically in a notebook for easy re-visiting. Each initial meeting lasted about 45 minutes, but some stakeholders were revisited with further questions.

3.1.2 Physical Testing

From the initial discussions and material reviewed, some crucial questions ascended regarding how much impact different components or structures had on the values of the dummy test results.

In order to define the solution space, these doubts formed the research questions 1 and 2:

RQ1: What prevents the seats from being reused in testing?

RQ2: What impact do the main components of structure, foam and upholstery have on the test results?

The goal of doing physical experiments early in the project was to find out how much changes in the setup configuration would impact the OOP testing results compared to a normal seat and to then know what simplifications can be made without changing the outcome too much.

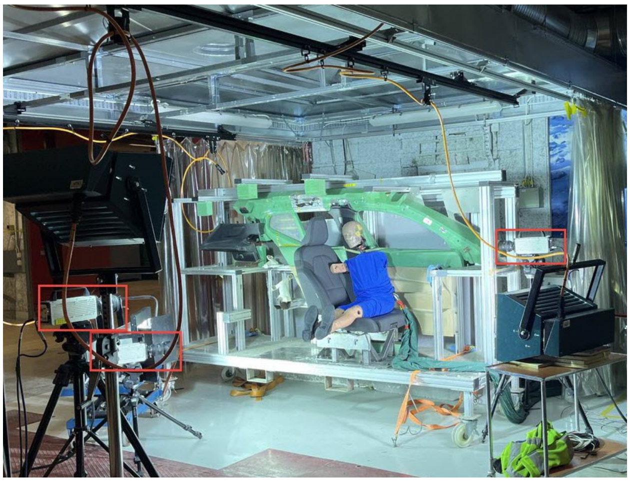
To not worry about confidentiality in publishing and have access to all information available it was decided to work with a car model already out on the market rather than one currently in development. That also meant old testing equipment and reference data were available to use and to benchmark against. For the proposed physical testing of seat configurations, the rig resembling the environment of Volvo XC40 (2017-) that was used for OOP certification for the SAB and IC was chosen (*Figure* 3.2a).

The dummy type and position were chosen based on what was believed to have the highest forces acting on the seat structure. Thereby having the potential to show large differences in seat structure behaviour. The setup showing these characteristics was found using reasoning and existing test data where seat deflections and dummy accelerations were observed. The chosen setup consisted of the dummy type SIDiis with 41 data channels and the position 3.3.3.6. SIDiis is based on a 5th percentile female and is in OOP used to represent a small teenager [31]. Position 3.3.3.6 Is a position where the dummy is positioned in the driver's and passenger seat facing inboard. The test includes seat-mounted airbags and is intended "to maximise chest interactions by aligning the centre of the top thoracic rib with the top edge of the airbag module" [8]. In this case, the position was chosen due to it being a position particularly hard on the seat, which was determined by visual comparison of seat deflection in older tests.

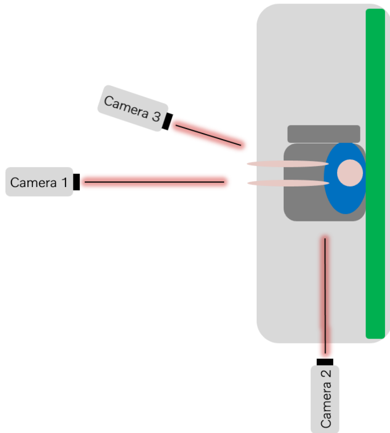
A test matrix was proposed for the involved personnel, and a rough plan of what would be tested was agreed on. An order for a rigid seat was made to prepare for the experiments in January. The XC40 testing environment seen in 3.2a first had to be slightly modified to be able to fit the rigid frame onto the floor. The environment was placed in a dedicated airbag testing spot with extensive ventilation, lighting and high-speed cameras.

The dummy is lifted into the seat by hand and then adjusted into correct position according to the instructions in OOP TWG 3.3.3.6. To ensure identical dummy position between tests, both the seat structure and dummy positioning was measured and photographed in different ways in relation to the rig. The dummy is equipped with accelerometers and transducers in every body part and joint measuring acceleration, forces and deflection.

The test was captured with a triple slow motion camera setup recording at 2000 frames per second to see the deployment from multiple angles in order to be able to visually analyse the tests in detail afterwards. In *Figure 3.2b*, Camera 1 and 2 aim to capture the seat back and dummy movement from different directions, whereas Camera 3 focuses on the fixation points between the seat back, seat cushion and



(a) Testing environment with cameras marked in red



(b) Overhead view

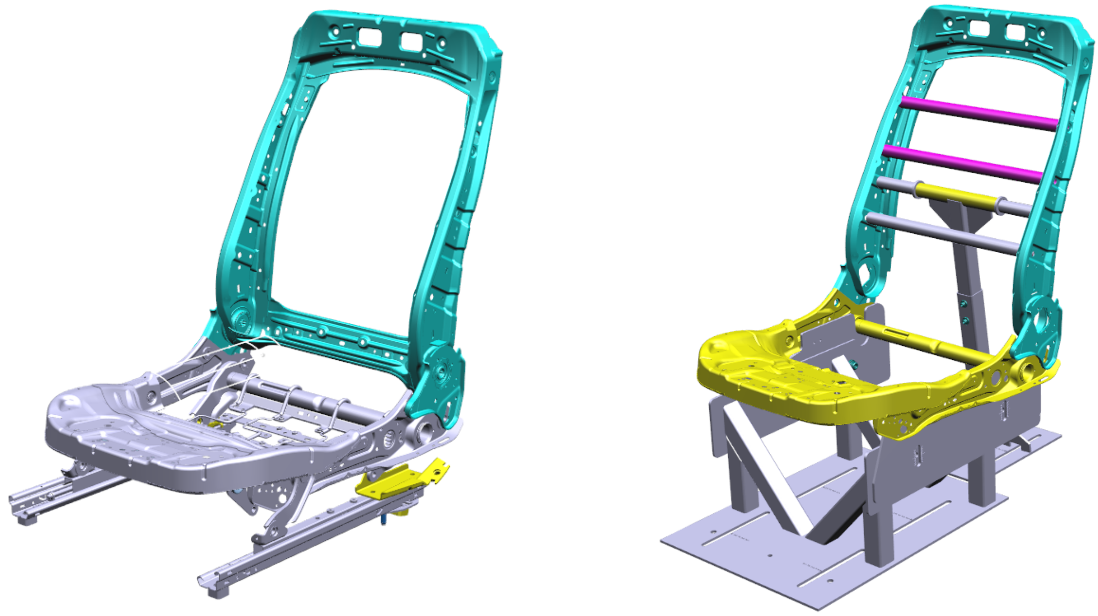
Figure 3.2: Testing environment and camera setup

adjustment rails. The slow-motion videos were later played alongside each other with grid lines and point tracking in a program called Kinovea to easily compare test results visually.

The testing activity consisted of twelve deployments in total with two variables, rigid (*3.3b*) or normal (*3.3a*) seat and new or used upholstery. To ensure that the variance of the setup did not impact the results, each test was repeated three times. Therefore, the four different setups are all performed three times, totalling twelve tests. In order to refer to the different setups, the same type of test is referred to as setups 1-4 and is colour-coded. The schematic of testing activities can be seen in the *Table* **??**.

Table 3.2: Testing scheme

Test no.	Setup	Dummy	Position	Seat structure	Seat no.	Upholstery no.	Breakthrough Material
1	1	SIDiiS (5th percentile female)	3.3.3.6	Rigid	1	1	Yes/New
2	2	SIDiiS (5th percentile female)	3.3.3.6	Rigid	1	1	None/Used
3	1	SIDiiS (5th percentile female)	3.3.3.6	Rigid	1	2	Yes/New
4	2	SIDiiS (5th percentile female)	3.3.3.6	Rigid	1	2	None/Used
5	1	SIDiiS (5th percentile female)	3.3.3.6	Rigid	1	3	Yes/New
6	2	SIDiiS (5th percentile female)	3.3.3.6	Rigid	1	3	None/Used
7	3	SIDiiS (5th percentile female)	3.3.3.6	New XC40	2	4	Slit
8	3	SIDiiS (5th percentile female)	3.3.3.6	New XC40	3	5	Slit
9	3	SIDiiS (5th percentile female)	3.3.3.6	New XC40	4	6	Slit
10	4	SIDiiS (5th percentile female)	3.3.3.6	Used XC40	4	6	None/Used
11	4	SIDiiS (5th percentile female)	3.3.3.6	Used XC40	4	6	None/Used
12	4	SIDiiS (5th percentile female)	3.3.3.6	Used XC40	4	6	None/Used



(a) Normal seat structure

(b) Rigid seat structure

Figure 3.3: Comparison of rigid vs normal seat structure

The rigid seat frame (3.3b) was used for the first six tests, deploying six airbags in three upholsteries (*Table 3.2*). Mounting a new upholstery on every other test, meaning tests no 1, 3 and 5 had brand new upholsteries, whereas tests no 2, 4 and 6 were deployed through an already torn upholstery.

Test no. 7, 8 and 9 were all done with new and complete XC40 seats, but the leather and foam were cut up using a knife to mimic an airbag already being deployed through it while still having a new structure. The last three tests in setup 4, called "repeated" testing, were all done without replacing anything but the airbag in order to see how the structure and foam hold up over time and what impact it has on the data values of the dummy when the structure is exposed to multiple tests.

The time series data gathered from the testing was noisy, and each channel of data was in a different file. A Python script for aggregating, filtering, plotting, and analysing the data was written. The data analysis library Pandas was used for this purpose. The time series data was stored in one folder for each test, and one file for each channel was organized into Datastores, one for each test. The datastores themselves were organized by having the time steps as rows and channels as columns.

3.1.3 Literature Search

An external search of secondary sources was carried out in several phases of the work. Initially, documentation related to OOP testing [8] and internal VCC documentation, such as requirement specifications for airbags and the Volvo Product Development System, were studied to grasp the problem.

To see whether the problem had been recognised before a search of sources such as SAE Mobilus, Elsevier, IEE Xplore and Espacenet was carried out searching for terms such as "reusable", "seat", "rig", "airbag" and "test"

When the project progressed and it was evident that a solution to the problem presented here did not exist nor the problem of testing SAB:s in the seat particularly well explored. The search was then widened to look at rig testing of airbags in a more general sense and not only for seats and side airbags.

The search took another direction in examining the area of seat and side airbag CAE models, as modelling the different aspects of the system, such as the tear seam, requires some understanding of the physical system.

3.2 Requirement Creation

From the interviews with stakeholders in airbag testing their desires and must-haves was interpreted in terms of customer needs. The collected customer needs was organised into a hierarchy, ranked in terms of importance and documented as a customer needs list. The needs were then translated into quantifiable stakeholder requirements where applicable. Combined with the learnings and observations of the physical testing of what actually matters for the testing results, a requirement specification was created. The compiled specification was then reviewed with the project supervisor and a senior designer at VCC to decide on the ranking of requirements and needs.

3.3 Concept Ideation

Firstly the problem was clarified by decomposing the problem into smaller sub-problems for which solutions were found internally & externally. To support the breakdown activity, function means modelling was used. The search for solutions partly coincides with the literature search. The internal ideation was loosely structured by having a brainstorming session where ideas were listed for each function, going through one function at a time. To further facilitate discussion and creativity the session was held in a storage unit. There, the group had easy access to a variety of seats and seat prototypes. Other than the objects for discussion pen and paper was used to quickly sketch the ideas.

Concepts were generated in a morphological matrix using sub-solutions to all the functions that have been found. The most complex functions that have the possibility to impact other functions were put first. To improve the usefulness of created concepts, synergies between sub-solutions were taken into consideration, combining solutions thematically as suggested by Lars Almefelt [23].

3.4 Concept Screening

The concepts were initially screened with an elimination matrix with elimination criteria inspired by Lars Almefelt [32]. The goal of the elimination matrix is to quickly get rid of concepts that are poor or unfeasible before pouring time into developing them. The criteria used were: **Solves main problem, Fulfils all demands, Compatible/Realisable, Reasonable cost, Safe, Enough Information**.

The concepts were later screened further by means of a Pugh matrix. Due to the difficulties in finding absolute values of performance Pugh's relative measure was deemed to be particularly important. The Pugh matrix in its normal form does not take into consideration the importance of the selection criteria. However, since some of the criteria were fundamental to the solution being useful at all, the Pugh matrix was modified to have weighted criteria. The selected screening criteria and weights are listed below in 3.3.

Table 3.3: Criteria for the Pugh matrix, higher weight means higher importance

Criteria:	**Weight**
Lifecycle cost	2
Lifecycle CO2	1
Weight	1
Testing flexibility	3
Adaptability (adaptable to next generation of seats)	2
Easy to adjust seat with precision	1
Easy to gauge seat position	1
Easy to lock seat position	1
Easy to determine top of module	1
Easy dummy positioning	1
Easy to access and replace airbag	1
Easy to reset rig (quick and little consumables)	1
Easy to replace parts that are not intended to be broken (special parts)	1

The weighted Pugh matrix narrowed the concepts down significantly. A few concepts were deemed most promising and presented to the airbag team at VCC where inputs and proposals were given.

Due to the low interaction between the breakthrough concepts and the structural concepts the remaining concepts could largely be combined in any way. There was not enough information to perform a final selection at this time. Due to the low interaction of the design areas, this did not present a large problem. The most promising solutions were thus developed further concurrently.

3.5 Concept Development

Promising concepts that passed through the initial screening were further explored and developed. Simple digital models and drawings were created to gain more insight into potential strengths and weaknesses as well as to be able to discuss the concepts effectively. Different types of substructures, seat back reinforcements and breakthrough imitations were all developed at the same time and continuously evaluated through discussions and simulations.

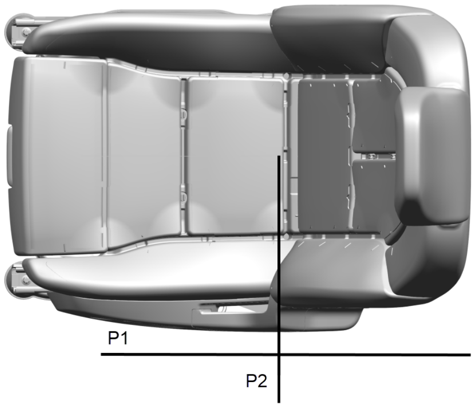
The breakthrough-mimicking solutions were developed separately from the structural solutions of the frame, this was because there was very low interaction between the areas. Meaning what solution is chosen for one area does not impact the circumstances for the other area. The breakthrough is a complex behaviour and multiple concepts were developed concurrently to improve understanding and obtain as much information as possible before ruling out alternatives.

3.6 Structural Optimisation

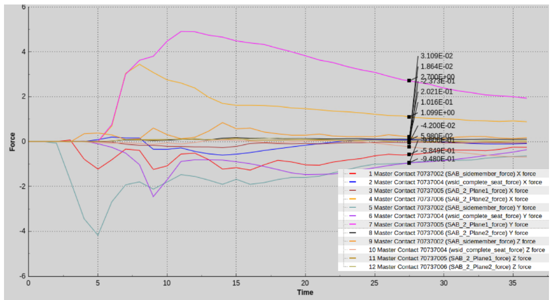
The purpose of performing optimisation, in this case, is to find a suitable load path or overall topology so as to not risk shifting the problem by introducing new stress concentrations due to new stiffness gradients.

3.6.1 Optimisation Setup

CAE tools were used to further understand the structural problems and aid the development of an improved solution. OOP testing is not a load case/position that is commonly evaluated through CAE methods, and thus, there were no models or simulations available for this purpose at VCC. Airbag deployment simulations are normally done in the tool LS dyna at VCC while structural optimisation is done in Altair Hyperworks. Firstly, the approximate load case of OOP position 3.3.3.6 was replicated in LS Dyna by taking an existing model and bringing in fixed, rigid planes in front of and to the side of the SAB; these can be seen in *Figure* 3.4a. This was to represent the obstruction of the SAB deployment in X that occurs when the dummy sits directly in front of the SAB exit point and the obstruction in Y from the door panel. The reaction forces in the SAB mount and along the sidemember were plotted (*Figure* 3.4b).



(a) Seat top view with planes

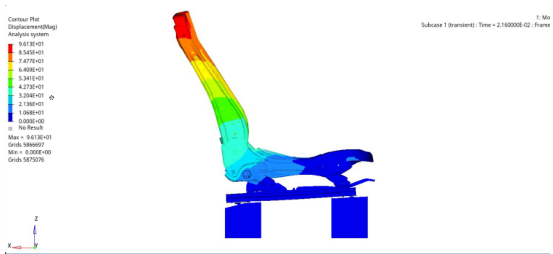


(b) Reaction forces

Figure 3.4: Study of reaction forces

To check whether the results were reasonable, the deflection of the seat with this setup was compared to videos of physical testing, and the magnitude of the forces was compared to accelerometer data from physical testing. The load case was then replicated in HyperWorks in order to perform the structural optimisation. The deflection of the load case was yet again compared to videos of physical testing to check the correlation with the physical system. A still image of this can be seen in *Figure* 3.5.

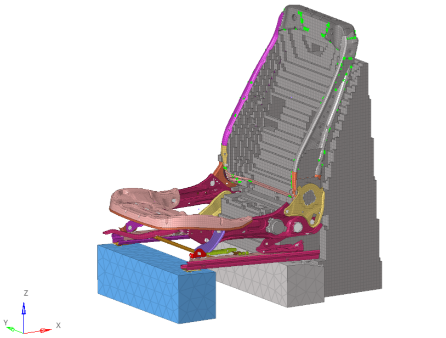
(a) Video from testing activities



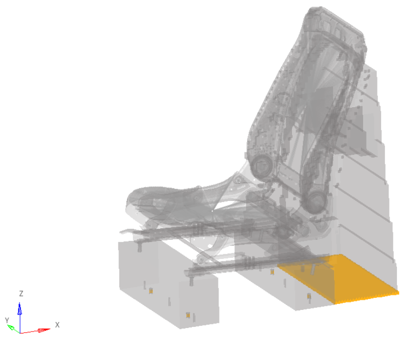
(b) Seat deflection in simulation

Figure 3.5: Correlation between testing and CAE

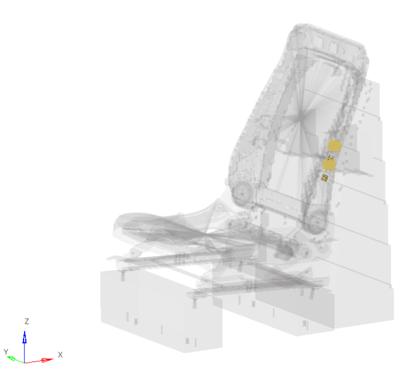
A design volume was created in Catia based on spatial and access constraints. This volume, along with suitable parts, was meshed using the voxel meshes in HyperWorks to create the design space. The design volume can be seen in *Figure* 3.6a. This space was then connected to the rest of the structure by means of RBE3 elements, and the bottom of the volume was constrained in all degrees of freedom using SPC:s. The boundary conditions can be seen in *Figure 3.6*. The load is applied in multiple steps as seen from *Figure 3.4b*. The different lines represent the load in a direction (XYZ) and on which surface the load is acting. The surfaces as they are defined in Hypermesh can be seen in *Figure 3.6c & 3.6d*.



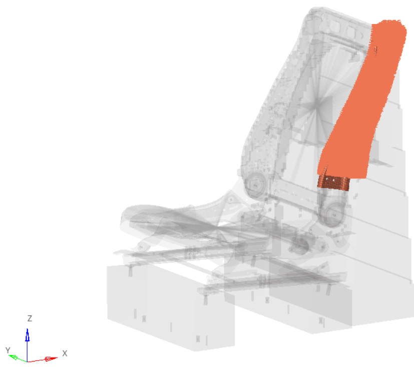
(a) Voxel mesh of design volume



(b) SPCs on bottom of design volume and substructure (in yellow)



(c) Pressure load on side airbag mount (in yellow)



(d) Pressure load over side member (in red)

Figure 3.6: Design volume and boundary conditions for optimisation problem

The optimisation problem was formulated as a minimisation problem where the compliance of the structure was minimised and it was constrained by a volume-fraction. This approach provides the most efficient material use given a volume fraction of the design space to retain. This method is also quite computationally cheap and allows for many iterations to be ran with differing constraints which was advantageous as it was not known what limits to set if the stress or deflection were to be constrained instead.

The initial results from the optimisation were quite hard to interpret into something manufacturable so some additional constraints were added. A symmetry constraint was introduced as well as a constraint for the minimum allowed member size which prevents the tendency to produce "web-like" structures and thus reduces the amount of parts necessary in the design interpretation.

Many configurations were tested, but the optimisation could be said to have been performed in two major loops, with the first one being exploratory and the second one focusing on a particular concept.

3.6.2 First Optimisation Loop

The first optimisation loop was performed in an exploratory manner, changing the variables and constraints to see what an ideal structure would look like depending on how the problem was posed. The resulting structures were compared with concepts for adjustments and locking mechanisms to find any synergies between the topology and mechanisms in the seat.

From the first optimisation loop a structure that would not allow the required seat adjustments was obtained. This is because the result is a structure and not a mechanism. This design was then forced into a different shape by cutting away from the design space and only allowing it to contact the ground in a much more constrained space. This led to a structure somewhat resembling the original seat rig used for testing.

3.6.3 Second Optimisation Loop

The selected concept was then designed in Catia and yet again exported to Hyperworks. This time the strut and seat was used as existing geometry and a design space set up to connect the two. The rest of the problem formulation was largely kept as before. The output from this optimisation was used as the basis for the design realised in CAD.

3.7 Component Design

The geometry was designed in CATIA V5 according to Volvo Cars internal CAD standards to allow for further developments to be made after project completion.

Based on spatial requirements a rough geometric layout could be created and the interactions found iteratively. For this purpose, a checklist may be used [33]. The checklist can be seen in *Appendix A.6*. Once it is deemed that the function has been fulfilled with a minimum compromise to other requirements detailed design may commence.

As a final solution could not be filtered out at the start of the design phase, multiple concepts for multiple design areas were developed concurrently. Catia models were made quickly at low level order to find functional or integration problems in the digital models as early as possible while at the same time evaluating the concepts feasibility to handle the load forces with calculations and static simulations.

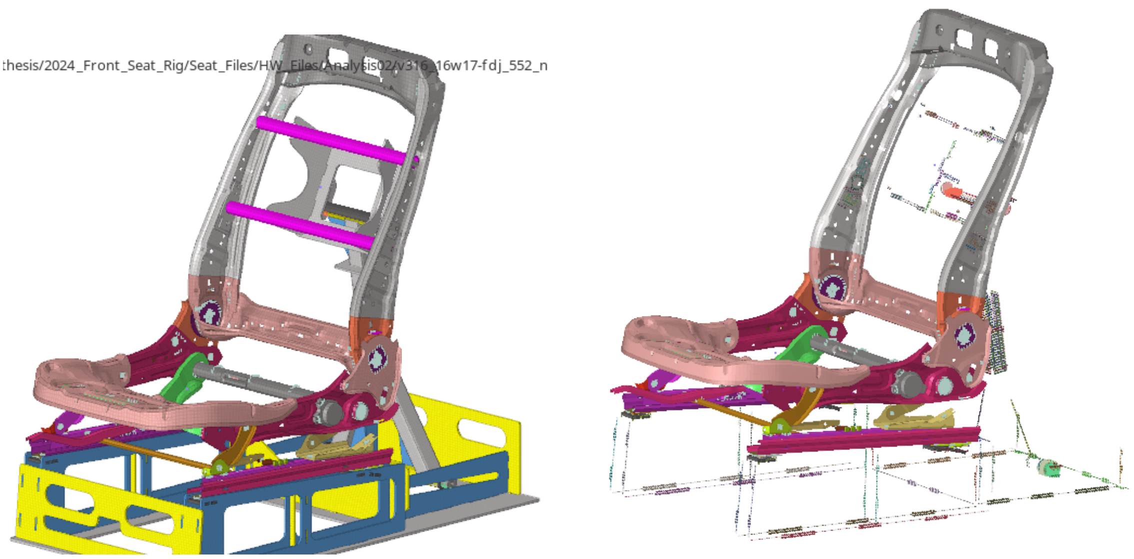
The resultant forces of the SAB deployment were primarily used to evaluate the most complex design area: breakthrough. With calculations, simulations and engineering judgement, more breakthrough concepts were discarded along the development phase as they could not realistically manage the loads needed.

Weekly presenting of digital models to more senior engineers and designers was a way to quickly and iteratively gain feedback on ideas before spending too much time on the details of each part. The constant presentations of new models gave a discussion point for input and proposals and allows for quick feedback loops making sure to reduce the chance of large changes coming in late in the design phase.

3.8 Verification

Testing, either physical or virtual can be used to verify that the requirements are met. It is also important to validate whether the customer's needs have been satisfied.

To verify requirement 1.1 A.3. a Finite element analysis was set up. A finite element model of the proposed structural solution was created and the load case created for initial evaluation and optimisation was reused. Due to the load being dynamic and large deformations the analysis was set up as an nonlinear explicit analysis in Hypermesh and solved in Optistruct. The mesh and all connections (i.e welds and joints) are shown in *Figure* 3.7. Since different kinds of elements had to be connected the welds were realised as TIE elements.



(a) Seat model and structural concept mesh

(b) Connections in the structural concept

Figure 3.7: FE model for evaluation of structural concept

To verify that requirements of category **3. Airbag testing similar behaviour as**

real seat were met physical prototypes were manufactured and tested by means of a static deployment test. The test setup included three camera views (front, back, top) and 2000 fps video recording. The breakthrough concept was mounted in a XC40 seat and set up next to an imitation door panel.

Remaining requirements were verified either by checking the CAD model or making an engineering judgement. All of the requirements and their respective method of evaluation or verification can be seen in A.3.

3.9 Life Cycle Assessment & Life Cycle Cost

To create a scope for the life cycle comparison similar to the LCA in [29] that fairly reflects the performance, discussions with stakeholders at VCC were held. Since the airbag testing activities usually is done in the order of magnitude of hundreds of tests for a platform, a benchmark number of 100 tests was decided on as the evaluation scope. The cost and CO_2 emissions for the current way of testing was requested and obtained by respective departments.

To calculate the emissions for one seat, internal material data for the seats materials and weights were compiled. Each material had a set emission factor that had been worked out and used internally at VCC. The weights of all components grouped by material was also obtained from the seat department in a spreadsheet. The emission factor was then multiplied with the weight for each respective material and summarised into a total emission per seat.

To calculate a baseline cost of the current testing methodology over 100 tests, invoices from previous testing activities were obtained which could be used to extract the cost per seat during the early development. By using the extracted cost and emissions per seat calculations from the data could be done to create a reference cost of the present procedure over 100 tests.

For the proposed rig the weights of all components extracted from the digital model were multiplied with the corresponding material emission factor. To estimate life cycle cost the internal cost of production and running costs was calculated. A comparison of emissions and cost between the current testing and proposed rig over 100 airbag deployments was made.

4

Results

In this part of the report, the results from the pre-study, development and matrices of screening concepts, the complete final solution, as well as a structural and life cycle evaluation of the proposed solution, are presented.

4.1 Data Collection

To guide the solution space, more information than available was needed. Data was primarily collected by testing, meetings and interviews at VCC. In this chapter the findings of the interviews and physical testing are collected.

4.1.1 Interviews

The interviews were mainly targeted towards answering RQ1: **What prevents the seats from being reused in testing?** But also to understand what is important in performing airbag testing from multiple stakeholders involved in order to be able to guide the requirements for the rig and thereby answer RQ3:**"What could a rig for testing side airbags without consuming a full seat for every deployment look like?"**.

4.1.1.1 Summary of Interviews

Summary of meetings with Airbags & Steering Wheels:

To balance adaptability and simplicity a rig for this use case would most likely be adapted to one platform as the seat structure is set for each car platform while the "tophat" i.e. foam, upholstery, airbag etc may change between the models on that platform. The priority for this stakeholder is getting something working as soon as possible. So, for the moment it is most desirable to focus on one use case, OOP.

It is not clear what is assumed to be known and what is truly known to be an issue in realising such a rig. The breakthrough packaging is designed to have minimal impact on deployment but the exact effects are unknown as there hasn't been incentive to test it. Minuscule plastic deformations have been observed and used as an argument against the reuse of structures but are not well documented nor examined more closely. To further understand this a meeting with stakeholders at Safety Centre is suggested. It is not believed that knowledge about this could be gained through CAE as these use cases simply aren't done in CAE and are thus not validated but a meeting to understand more is also suggested.

From experience in designing different kinds of test rigs it's usually desirable to keep things as simple as possible. Flexible parts with springs and rubber have caused issues in repeatability and resonances and overly complex adjustment mechanisms might cause issues as well. They at the same time point out that if simplifications are made the effect of these changes must be known.

Summary of meetings with Seats:

A rig such as this is interesting and could be used for e.g. testing of foam and upholstery concepts if a structure that could be reused is made. Necessary adjustments would be min max and middle positions of length and height adjustments of the seat. It is pointed out that the seat back not only pivots but oscillates and that the seat pan changes angle depending on the height setting as the links in the front and rear are of different lengths.

From observations there is significant deflection in the seat height adjustment mechanism in OOP testing. The different stiffness left to right is also pointed out as only one side of the linkage is connected to the motor and the others pivot freely. It is unknown if plastic deformations or any other issues occur after repeated deployment. The seat recliners and length adjustment rails are bought components and no exact specifications are available, but the height mechanism is believed to be the weak spot.

It is pointed out that the foam has metal wires in it as well as a stiffener on the backside of the foam. The foam is also of varying stiffness across the seat to provide comfort and good appearance. These features may locally change the stiffness and "direct" the airbag somewhat.

It is not currently possible to do OOP testing in CAE and seats and SABs are particularly tricky to model by themselves. Structural analysis is usually done by the supplier, and thus, some current simulations (not OOP) are requested and reviewed. From these the plastic deformation is very localised around the SAB mounting holes.

Summary of meetings with Safety Centre:

A rig for airbag testing is believed to be a significant improvement and could be used for various kinds of testing.

The upholstery and breakthrough packaging break upon every use by design. Other than that, the most notable is the airbag mounting. As the airbag is mounted either by screws or studs in thin sheet metal it's very likely to break. Screw holes may be deformed and studs may break off. The height mechanism might be slightly deformed in static tests and is guaranteed to deform in dynamic ones. In concepts where the foam doesn't tear upon deployment, it has been successfully reused but degrades over time.

It is believed that almost all properties of the original seat are important for the testing results, and there is, thus, some scepticism towards simplification. The outer geometry of the seat and the foam stiffness affect dummy positioning, and OOP is heavily dependent on positioning. Due to the high deflections in the seat, it is believed that reinforcements would impact test results as well. It is thus suggested that tuneability is of high importance for a potential breakthrough concept and the idea of a modified structure must be further examined.

For OOP it is necessary for the seat to be positioned in the min/max positions height wise. The angle of the seat back is always 25 degrees but changes with height. The length adjustment has some loosely defined positions in TWG that require fine tuning so a full range of motion is required. Electric adjustments are preferred for their smoothness.

4.1.1.2 Takeaways from Interviews

There is one problem with the reuse of seats for this purpose that is inherent in the seat design. Namely that the tear seam tears open upon airbag deployment. In the studied seat there is also foam in the path of the airbag. After discussions with topic experts, this was deemed to be of high importance that this breakthrough behaviour is well replicated in the reusable rig. Other aspects that were deemed important were seat stiffness, geometry of outer surfaces, travel box and stiffness of cushions. From these meetings, a preliminary stakeholder needs list was constructed. The user, in this case, is the test technician performing the setup and testing activities at the Volvo safety centre or at the airbag supplier. This can be seen in *Table 4.1*.

Table 4.1: Preliminary customer needs list

Stakeholder	Expectation	No.	Need	Dimension
1. Volvo Cars	Lower cost and material/co2 usage during testing	1	Rig or parts of rig that lasts for multiple tests	Durability, Economy and sustainability
		2	Be able to replace destroyed components	Modularity
		3	Low cost rig	Economy
		4	Low weight (shipping cost, and handling)	Economy
	Compatible with generic sled	5	Rig fits within the design space	Design
		6	Rig compatible with the mounting points	Design
	Accurate testing	7	Similar surface geometry behaviour	Testing performance
		8	Similar surface friction?	Testing performance
		9	Similar resistance to airbag deployment?	Testing performance
		10	Similar effect on deployment direction	Testing performance
		11	Same angle of seat back	Testing performance
		12	Similar deflection & stiffness of the seat frame?	Testing performance
	Compatible with test protocols	13	Adjustable in z (theoretically discrete is ok)	Testing performance, Easy handling
		14	Adjustable in x (theoretically discrete is ok)	Testing performance, Easy handling
	Fulfill seat design guidelines	15	No overlap in x	Design
		16	No sharp corners (r<3.2) towards the airbag	Design
		17	No protruding elements, e.g. seams	Design
2. User	Accurate testing	19	Similar surface geometry & dimensions	Testing performance
		20	Similar surface friction	Testing performance
		21	Similar resistance to airbag deployment	Testing performance
		22	Similar effect on deployment direction	Testing performance
		23	Same angle of seat back	Testing performance
		24	Similar deflection & stiffness of the seat frame	Testing performance
	Compatible with test protocols	25	Adjustable in z	Easy handling
		26	Adjustable in x	Easy handling
	Easy handling	27	Low weight	Maneuverability
		28	Good handles and gripping possibilites	Maneuverability
		29	Simple adjustments	Easy handling
		30	Easy access to airbag module	Easy handling
	Easy test setup	31	Easy to find correct test setup positions	Easy handling

It was at this point in time believed that most aspects of the seat must be replicated and it was not known what prevents reuse besides the upholstery. Since the upholstery was known to prevent reuse, but its implications on the test results were not known, it was of particular interest. It was not known whether the structure would need reinforcements, and mixed answers were given. From CAE simulations (not OOP) no plastic deformations were seen. Speaking with technicians, plastic deformations sometimes occur. Thus it was proposed to test the same structure multiple times and scan it afterwards, finding the weak points and potentially closing one gap between CAE and reality. Since it was believed reinforcements would be necessary the effect of these on the test results is also of interest. A reinforced and thus stiffer seat would absorb less energy, perhaps altering the test results. Other aspects of the seat, such as A-surface geometry, cushion stiffness, etc., were deemed to not inherently prevent reuse nor be particularly difficult to replicate if the original parts cannot be recycled in the design entirely.

Thus, it was proposed to test the seat "to failure" and to see the impact of breakthrough material and seat stiffness on test results. However, OOP has many different variations. Different dummies in different positions. Speaking with analysis engineers tests with the Hybrid 3YO are usually the most critical in terms of how close the test results are to the accepted levels. However, since the dummy has the smallest mass of all eligible for OOP it doesn't affect the seat particularly. Tests involving the heavier SIDiis are much harder on the seat and significant (10cm) elastic deformation may be seen at the top of the seat back. Thus it was argued that this is the test where the most impact on the seat and of the seat would be seen. Initially, it was proposed to test multiple positions using the SIDiis. However, not enough time nor material was granted to perform more than one position. Because of this the most critical (for the seat) position had to be found. Old high speed footage of previous tests was reviewed in video software called Kinovea. And visually it appeared that 3.3.3.6 was the most demanding position for the seat structure.

4.1.2 Physical Testing

The physical testing was made to answer RQ1: **What prevents the seats from being reused in testing?** and RQ2: **What impact do the main components of structure, foam and upholstery have on the test results?**.

The results from testing are obtained in two primary ways, slow-motion video and time-series data from all transducers in the dummy. For a more in-depth analysis, the raw time-series data must be processed with filtering and compiled in preferred ways. To minimise variation and to compare the different types of set-ups, the average values of the three tests of each setup in *Figure* 4.1 are used.

Test no.	Setup	Dummy	Position	Seat structure	Seat no.	Upholstery no.	Breakthrough Material
1	1	SIDiiS (5th percentile female)	3.3.3.6	Rigid	1	1	Yes/New
2	2	SIDiiS (5th percentile female)	3.3.3.6	Rigid	1	1	None/Used
3	1	SIDiiS (5th percentile female)	3.3.3.6	Rigid	1	2	Yes/New
4	2	SIDiiS (5th percentile female)	3.3.3.6	Rigid	1	2	None/Used
5	1	SIDiiS (5th percentile female)	3.3.3.6	Rigid	1	3	Yes/New
6	2	SIDiiS (5th percentile female)	3.3.3.6	Rigid	1	3	None/Used
7	3	SIDiiS (5th percentile female)	3.3.3.6	New XC40	2	4	Slit
8	3	SIDiiS (5th percentile female)	3.3.3.6	New XC40	3	5	Slit
9	3	SIDiiS (5th percentile female)	3.3.3.6	New XC40	4	6	Slit
10	4	SIDiiS (5th percentile female)	3.3.3.6	Used XC40	4	6	None/Used
11	4	SIDiiS (5th percentile female)	3.3.3.6	Used XC40	4	6	None/Used
12	4	SIDiiS (5th percentile female)	3.3.3.6	Used XC40	4	6	None/Used

Figure 4.1: Testing scheme for the twelwe physical tests

4.1.2.1 Video Results

By analysing the slow-motion videos captured of all the tests in the software Kinovea, the behaviour of the dummy leaving the seat looks very similar between all the setup configurations. At maximum structure deflection of around 37 milliseconds, the rigid seat deflects only 25% backwards of what the normal seat does, also with less torsion of the back which can be observed in *Figure* 4.2 and 4.3.

From watching the camera-view of Camera 2 *(3.2b)*, the side-wards deflection on the normal seat is not as large as backward and does not get reduced as much by the rigid one. However, there is a noticeable sag visible from camera 3 on the right side of the height mechanism in the normal seat of three centimetres whereas the rigid structure does not sag at all. There is no visual difference on the dummy ejection behaviour to have breakthrough material or not in the rigid seat structure.

The deployments of setup 4 where the same structure undergoes repeated testing did not have any large differences between them, the fourth deployment of test 12 compared to test 9 has tiny more deflection and torsion and sag.

Figure 4.2: Rigid (left) and normal (right) seat structure before signal

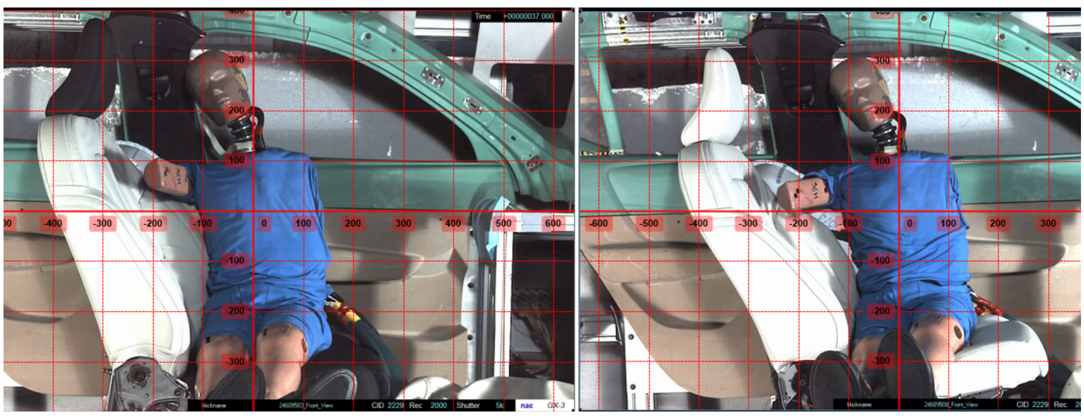


Figure 4.3: Rigid (left) and normal (right) seat structure 37 milliseconds after signal

4.1.2.2 Data Results

For each of the four setups of in *Figure* 4.1. The average maximum values as a percentage of limit values in three different ribs are displayed in *Figure* 4.4. The different plots follow a similar pattern in descending order with setups 3, 4, 1 and 2. Setup 3 is closest to the limit and 2 is the furthest from it. The first four setups generally have a difference between 10 and 15 percentage points. This result was surprising as the general thought of people involved was that making the seat rigid as well as removing breakthrough material would generate higher peak forces on the dummy, but the opposite was showing in these results. Also the reference data of setup 5 from a previous certification is slightly lower in most tests.

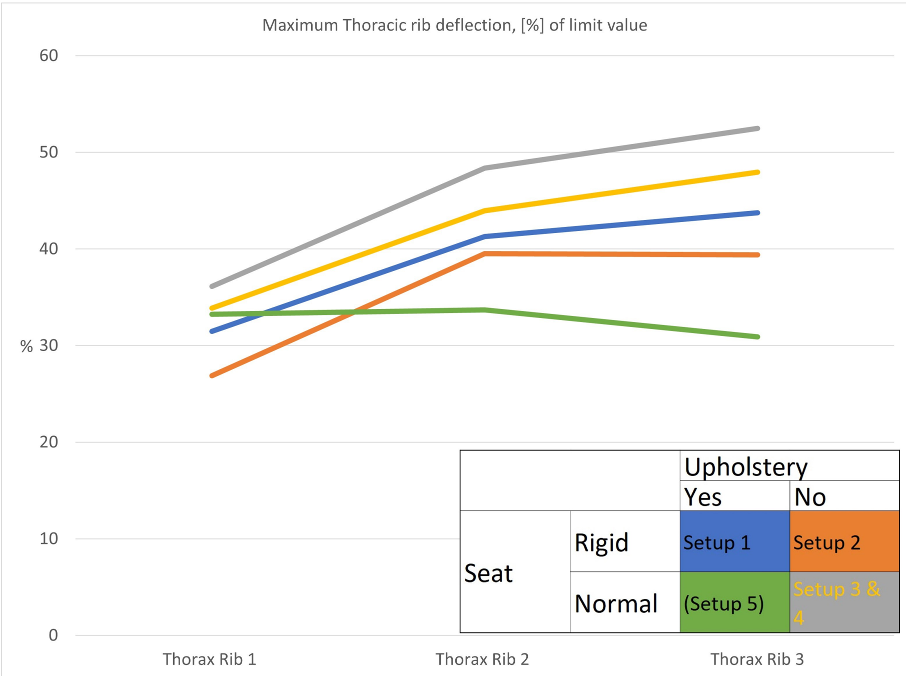
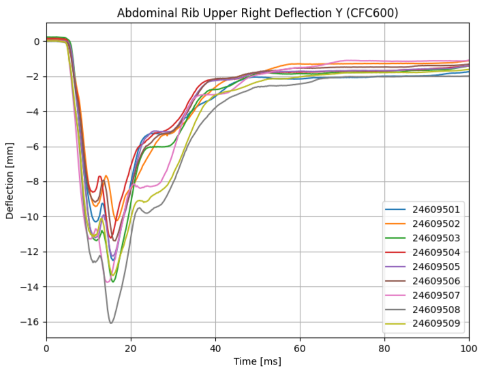
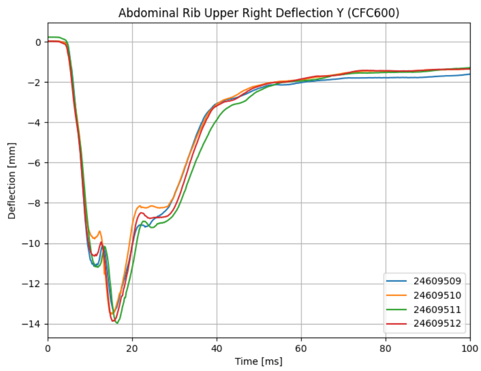


Figure 4.4: Average maximum registered values on three different ribs

The graphs from the repeated tests in Setup 4 (*Figure 4.5b*) follow each other very closely within 10 - 15% from the smallest to the largest peaks. This means there seems to be negligible deterioration on the repeated tests, at least up to 4 times; how long is unknown. Comparing setup 1, 2 and 3 in *Figure 4.5a* they also follow each other very well, with some larger differences of up to 50% from lowest to highest peaks, but there are close to similar levels of variation within setups as between them. Overall, the dummy movement did not visually vary much, no matter which setup was being tested: breakthrough material or not, rigid or not. The graphs from all tests can be seen in A.2 and the code used for generating these graphs can be found in A.1.



(a) The first nine tests



(b) Repeat tests

Figure 4.5: Test data from dummy Abdominal Rib

4.1.2.3 Physical Testing Summary

- Small permanent damage was made to the seat structure from the repeated testing, after inspection and scanning the structure was relatively unaffected after four tests.

- There was generally very similar results no matter if there was breakthrough material or not and if the structure was rigid or not, meaning simplifications can be made without risk of changing the results to much from the original seat.

- In the reinforced structure, the crossbar enclosed within the brace to the floor has a crack in the weld attaching it to the side seat structure. Meaning the load was not sufficiently distributed and stress concentrations were too high around the crossbar to structure weld.

- It was relatively tedious and time consuming to change the full upholstery of the rig between every test, about ten minutes of heavy and precise manual labour.

4.2 Customer Needs & Requirements

The collected needs and requirements from the held interviews, physical testing performed and literature study are summarised and compiled into lists and specifications for greater visibility and presented in this chapter.

4.2.1 Customer Needs List

The initial customer needs list was first created after the interviews and was updated with the knowledge gained in the previous steps. This update mainly removed needs that were assumed from the interview such as the need to have similar seat deflection. The updated list can be seen in *Table 4.2*.

Table 4.2: Updated customer needs list

Stakeholder	Expectation	No.	Need	Dimension
1. Volvo Cars	Lower cost and material/co2	1	Rig or parts of rig that lasts for multiple tests	Durability, Economy and sustainability
	usage during testing	2	Be able to replace destroyed components	Modularity
		3	Low cost rig	Economy
		4	Low weight (shipping cost, and handling)	Economy
	Compatible with generic sled	5	Rig fits within the design space	Design
		6	Rig compatible with the mounting points	Design
	Accurate testing	7	Similar surface geometry behaviour	Testing performance
		8	Similar resistance to airbag deployment	Testing performance
		9	Similar effect on deployment direction	Testing performance
		10	Same angle of seat back	Testing performance
	Compatible with test protocols	11	Adjustable in z (theoretically discrete is ok)	Testing performance, Easy handling
		12	Adjustable in x (theoretically discrete is ok)	Testing performance, Easy handling
	Fulfill seat design guidelines	13	No overlap in x	Design
		14	No sharp corners (r<3.2) towards the airbag	Design
		15	No protruding elements, e.g. seams	Design
2. User	Accurate testing	19	Similar surface geometry & dimensions	Testing performance
		16	Similar resistance to airbag deployment	Testing performance
		17	Similar effect on deployment direction	Testing performance
		18	Same angle of seat back	Testing performance
	Compatible with test protocols	19	Adjustable in z	Easy handling
		20	Adjustable in x	Easy handling
	Easy handling	21	Low weight	Maneuverability
		22	Good handles and gripping possibilites	Maneuverability
		23	Simple adjustments	Easy handling
		24	Easy access to airbag module	Easy handling
	Easy test setup	25	Easy to find correct test setup positions	Easy handling

4.2.2 Requirement Specification

The requirement specification was made based on the customer needs list but complimented with the "hard" data to have actual values that need to be fulfilled. In order to better constrain the possible solutions, more precise requirements had to be made. See extract of the requirements in *Table 4.3* and the full specification with desires and justifications in *Appendix* A.1, A.2.

Table 4.3: Requirement specification summary

RQ No.	Criteria	Target value
Cost and material usage reduction		
1.1	Seat or parts of seat that lasts for multiple airbag deployments (forces and heat)	Minimum 5 deployments, preferably for the entire testing of a specific car model
1.3	Low cost rig	- 50% cost reduction over 100 tests
Compatible with existing testing equipment and design guidelines		
2.1	Rig must fit within design space	TRUE
2.2	Rig must be compatible with existing mounting points	TRUE
2.3	No stiff (structural) elements in front of airbag (overlap in x)	TRUE
2.4	No sharp corners in direction of airbag	Radius>3,2 mm
2.5	No protruding elements that may interfere with airbag deployment	TRUE
Accurate testing - Similar behaviour to real seat		
3.1	Same surface geometry	A-surface needs to be same
3.2	Same seating foam stiffness	Same as real seat
3.3	Geometrically same airbag mounting points as seat	Same coordinates
3.5	Similar surface friction between airbag and expansion points of contact	Within reason
3.7	Not affect deployment direction	Same direction
3.8	Consistent & predictable test result	Measurable and predictable deviation
3.9	Adjustable angle of seat back	Must be able to maintain design angle regardles of set height
3.10	Adjustable in x	Continous through full range
3.11	Adjustable in z	Highest and lowest setting corresponding to seat travel box

4.3 Concept Creation

By breaking the problem down into smaller problems or functions, sub-solutions for every sub-problem can be solved. By looking at every sub-problem individually, it is easier to find solutions that can later be combined into a full solution.

4.3.1 Functional Decomposition

Making a function-means model over the airbag testing rig facilitated the identification of functions that needed to be fulfilled in order for the rig to be useful. The function means tree also included interactions between components and it could be noted that some of the seat adjustment functions had interactions with other adjustments. The height mechanism does not only change the height but also the back and seat angle. This property must be taken into consideration in the concept generation so that the positions reached by the concept are the same. The function means the tree can be seen in *Appendix A.3*.

4.3.2 Concept Generation

For concept generation eleven functions were selected with the help of the function-means tree to cover the functional needs of the rig in the morphological matrix. A condensed version of the morphological matrix can be seen in *Figure 4.6*.

Function	Solutions														
Direct airbag	Nothing	Silicone Tube (zf)	Trimlist (like spa1)	Ureol	Walls	Tube + foam	Hinge with springs	Tough foam	Chute	SPA like + space fabric	Modular bolster (connecting foam to foam	Projectile bolster	Frigolit block	Silicone bolster
Restrict airbag expansion	No breakthrough	Foam and Upholstery	Only foam	Only upholstery	Thin Plastic or rubber Sheet (IP simulator)	Only restricted area (using the directioning	Velcro	Tape	Magnets	Burst zipper	Friction metal buttons	Flap	Spring	Replaceable tear seam
Adjust Length	Original electric	Slots (moving the adjustment down to the support	Original e-mech with brace	Manual screw axle, Pelarborr korsbord	rack & pinion	Original mechanical	Gym length mech	Travers(balkvagn/löpvagn)/lisebergs bana						
Lock length	Original electric	hole & pin	screw	lead screw	Gym length mech	Clamp (skruvstäd)	worm drive							
Adjust height	Original e-mech	Slots & bolts(like Florins)	Curved slots (same tilt as normal)	Original concept reinforced	Gym mech	have 2 different seats with locked height								
Lock height	Original	bolts(like Florins)	Original w brace	Hole & plunger	worm drive	Serrated washer	have 2 different seats with locked height							
Adjust angle	Original e-mech	Gym mech hole & plop	Original w brace	Office chair	Manual wind, like mechanical 316	Have 3 different backs and welded recliners								
Lock angle	Original recliner	Gym mech hole & plop	Original w brace	Office chair	worm drive	Have 3 different backs and welded recliners	screw clamp	brace + recliner						
Provide correct geometry	Origional seat foam	Ureol	Styrofoam	Cloth padding, heat resistant	Tough foam									
Attach seat to rig-floor	Like normal (Ureol blocks)	metal structure (sånna mattias hämtade)	New rigid metal structure without adjustments	New custom lenght adjustment rails										
Attach airbag to seat	Like normal	Re-enforce structure holes with sheet metal	Replacable nuts and bolts	Pins & clips (easy click in)										

Figure 4.6: Morphological matrix

From the concept generation using the morphological matrix a set of 20 concepts of vastly different solutions were compiled. See combination and names in *Figure 4.7*. A few important ones can later be seen as digital models in Chapter 4.4.3.

Concept no.	Func. 1	Func. 2	Func. 3	Func. 4	Func. 5	Func. 6	Func. 7	Func. 8	Func. 9	Func. 10	Func. 11	Name /Description
1	1	1	1	1	1	1	1	1	1	3	1	The Simplest Possible (just doing multiple shots in normal seat)
2	6	1	3	1	1	1	1	1	1	3	1	COP inspired
3	6	1	1	1	1	1	1	1	1	3	1	COP with improved A surface
4	7	1	1	1	1	1	1	1	1	3	1	The hinge
5	7	12	1	1	1	1	1	1	1	3	1	The hinge + flap
6	1	2	1	1	3	2	6	6	1	3	1	The Andeas special: Stiff base, welded backs, replace upholstery
7	8	9	1	1	1	1	1	1	1	1	1	Tough foam + magnets
8	4	5	1	1	1	1	1	1	1	1	1	Ureol + IP
9	8	6	4	4	2	2	6	6	1	3	2 & 3	Very mechanical
10	10	1	1	1	1	1	1	1	1	1	1	Spa + Ironing board
11	1	5	1	1	4	3	1	1	1	3	2 &3	Mimic breakthrough with rubber simulator
12	12	2	2	3	2	2	1	1	1	3	3	The projectile
13	13	1	2	3	2	2	1	1	1	1	1	Freddans specialare
14	11	2	1	1	1	5	1	1	1	1	1	Modular bolster
15	1	3	1	1	4	3	1	1	1	1	3	OF (only foams)
16	7	9&12	1	1	1	1	1	1	1	1	2&3	Hinge + magnetic flap
17	14	1	1	1	4	3	1	1	1	1	1	Plastic fantastic
18	1	4 & 7	1	1	4	3	1	1	1	3	2 & 3	Silver tape
19	7	12	1	1	6	7	1	1	1	3	2&3	Outward hinge & 2 separate height seats
20	7	9&13	1	1	1	1	1	1	1	1	2&3	Spring flap
21	1	2	2	3	2	2	5	1	1	4	2 & 3	Florin inspired

Figure 4.7: First concept catalogue

4.4 First Screening & Concept Development

The concepts generated in the previous chapter were repeatedly screened and developed as more knowledge was gained. The outcomes and inputs of each screening matrix are shown in detail by the figures and explaining text.

4.4.1 Concept Elimination

The initial screening of concepts was made using an elimination matrix seen in *Appendix A.4*. The output of the first elimination matrix was that 4 of the 21 concepts was eliminated. The remaining concepts were then reviewed and re-imagined by splitting and combining the ideas that were deemed to be the best. The elimination matrix was performed once again with the merged and developed concepts. This second loop resulted in another 8 concepts being eliminated. The resulting concepts are presented by name and function combination in *Figure* 4.8.

1	1	1	1	1	1	1	1	1	3	1	The Simplest Possible (just doing multiple shots in normal seat)
7	12	1	1	1	1	1	1	1	3	1	The inward hinge + flap
1	2	1	1	3	2	6	6	1	3	1	The Andeas special: Stiff base, welded backs, replace upholstery
13	6	4	4	2	2	6	6	1	3	2 & 3	Very mechanical freddy
11	2	1	1	1	5	1	1	1	1	1	Modular bolster
7	12	1	1	6	7	1	1	1	3	2&3	Outward hinge & 2 separate height seats
6	1	3	1	1	1	1	1	1	3	1	COP inspired
8	9	1	1	1	1	1	1	1	3	1	Tough foam + re-sealing
1	2	2	3	2	2	5	1	1	4	2 & 3	Florin inspired

Figure 4.8: Second concept catalogue

The remaining concepts were then compared relative to each other in a modified Pugh matrix with weighted criteria. A matrix from the initial round of comparisons can be seen in *Figure* 4.9.

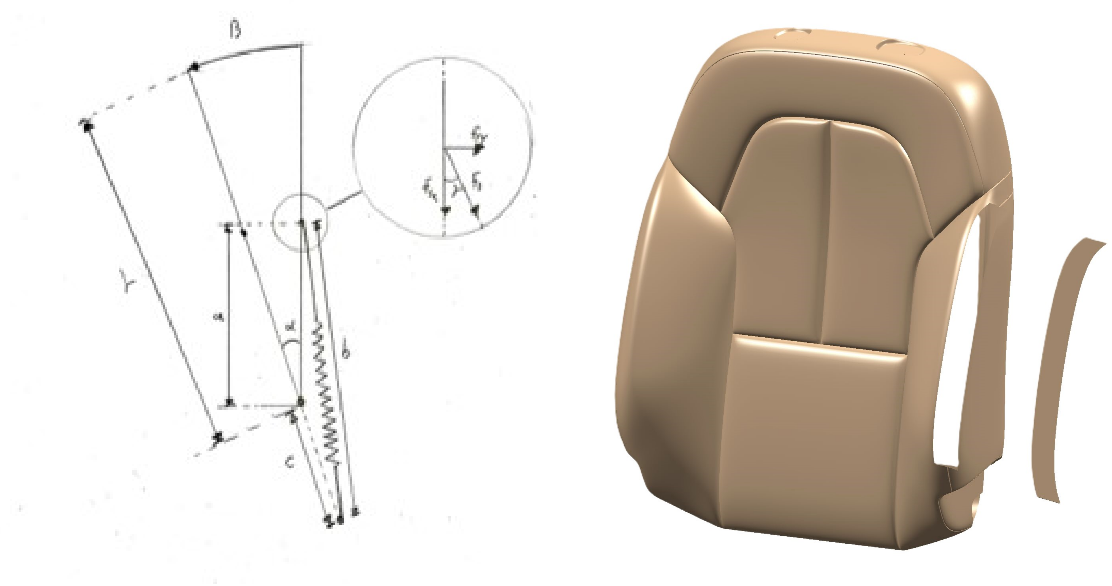
Criterias	Criteria Weight	Concepts: The Simplest Possible	The inward hinge + flap	Stiff base, multiple welded backs, replace upholstery	Very mechanical freddy	Modular bolster	Outward hinge & 2 separate height seats	COP inspired	Tough foam + re-sealing	Florin inspired
Lifecycle cost	2	REF	1	1	1	-1	1	1	0	1
Life cycle CO2	1		1	0	1	-1	-1	1	0	1
Low weight	1		-1	-1	-1	0	-1	0	0	-1
Testing accuracy (breakthrough & positioning)	3		1	1	0	1	1	-1	0	1
Adaptability to future seat changes	2		1	1	1	1	1	-1	0	1
Easy to adjust seat with precision	1		0	0	-1	0	0	0	0	-1
Easy to guage seat position	1		0	1	0	0	1	0	0	0
Easy to lock seat position	1		0	-1	0	0	0	0	0	-1
Easy to determine top of module	1		0	-1	0	-1	0	0	0	0
Easy dummy positioning	1		0	0	-1	-1	0	0	0	0
Easy to access & replace airbag	1		-1	0	0	0	-1	0	0	0
Little consumables	1		0	-1	-1	-1	0	0	0	-1
Repairability	1		-1	-1	0	0	-1	-1	-1	0
Relative performance		REF	5	3	1	-1	4	-3	-1	4
Advance to next step		yes	yes	yes	no	no	yes	no	no	yes
Reason		Good baseline solution to compare to	Provides good test accuracy and repeatability at reduced cost	Gives very lasting frame and repeatabilty and breakthrough accuracy, but takes more	Hard to join the styrofoam bolster into seat back foam in a good way, clunky adjusting	Unpredictable, might be more expensive than ref solution	Provides good test accuracy and repeatability at reduced cost, with strong frame	Does not mimic airbag expansion good enough	More complex than ref solution, but similar performance	Gives very lasting frame and repeatabilty and breakthrough accuracy, but takes more

Figure 4.9: Pugh matrix with some of the criteria weighted higher than 1, where four out of nine concepts were discarded

The initial round of Pugh eliminated four concepts for being worse than the other five in relative performance: Very mechanical, Modular bolster, Silicone tube, Tough foam + re-sealing did not seem as promising when the weights were introduced.

4.4.2 Introduction of New Concepts

The remaining concepts were further developed before the second loop of comparison. An idea brought in at this stage was the overcenter spring concept as well as the replaceable tear seam concept. The idea behind the overcenter spring concept being that the force needed to open the flap gradually increases until the spring is 180°relative to the flap and then drops to zero. The replaceable tear seam concept means that the tear seam is placed in a smaller module and a connection means for attaching this module to the rest of the upholstery introduced. This means that the correct geometry and hardness of the seat and bolster can be kept as well as obtaining the correct breakthrough resistance and the "brittle" failure of the seam. The concepts can be seen in 4.10.



(a) Overcenter spring **(b)** Replaceable tear seam concept

Figure 4.10: New concepts introduced after concept presentation

The concepts at this time, along with their pros and cons, were presented to members of the airbags & steering wheels group and discussed. This session focused on breakthrough concepts, which were deemed to be the most important to get feedback on. The low level of interaction between the breakthrough concepts and structural concepts also meant that all combinations were possible. Feedback on current ideas and new ideas were proposed.

4.4.3 Interim Concept Catalogue

Here, a few concepts that were developed into digital models are presented. Some of them were more or less quickly discarded, but most of them provided valuable insights for further development. Important realisations often came when having a detailed model in the correct scale to view and discuss.

4.4.3.1 Substructure & Adjusters

Two large lying H's would allow very rigid and robust continuous setting of the seat height and length. As shown in *Figure 4.11* the lying H's would require very large side-plates in order to fit the entire slots.

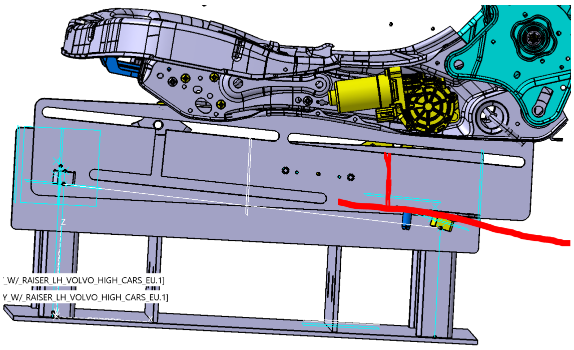
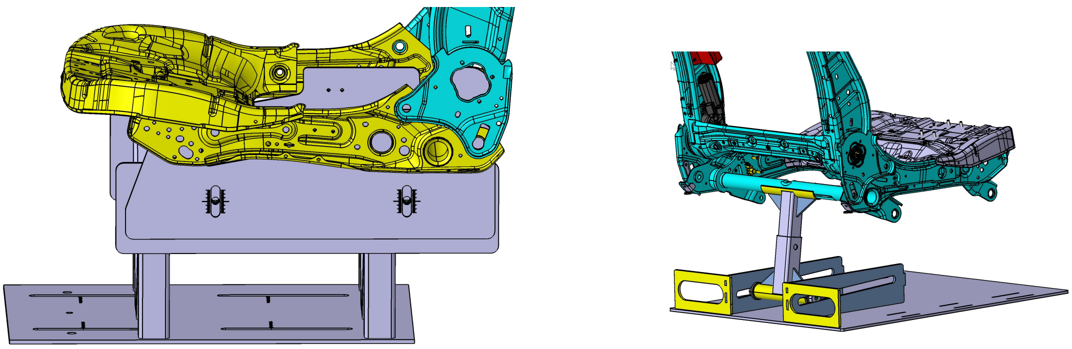


Figure 4.11: Lying H Adjustment concept

The rig was built during autumn for the initial physical testing. The rig was designed by a design engineer at the Airbags & Steering Wheels team. This solution has height adjustment on the side walls and length on the bottom plate (*Figure 4.12a*).

Another concept that seemed potent of both assisting with great support and also not obstructing the adjustment over the full travel box was the strut or telescope concept that is only engaged after adjusting the seat into the desired position (*Figure 4.12b*).



(a) Florin concept

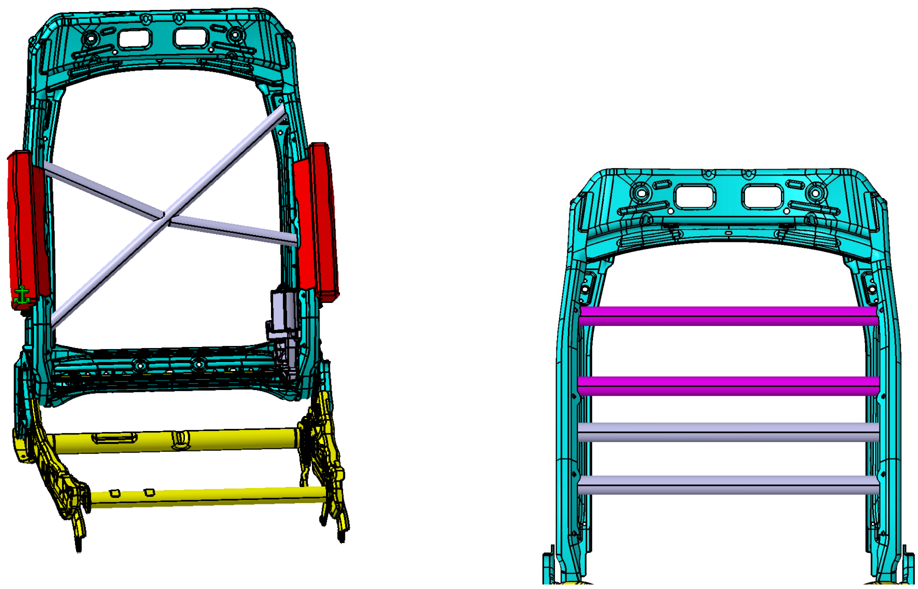
(b) External strut concept

Figure 4.12: Substructure concepts

4.4.3.2 Backrest Reinforcements

The simplest way to combat the forces acting in Y from both the side airbags is to make a cross in the structure. This provides solid reinforcement to the back, but moves the problem downwards by making the recliner joint take all the load. A solution that could transport the loads from the backrest directly to the ground was looked after instead (*Figure 4.13a*).

The rig was built during autumn for the initial physical testing. The rig was designed by a design engineer at airbags & steering wheels. The reinforcements were done horizontally to easily be able to attach support down to the floor (*Figure 4.13b*). But there were unnecessarily many, and they were partly in the way of airbag mounting during testing and needed to be cut in some parts.



(a) Cross back reinforcement **(b)** Horizontal back reinforcements

Figure 4.13: Backrest concepts

4.4.3.3 Breakthrough Mimicking

The overcenter spring was thought to be a way of achieving the distinct behaviour of the tear seam by gradually increasing resistance until it suddenly drops to zero as the flap gets aligned with the spring and then past. This idea was imagined to be used in combination with any of the "flap" or "hinge" concepts.

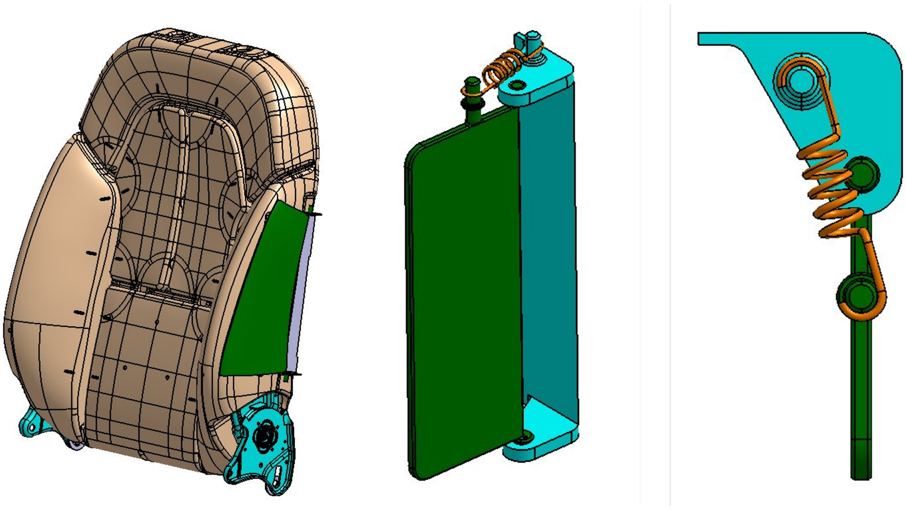


Figure 4.14: Spring concept

The input and discussions from the team lead to one new concept being added. The breaking flap. The idea was to have a plastic flap in order to get repeatable breaking behaviour in a controlled and easily replaceable manner by having a notch.

4.5 Further Development

Further developments of the sub solutions that existed within the remaining concepts was made. Concurrently, iteratively and intertwined with this process a structural optimisation was performed.

4.5.1 Breakthrough Concepts

The overcenter spring concept was further developed until it was proven impractical due to the force component that acts in the direction of the tear seam would be only a fraction of the force exerted by the spring. This is partly inherent to the concept but worsened by the spatial constraints limiting the placement of the spring and pivot points. Because of this the concept was scrapped.

The breaking flap concept (*Figure* 4.15) was further developed but no practical solution to achieving the desired strain, resistance to opening and tear behaviour was found. The flap would need to deform about 50 mm with linearly increasing resistance and then snap without any ductile behaviour. The design also had issues in obstructing the airbag expansion, the airbag usually protrudes side-wards and backwards before breaking the tear seam. The concept was tested with a 3D print of PLA (polylactic acid). The test object broke in a very ductile, non-desired way with way less resistance than expected. Thus, this concept was cut.

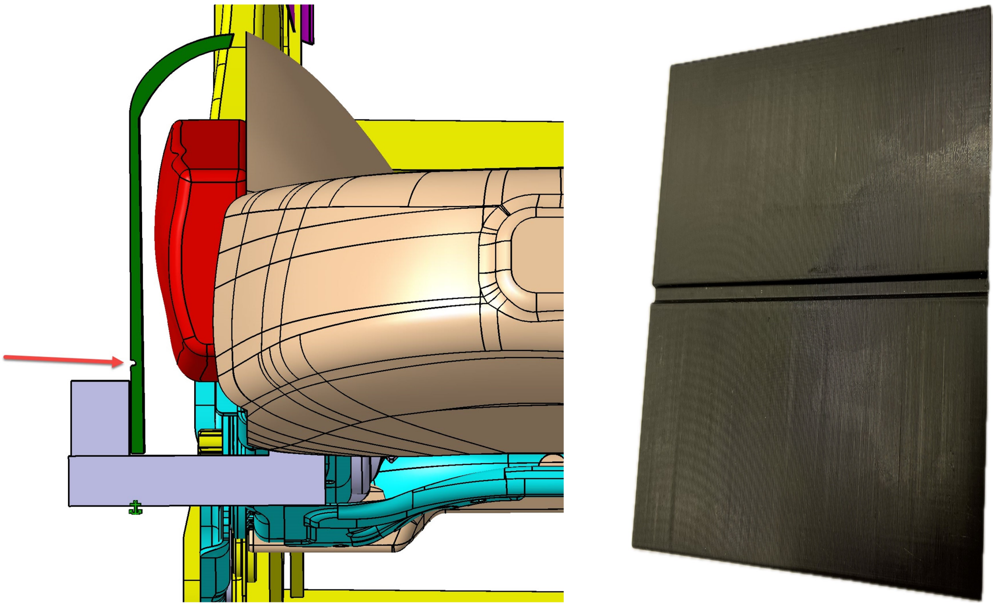
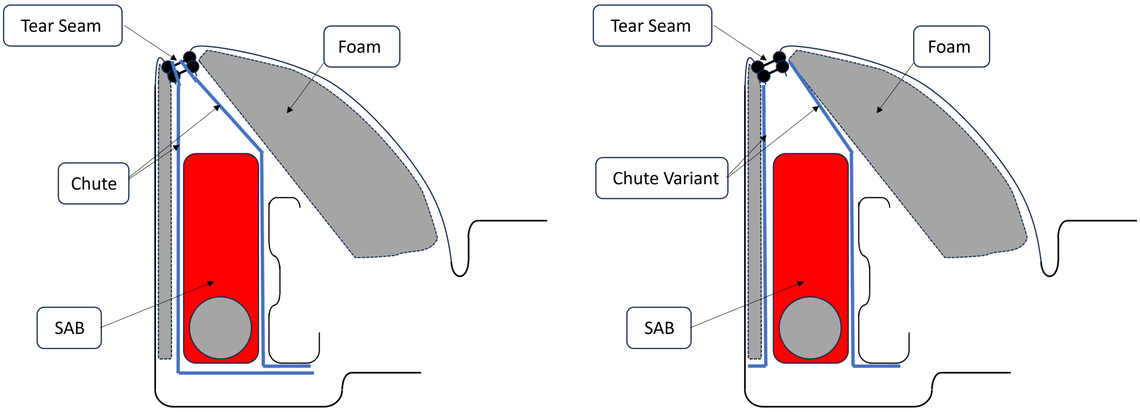


Figure 4.15: Breaking flap concept with notch marked by the red arrow to the left and the printed test piece to the right

The replaceable tear seam concept (*Figure 4.10b* was further developed by adding multiple potential connection means to be evaluated. The concept was presented to members of the airbags & steering wheels team at VCC and the concept was received positively. Meetings were also held with employees knowledgeable in sewing upholsteries, and the possibilities for embodying this solution were discussed. One potential problem brought up in this phase is that of the foam gradually breaking down from repeat deployments. The proposed idea for solving this issue is a variant of what at VCC is known as a "chute" or "shooting channel". A "chute" in this context is a sock made out of airbag fabric that encapsulates the airbag and guides it towards the tear seam. This solution is normally employed to improve the robustness of the system as it aids in the guiding of the airbag. In this solution, a slight change to the concept is proposed. Changing where the fabric is attached protects the foam and does not improve the performance in any other way. A normal chute and the proposed solution are shown in *Figure 4.16*.



(a) A normal chute (b) The concept fabric covering

Figure 4.16: The conceptual chute modifications

4.5.2 Structural Optimisation

This chapter presents the results of both topology optimisation loops. From the first exploratory loop, a wide variety of topologies were obtained. In the second loop, a concept was selected, and the topology for the telescopic strut and the connection to the seat back are presented.

4.5.2.1 Optimisation Setup

The optimisation problem was formulated as a minimisation problem where the compliance of the structure was minimised and it was constrained by a volume fraction. Additional constraints for manoeuvrability were a minimum member size as well as a single plane symmetry ensuring symmetry right to left.

Objective:

- Minimise compliance

Design Variables:

- The design volume

Constraints:

- Volume fraction
- Minimum member size
- Symmetry

4.5.2.2 First Optimisation Loop

The first optimisation loop was exploratory and resulted in a large variety of topologies. Some of the resulting topologies can be seen in *Figure 4.17*. The difference in these results comes from varying how the problem is posed, e.g. changing what amount of material to retain as well as cutting away some of the design volume that is never used to save computational cost.

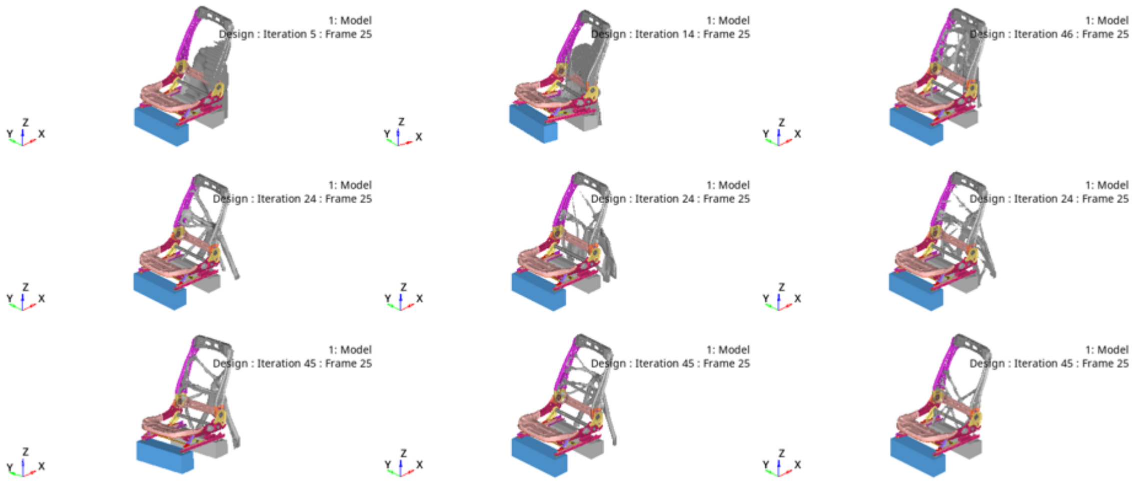


Figure 4.17: Exerpt of catalogoue of resulting topologies

The topologies were compared against structural concepts for the different mechanisms in the seat while the concepts themselves were concurrently developed. Any potential synergies between the topologies and the mechanisms were considered to find a topology that would easily translate into a mechanism.

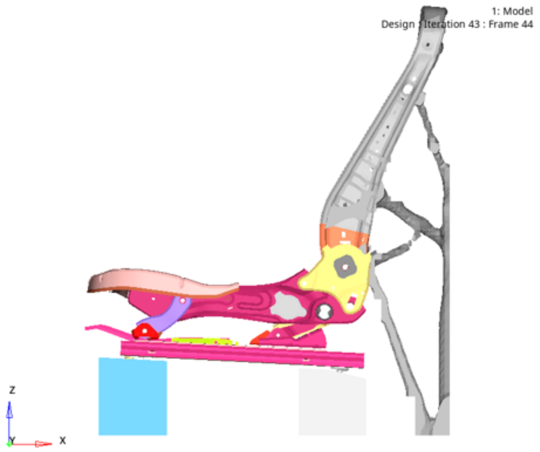
The two H's become too large when having to cover the full travel box of the seat, forcing an unreasonably large side plate size. It would also be physically exhaustive to move and adjust, with a great chance of getting stuck due to the alignment of metal plates. Thus the H's were cut as a concept.

The Florin concept was the only concept thoroughly tested as a physical version in full detail was used for the testing performed at the beginning of the project. It did survive multiple deployments and could be slightly adapted to cover the full travel box. However, it proved very physically challenging to work with during testing, and the current iteration had a weld crack during testing. Thus, this concept was kept for now.

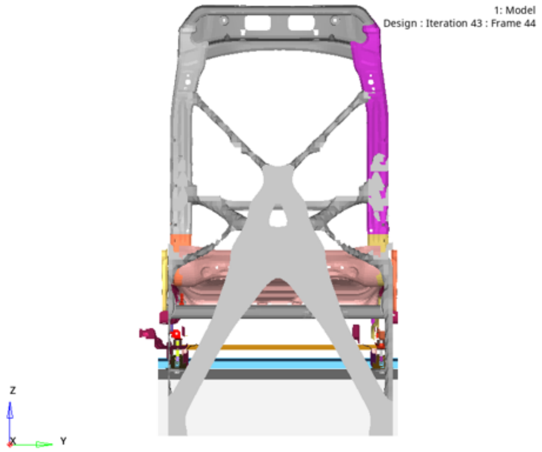
The external strut concept relied on the original mechanisms and would thus be easy to adjust. There were some concerns regarding the structural integrity of this solution as well as the potential for user error.

4.5.2.3 Second Optimisation Loop

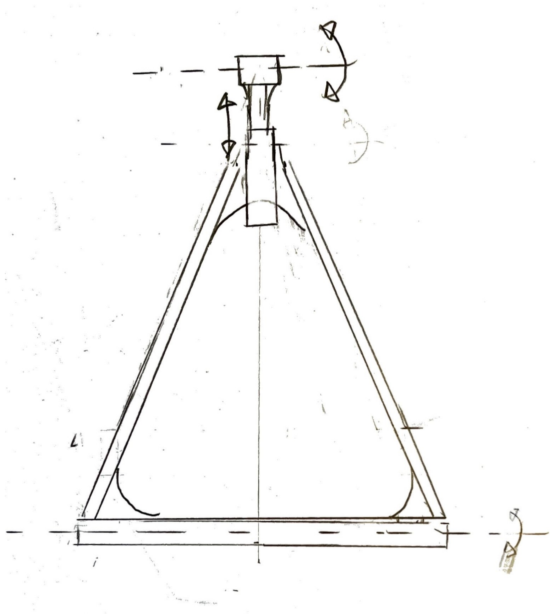
From the first optimisation loop a structure that would not allow the required seat adjustments was obtained. The result was a structure and not a mechanism. This design was then forced into a different shape by cutting away from the design space and only allowing it to contact the ground in a much more constrained space. This topology can be seen in *Figure 4.18a & Figure 4.18b.* The resulting topology was interpreted as something reminiscent of the Florin/External strut concept. The initial sketch for this can be seen in *Figure 4.18c.* This design is an attempt to bring pivot and length adjustments to the triangular base of the previously obtained topology. The arrows in the sketch show the degrees of freedom for this triangular telescopic strut. The idea of this simple drawing was then designed in Catia and yet again exported to Hyperworks. This time, the strut and seat were used as existing geometry, and a design space was set up to connect the two. The rest of the problem formulation was largely kept as before. The output from this optimisation can be seen in *Figure* 4.19 and was used as the basis for the design realised in CAD.



(a) Side view of topology



(b) Rear view of topology



(c) Rear view of telescopic strut sketch

Figure 4.18: Topology and design interpretation

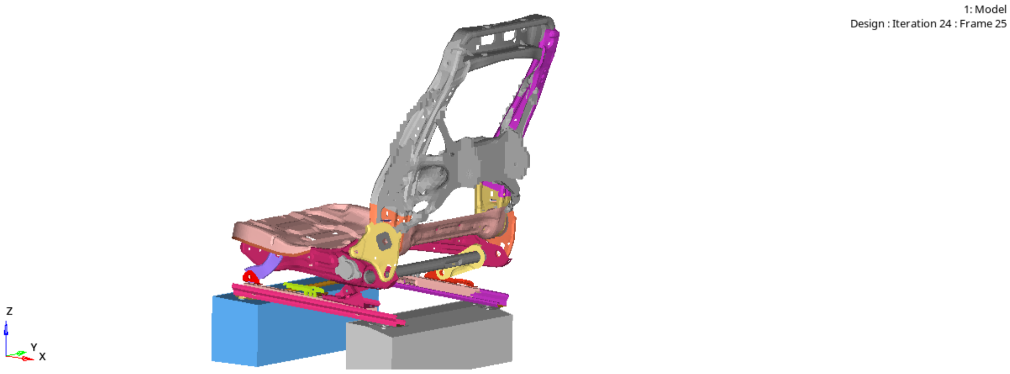


Figure 4.19: Optimised topology between seat and strut

4.6 Second Concept Screening Loop

More details of how each concept should be realised was developed, and the optimisation gave guidance of how an effective and efficient structure can look. Knowledge that had been lacking during the first iteration of Pugh had been obtained. A second loop of comparative evaluation was done using the modified Pugh matrix with weighted criteria.

		Concepts				
Criterias	Criteria Weight	The inward hinge + flap (overcenter)	Outward hinge & 2 separate height seats (overcenter)	Florin inspired	Breaking flap	Secret Concept
Lifecycle cost	2	REF	0	-1	-1	-1
Life cycle CO2	1		0	-1	-1	-1
Low weight	1		-1	0	0	1
Testing accuracy (breakthrough & positioning)	3		0	1	-1	1
Adaptability to future seat changes	2		0	1	0	1
Easy to adjust seat with precision	1		0	-1	0	-1
Easy to guage seat position	1		0	0	0	0
Easy to lock seat position	1		0	-1	0	-1
Easy to determine top of module	1		0	0	0	0
Easy dummy positioning	1		0	0	0	0
Easy to access & replace airbag	1		0	0	0	0
Little consumables	1		0	-1	0	-1
Repairability	1		0	1	1	1
Relative performance		0	-1	0	-5	1
Advance to next step		no	no	yes	no	yes
Reason		Poor testing performance	Poor testing performance	Gives very lasting frame and repeatabilty and breakthrough accuracy, but takes more manual work	Poor testing performance	Gives very lasting frame and repeatabilty and breakthrough accuracy, but takes more manual work

Figure 4.20: Second round Pugh matrix

The output of this loop showed two concepts outperforming the rest, and one being marginally better than the other. The two remaining concepts were the Florin-inspired and the replaceable tear seam concept. These concepts were, in the end, combined into the final solution. Structurally, it is a combination of the Florin concept and the external strut with the replaceable tear seam concept.

4.7 Proposed Solution

The proposed design has been created in Catia V5 with the guidance of senior design engineers at VCC. In short, the solution can be described with a substructure fully made of sheet metal, a telescopic strut that can cover the Z-direction with the telescopic function and X-direction of the travel box by sliding in slots, and two horizontal bars with a sturdy box-like adapter that connects the seat structure down to the strut. See overview in *Figure 4.21*.

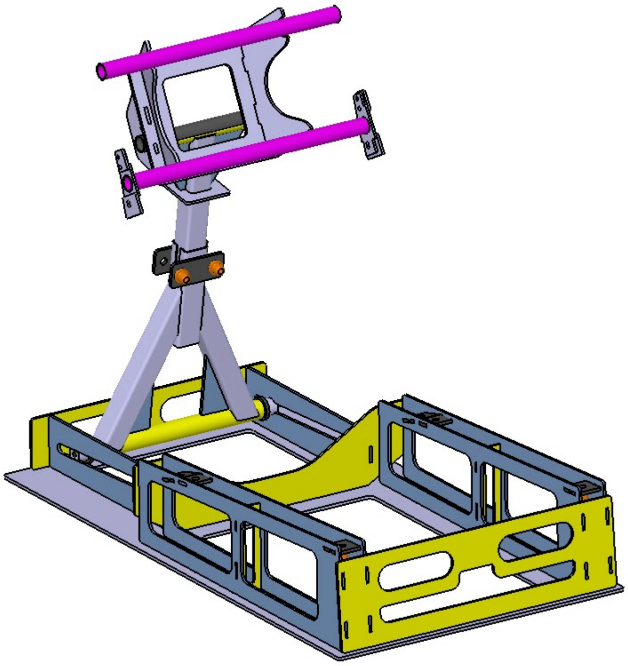
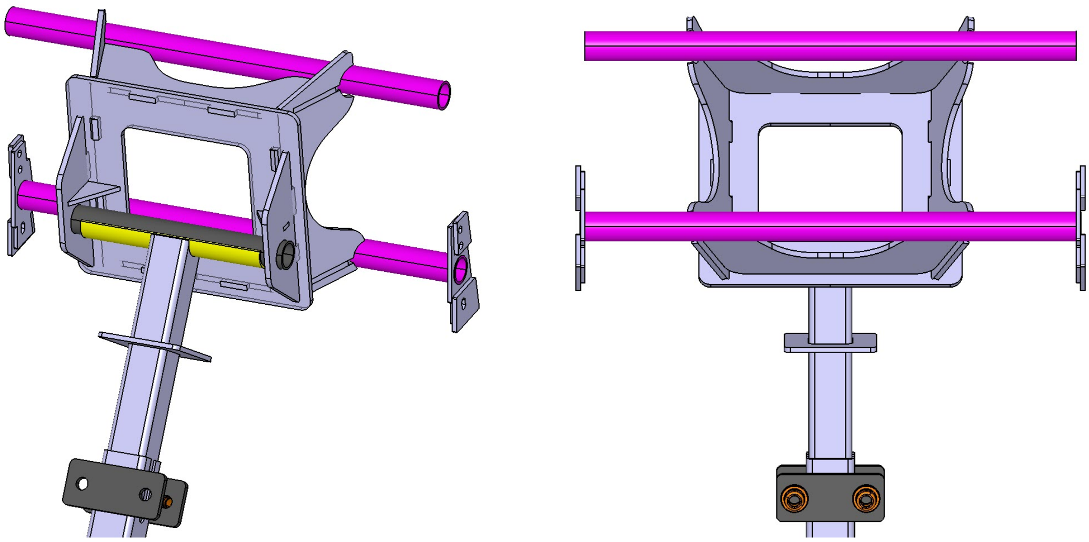


Figure 4.21: Proposed Rig front isometric view

The proposed design keeps the original electrical adjuster mechanisms and motors. The reinforcement telescope bar is only fastened into place after the seat has been put in the desired position, and is not always engaged. The substructure is placed on a bottom-plate that everything is mounted on and welded in place. Handles in the front and rear makes carrying the rig possible despite it's relatively heavy weight of 31 kg without the seat.

The connecting plate (*Figure 4.22*) that connects the telescopic strut to the horizontal reinforcement bars is called "spider plate" after how it looked in the early optimisation and the name has been kept since then. It consists of multiple interlocking plates designed to withstand and evenly distribute the great forces coming from the horizontal bars down to the telescope strut.



(a) Spider plate rear iso

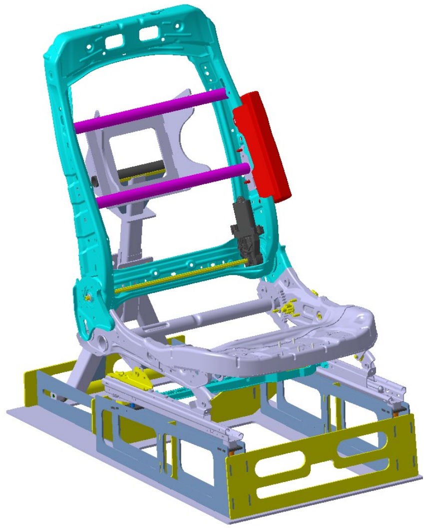
(b) Spider plate front

Figure 4.22: Connecting joint plates, (spider plate)

The reinforcement structure consists of a telescope bar ending with a yellow half-moon bracket that should be placed against a black tube and locked with a clamping force of screws when in the correct position seen in *Figure 4.22a*.

To cover the full travel box that is needed in OOP testing, the height coverage is realised by the compression and extension of the telescope bar as well as the length being covered by the plates with tilted slots (*4.23a*). To counteract the large side-ward acting forces of SAB deployment, the telescope is connected by two angled rectangular profiles down to the bottom plate, and three large yellow plates in the front, middle and rear of the bottom plate connect the two sides to each other.

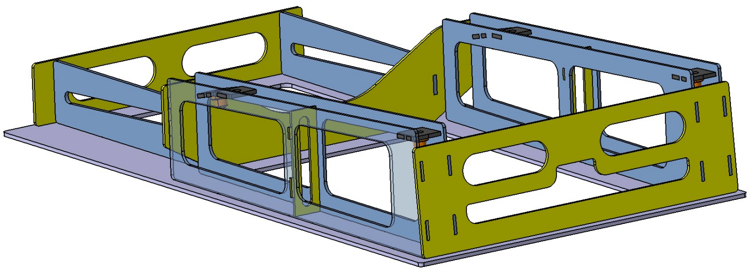
(a) Proposed Rig rear isometric view



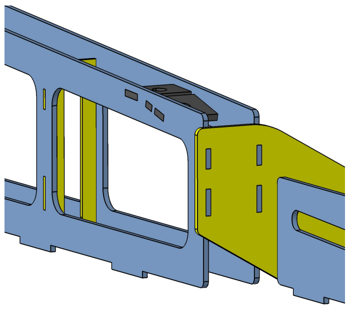
(b) Proposed Rig front isometric view with seat structure and airbag in red

Figure 4.23: Rig with seat structure

The substructure (*Figure 4.24a*) that connects the seat rails to the bottom plate is made from sheet metal in multiple planes joined in a jigsaw-like configuration. The jigsaw design (*Figure 4.24*) comes from a desire for the manufacturing function as this both makes the alignment and positioning for welding easy. However, it also makes the structure very resistant to shearing forces.



(a) Proposed substructure



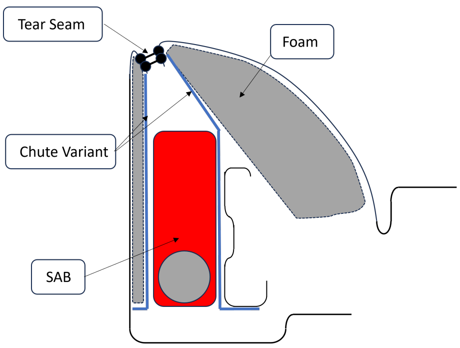
(b) Jigsaw notches in detail

Figure 4.24: Substructure detail view

For the solution regarding breakthrough behaviour, a concept has been developed based on the simple idea of modularisation. By customising the upholstery by making a section or strip of it attachable and detachable, for example, with zippers or buttons, it is possible only to replace the section near the tear seam, which is broken during deployment. Thus, only a small portion of the upholstery must be swapped out between tests and not the entire thing. An early conceptual model of the solution can be seen in *Figure 4.25a* and a physical prototype with buttons as connection means in *Figure 4.25b*. The addition of a protective fabric for the foam is explained in *Chapter 4.5.1* seen in *Figure 4.25c*. For a detailed explanation of the implementation of the replaceable tear seam solution, see *Appendix A.7*.

(a) Conceptual model of the replaceable tear seam

(b) Physical prototype of replaceable tear seam section solution using buttons as connection means



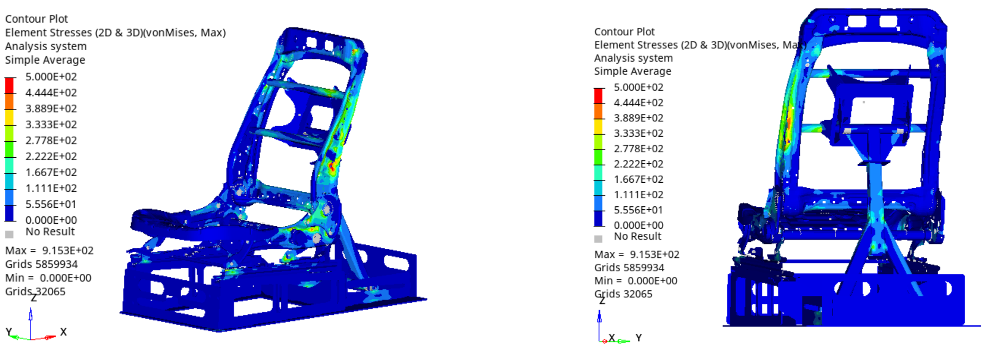
(c) The proposed fabric covering to protect the foam from repeated airbag deployments

Figure 4.25: Replaceable tear seam solution

4.8 Design Verification

To evaluate requirement 1.1, i.e. that the rig should last for multiple deployments, the proposed concept was evaluated structurally using FEA. The structure was exported from Catia, and an FE model was built for the new concept. This model was combined with the old seat model and the load case that was developed for the topology optimisation.

The analysis was set up as an explicit non-linear analysis in Hypermesh and solved in Optistruct. This software was used as the seat model, and the load case was already defined for the optimisation performed earlier. Also, the experience gained with this tool in the previous phase made it preferable. The visualisation for one time step can be seen in *Figure* 4.26. The colour grading has been scaled so that red corresponds to stresses at or above 500 MPa, which is the yield limit of the material.



(a) Stress result front ISO view

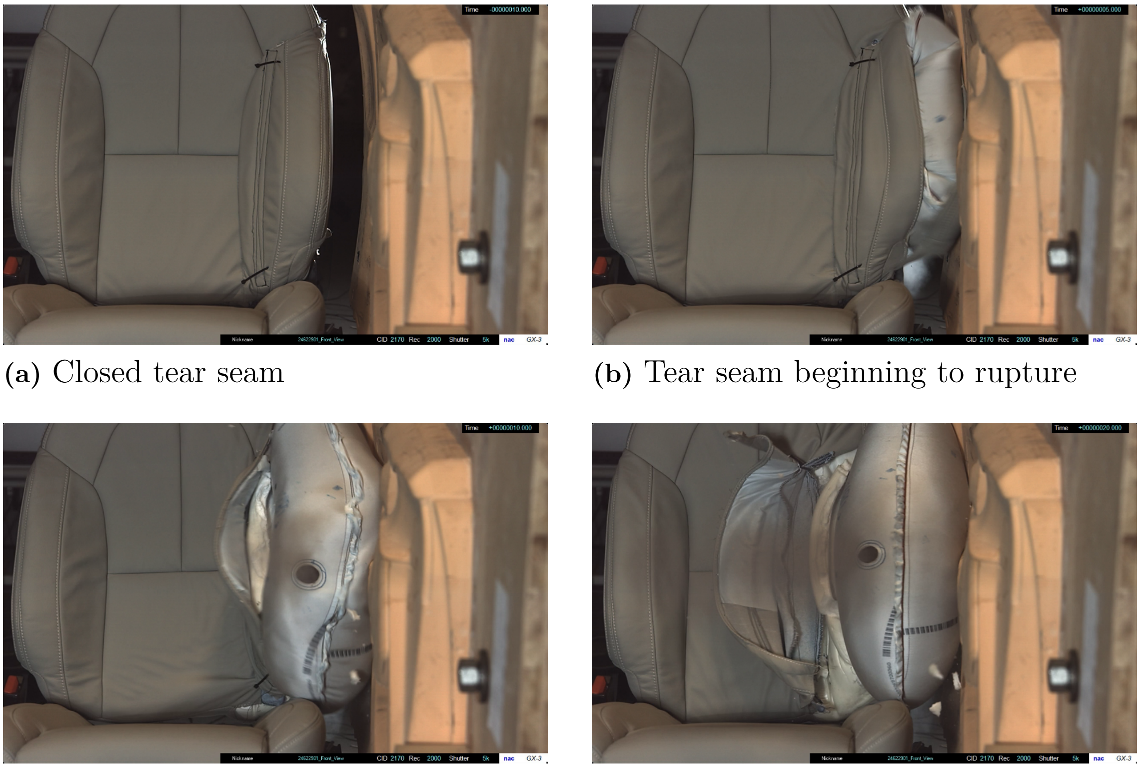
(b) Stress result rear ISO view

Figure 4.26: FEA design verification

The results show two stress concentrations. One is in the SAB mount, and the other is close to a weld where the side member connects to the top of the seat. These points show stress magnitudes above the allowable limit; however, they are believed to be caused by modelling issues. The dark blue area close to the SAB mount is the support plates clipping through the mesh of the seat model. This poor geometric fit comes from the mesh of the seat model not correctly representing the geometry of the side member. This poor fit can cause local stress concentrations as the steel plates are meant to give a smooth stiffness gradient instead, resulting in a sharp stiffness increase where it is connected. The other stress concentration lies in a single element with one corner connected to a weld. It is believed that the way this is modelled is causing the issue. The other elements attached to the weld show stresses of approximately 400MPa and thus about a 25% margin of safety. Besides these two points, the stress levels are well below the yield limit *Figure* 4.26. It is possible that local effects may cause issues with fatigue. However, such an analysis hasn't been performed due to the modelling issues mentioned.

4.9 Breakthrough Concept Testing

Prototypes for three replaceable tear seam solution variants were manufactured and evaluated using physical testing. The three chosen variants were Hook and loop, zippers and buttons. The test results of the hook and loop concept can be seen in *Figure A.9*. The figures for the other concepts can be seen in A.8.



(a) Closed tear seam

(b) Tear seam beginning to rupture

(c) Tear seam completely open

(d) Airbag in position

Figure 4.27: Stages of tear seam opening

All of the tested connection means held up longer than the tear seam, meaning that the tear seam failed as intended. Two out of three concepts, however, did come undone at a later stage when the airbag was closer to fully inflated. This means that the concepts worked as intended, but a stronger connection could be preferred as to reduce the tendency for pieces to fly off.

4.10 Life Cycle Assessment & Life Cycle Cost of Airbag Testing

Internal documents that were presented upon request showed that each seat bought in the early development phase costs several times as much as when compared to final production costs and emits 90 kg of CO_2. With a hundred seats consumed, that means a cost in millions of SEK and 9 tonnes of CO_2. The seat cost can, from the data obtained, be broken down by components and assembly. In *Figure 4.28*, it can be seen that structure and assembly represent over half of the cost for a seat. Both of those categories are avoided by the rig, which reuses the reinforced structure. A similar case is present for the emissions shown in *Figure 4.29*. Around half the emissions are derived from the metal structure and another large part from the polymers. Meaning foam and upholstery.

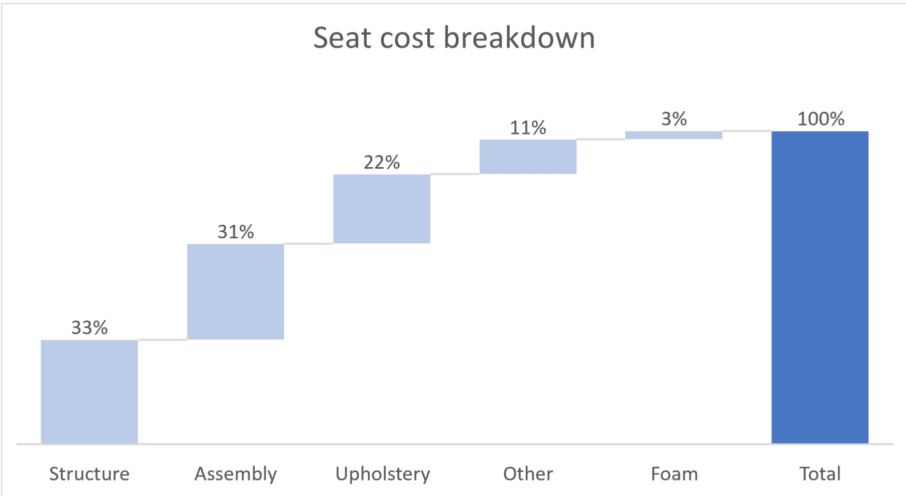


Figure 4.28: Seat cost breakdown per category

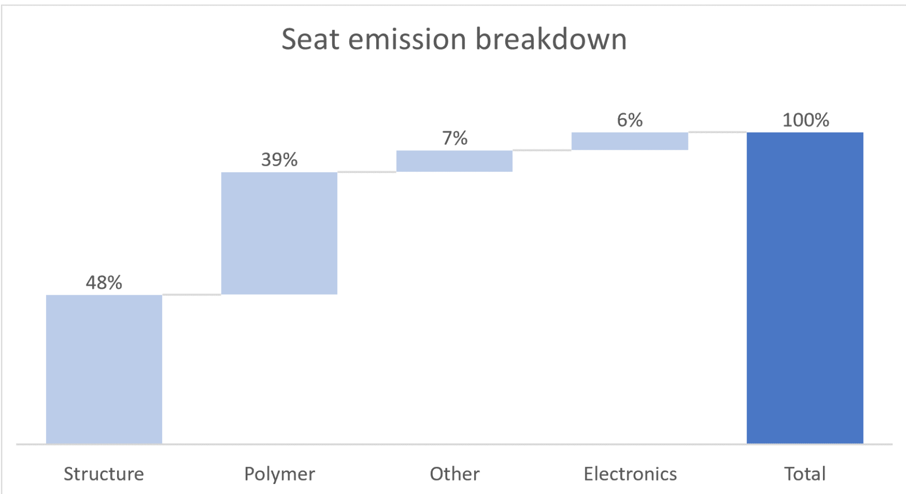
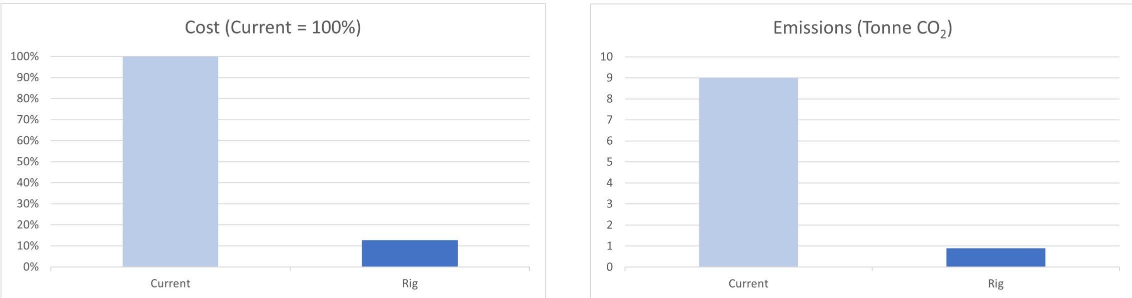


Figure 4.29: Seat emission breakdown per category

To calculate the emissions of the seats and proposed rig, material data obtained from the sustainability department at VCC was used. The data has been worked out internally and used for assessing complete cars over a lifetime like in [29] but certain useful information for this project could be extracted. For example, the emission factor for steel was 2,74 kg CO_2 per kg. Multiplication of the emission factor times the weight for each material was done and summarised to a total emission for a seat. For the rig, which is fully made of steel, 31 kg steel adds an additional 86kg CO_2 on top of the 90 kg CO_2 from the base seat.

By estimating the probable cost of verification and usage cost for the rig, a comparison to the current way of testing can be made. The estimated verification cost and production cost of the rig with upholstery changed every five tests gives a total cost of 230 thousand SEK for 100 tests with a new rig. Compared with the current methodology, the above assumptions could lead to an 86% reduction of cost *(Figure 4.30a)*. In the same scenario of changing upholstery every 5 tests, the running emissions along with the initial production of the rig would lead to a 90% reduction in emissions *(Figure 4.30b)*.



(a) Cost current vs rig

(b) Emissions current vs rig

Figure 4.30: Current testing cost and emissions compared to proposed rig over 100 tests

5

Discussion

The test results, the resulting model from the development and a life cycle evaluation of the rig have been presented. This chapter will discuss the findings presented and highlight why things were done and if something could have been done differently.

5.1 Result

This section discusses the project execution and results. Questions like are the findings reliable, were there specific problems, was the focus right, and could something else have been done are reflected upon.

5.1.1 Scope

The project had quite a large and ambitious scope as it intended to go from a problem to a first iteration of a new product in just 20 weeks. It requires several time-consuming steps with long lead times and several widely different areas of skill. Several of these steps could've been expanded upon to reach a smaller but more polished end result. A possible advantage of the approach taken is a holistic view of the end product and less knowledge lost in translation between steps. Additionally, the customer, VCC, favoured a simple but functional solution. It was thus preferable to deliver not only part of a solution but the entire system to evaluate and potentially bring in to use as soon as possible.

The problem itself was set from the beginning as a development project for a physical test rig. An even better solution to the cost and sustainability problem presented would be utilising more CAE. This would also require substantial physical testing to ensure the validity of the models. A rig can thus be seen as an intermediary step on the road towards model-based design.

5.1.2 Physical Testing

The physical testing provided valuable insight into the design freedom for a reusable test rig. The results from this testing guided the project towards the use of a stiff rig as well as to attempt some form of breakthrough mimicking.

The testing was intended to compare all possible combinations of the two design variables, seat stiffness and breakthrough material, with two discrete values for each variable. I.e rigid and normal seat as well as normal breakthrough and no breakthrough. The intention was to use old data for the reference case of everything being as normal; however, this data proved to be unusable as the testing setup was not comparable. This means that it's not possible to say with absolute certainty that the direction the project took was the correct one. However, as the difference between the test setups actually tested was small, it is possible to argue that it is likely that the correct conclusion was reached.

The goal of quantifying uncertainty is to be able to justify the conclusions drawn from the results gained by knowing to what extent the variation could impact the analysis [34]. The main potential source of variance in results was the positioning of the dummy in the seat. To combat this the first test position was placed in a robust way, measured and photographed in multiple angles. All the following tests were then placed in the same position, using easy rules of thumb, measurements, and photographic guidance.

The different types of transducers in the dummy that measure the forces have an uncertainty of between 1 and 6%. On top of that variation, many other parameters of the setup, like temperature, could influence the resulting data. This could have some impact on the resulting graphs but is viewed as very small in relation to the noise and position setup variation. And even if the transducer errors of 6% were present, it would mostly impact the peaks, but the analysis mostly focused on the graphs being over or under each other on average, and hence would not change the conclusions drawn from the results.

5.1.3 Development

The start of the concept development was the concept generation. For this part of the work, both an external & internal search was carried out. The external search yielded relatively few results, which could be due to a too-narrow search or simply due to the niche nature of the SAB OOP test rig. In the end it was deemed that a good selection of concepts were created both in terms of quantity, quality and variety.

The screening and selection of concepts was made based on both subjective judgement as well as some but limited objective data. It was facilitated through an elimination matrix as well as a modified Pugh matrix. The detail level of the concepts at this phase did not allow for a more sophisticated and objective approach. Due to the limited time frame and large scope, it was deemed not possible to concurrently develop the concepts far enough for more objectivity. It is, however, the view of the authors that an appropriate balance was struck given the timeframe. When the prerequisites for an objective analysis existed, it was performed. For example, consider the structural aspect of the concept. A more subjective approach was taken when the prerequisites did not exist and would require substantial work in prototyping and testing.

There were multiple dilemmas along the way, such as how ease of use should be balanced against durability. The balancing in the concept phase was partly facilitated by means of modifying the Pugh matrix, and the importance of the criteria was discussed with members of the airbag & steering wheel team at VCC. The particular weights could've been discussed with a wider audience, including other stakeholders such as test technicians. This could've resulted in higher weight for the ergonomic requirements, but due to the desire to create a simple solution in a limited time, it is likely that the prioritisation would've been the same in the end.

5.1.4 Verification

The structural aspect of the concept was evaluated through FEA. Some simplifications were made in the modelling as compared to the real system. The welds, for example, were modelled as TIE elements and can thus make the model over stiff. Likewise, the frictional connection in the strut was modelled simply as TIE connections, as it was assumed that no slippage would occur in the real world. As was stated in the chapter regarding the FEA, two stress concentrations appeared, and it is believed by the authors and CAE engineers at VCC who have looked into the simulation that the values in the concentrations do not reflect reality and that they are caused by something in the modelling. The evaluation only covers failure against yield and not failure due to fatigue that might occur after repeated tests. Thus, it can't be said with absolute certainty that the concept will hold up, but it is an initial indication that it will.

The selected breakthrough concept was evaluated through a series of static deployment tests. These tests show promise in terms of the solution performance but also a need for tuning. The initial airbag unfolding takes place slightly higher up than in the reference test.

The connection means, however, in all cases, held up for longer than the tear seam and thus, all could work given tuning. It is currently believed that the high opening is due to slack in the upholstery above the tear seam module. This could be corrected in a future iteration by letting the connection interface move higher up above the tear seam. Eliminating the gap created by utilising the existing seams. To prevent failure of the connection it could also be preferable to move the connection from the corners and into the larger flat area. This could, in particular, help against the issue of peeling.

5.1.5 Design

To ensure the delivered design and project course fulfil the goals and are in line with the expectations of both main stakeholders (VCC and Chalmers), weekly checkups were done to avoid going too long in the wrong direction without notice. Design inputs were given by senior designers at VCC throughout the development. The proposed solution has been checked with all requirements in *Figure 4.3* and fulfilment verified.

By having thorough and clear documentation on which the decisions are based and presenting the development process, it is possible to argue for the final design. Many inspirations from other testing rigs at VCC were taken, and the best parts from each were extracted. This way, the chances of creating a good rig were high. A similar structure could be obtained in many different ways, and if the proposed design is the optimal design, it is hard to argue for, but it should be good enough for the purpose and at least as good as previous ones.

5.1.6 Life Cycle Assessment

The LCA was done in companionship with the sustainability department at VCC. Using their data of emission factors and weights of each material to calculate the total emissions. A more detailed analysis could have been done, but it was necessary to do it the same way as it was done for the XC40 in order to have a fair comparison.

The costs and use case are set arbitrarily to some degree but in a reasonable span that should give a representative indication of the possible results of using the rig. Assumptions have been made on the "lower" end to create some margin and not make the rig look too good. Of course, the assumptions could be way off, but the output results were not that sensitive to changes in, for example, rig production cost. Knowing the resulting cost and emissions won't change very much even if the input assumptions are poor, gives more credibility.

5.2 Limitations

Topics that might have acted as limitations, as in reduced or impacted the usefulness of the findings and design or in other ways impacted the project, are brought up and discussed.

5.2.1 Solution Transferability

Development has been done on an old platform to avoid confidentiality conflicts. The results and design are made on a close to ten-year-old seat structure. Large changes in the seat structure could potentially invalidate the findings made. For example, answers to the research questions might not be valid for next-generation seats if the design of those differ too much. The work has, however, been performed with this in mind and aimed to produce as general solutions as possible, with the ability to be easily adapted for changes in seat structure.

5.2.2 Literature

The external literature search did not yield many results and did not significantly guide the course of the project. As there were very limited resources it could mean that there is a gap in literature about this subject. This could be due to the development of this kind being commercial and information mostly being internal to automakers, seat suppliers and airbag suppliers. To some extent, this issue has been circumvented as the work has been carried out at VCC.

5.2.3 Planning & Organisation

One challenge in the planning of specific events or resources was to manage the scheduling between different functions of VCC and get the collaboration to operate efficiently. A known difficulty was the long lead times of securing material or knowledge resources when needed. For example, more testing or help with prototype building could have been wished for but was not possible. As the highest priority from the company perspective is to handle crucial errands of projects in production or soon-to-be in production, tasks coming from concept and development usually have to be planned far in advance or simply wait.

5.3 Societal, Ethical and Environmental Aspects

The goal of this project has been to reduce waste in the development of a life saving product, the side airbag. In particular the developed rig is meant to be used for out of position testing. Testing is intended to ensure the safety of the side airbag for smaller occupants such as children and, in particular, when said children sit incorrectly or out of position. The goals and intentions of the product developed in this thesis can thus be argued to be good. The nature of the test rig, being used "behind the scenes" at an airbag supplier means that the societal impact of this product is expected to be negligible.

The development of the rig did require some non negligible resources. The testing performed in the development of the rig thus far has consumed seven complete seats and sixteen airbags as well as a custom stiff rig. Further developments of the rig will require further testing and further resources. Due to the current state of SAB OOP simulations, as well as the need for validation against physical data, this resource use was a necessary evil. The expected outcome of this work is still a significant improvement in terms of material waste and roughly a 90% reduction in terms of CO_2 emissions.

The development of a rig made especially for testing purposes opens up the opportunity to design it for the new intended user, the test technician rather than the occupant. The financial goals and ergonomic goals are somewhat at odds with each other, the former prefers a durable and thus heavy rig which could negatively affect the ergonomics. All criteria were included in the concept development and taken into consideration. Due to the time frame some ergonomic improvements weren't implemented but suggested as future developments.

6

Conclusion & Future Work

In this final chapter of the thesis the findings presented previously are concluded in answers to the research questions stated in the beginning of the report. An explanation how to reach the end goal of reducing seats consumed as well as proposals for taking the project further are presented.

6.1 Answering the Research Questions

RQ1: What prevents the seats from being reused in testing?

The upholstery sometimes breaks more than just the tear seam, often fastening clips as well. Foam can be more or less broken depending on temperature but is destroyed. The structure takes some beating especially in the height mechanism. For the structure in the testing done in this project (XC40), not much seem to prevent reuse. The structure held up quite well over four repeated tests. However in interviews it has been said that in other seat platforms the airbag attachment points often break which would prevent reuse of the seat.

RQ2: What impact do the main components of structure, foam and upholstery have on the test results?

Negligible, the airbags reach the end position faster and become larger when not restricted by tear seam, but do not impact dummy results. The structure stiffness does not have a large impact on the test results. The foam does not seem to impact the breakthrough, forces or direction but could provide support for the dummy. See *Chapter 4.1.2* for in-depth figures.

RQ3: What would a rig for testing side airbags without consuming a full seat for every deployment look like?

By building a solid substructure to which the seat can be secured, a telescopic reinforcement bar can be put up against the added support structure of the seat back. In order to cover the entire travel box in a continuous motion, the solution only reinforces after the seat is put in the desired position and not all the time. For more detailed explanations and figures, see *Chapter 4.7*.

RQ4: What impact in terms of emissions and economy could a "rig" solution have compared to the current method?

As seen in the LCA and LCC, the structure has the biggest impact on both cost and emissions. By not consuming a new structure for each test, large savings can be made. With the usage assumptions presented in *Chapter 4.10*, the rig could reduce the emissions by 90% and cost by 86% compared to the current testing method.

6.2 Next Steps

To reach real implementation of the proposed rig, some additional work needs to be done. The process towards the end goal is visualised in *Figure 6.1* and starts by acknowledging the checkpoint of the proposed solution done for the old XC40 seat. The solution has been tested in subsystems with promising results, the structural part verified in *Chapter 4.8* and the breakthrough solution in *Chapter 4.9*. The next step for the project would be to update the model in Catia to fit an upcoming model seat structure instead of a ten-year-old one. After the adjustments have been made, the rig can be physically built.

But the most important step before implementing the rig as a substitute for ordinary testing activities would be to validate it through physical and virtual testing. The two main features to confirm are the structure's resistance to fatigue over a high number of airbag deployments, and that the rig setup gives similar and consistent results for the dummies compared to the reference setup. The structural evaluation using FEA performed up until this stage is inconclusive and does not include evaluation for fatigue. It is thus recommended to perform further finite element analysis once the model has been updated to the next generation seat structure.

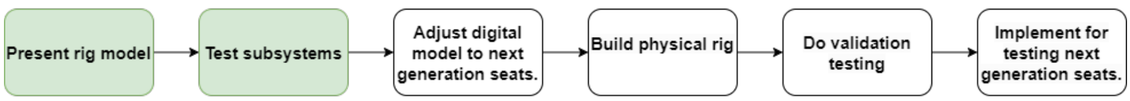


Figure 6.1: Road map for continuing the project until final goal

Some minor desires that were taken into consideration but could not be implemented due to time constraints could be further looked upon in the coming adjustment of the model phase. Most of them are in regards to usability or avoiding faulty handling, for example:

- Seat position is documented for every test, currently measured with a tape in cumbersome positions like inside the length rails. In some way, make markings that are easy to read from the outside instead of having to rely on a handheld tape measure.

- In some way, make it apparent when the strut angle is good or restrict movement to only work in the desired range. If the user of the rig does not know how it is intended to be used, there is a possibility of adjusting the strut to an unfavourable position to absorb the load.

- Make an instruction manual and/or working procedure in what bolts should be screwed or unscrewed in which order, and how it should look before and after adjusting the seat into the desired position.

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A

Appendix

A.1 Python Code

```python
import pandas as pd
import glob
import os
import io
import matplotlib.pyplot as plt
import numpy as np
from scipy import signal
from matplotlib.backends.backend_pdf import PdfPages
import matplotlib


# Code for collecting, ordering, filtering and plotting physical test results as part of the master's thesis "Front Seat Rig"

matplotlib.rcParams['figure.max_open_warning'] = 0

# Specifying dirctory
main_directory = 'C:/Users/JLINDHO4/OneDrive - Volvo Cars/Front seat rig/Testing'


# Obtain list of all source folders
source_folders = [folder for folder in glob.glob(os.path.join(main_directory, '246095*')) if os.path.isdir(folder)]

print('Source folders:', source_folders)
source_dataframes = {}

# Filter
CFC1000 = signal.butter(4, 1650, btype='low', analog=False, output='sos', fs=10000)
CFC600 = signal.butter(4, 1000, btype='low', analog=False, output='sos', fs=6000)
CFC180 = signal.butter(4, 300, btype='low', analog=False, output='sos', fs=1800)
CFC60 = signal.butter(4, 100, btype='low', analog=False, output='sos', fs=600)


# loop through each source folder
for source_folder in source_folders:
    print(f'Reading folder: {source_folder}')

    if os.path.basename(source_folder).startswith('176103'):
        filelist = os.listdir(source_folder)
        file_pattern = os.path.join(source_folder, 'CHANNEL/176103*')
```

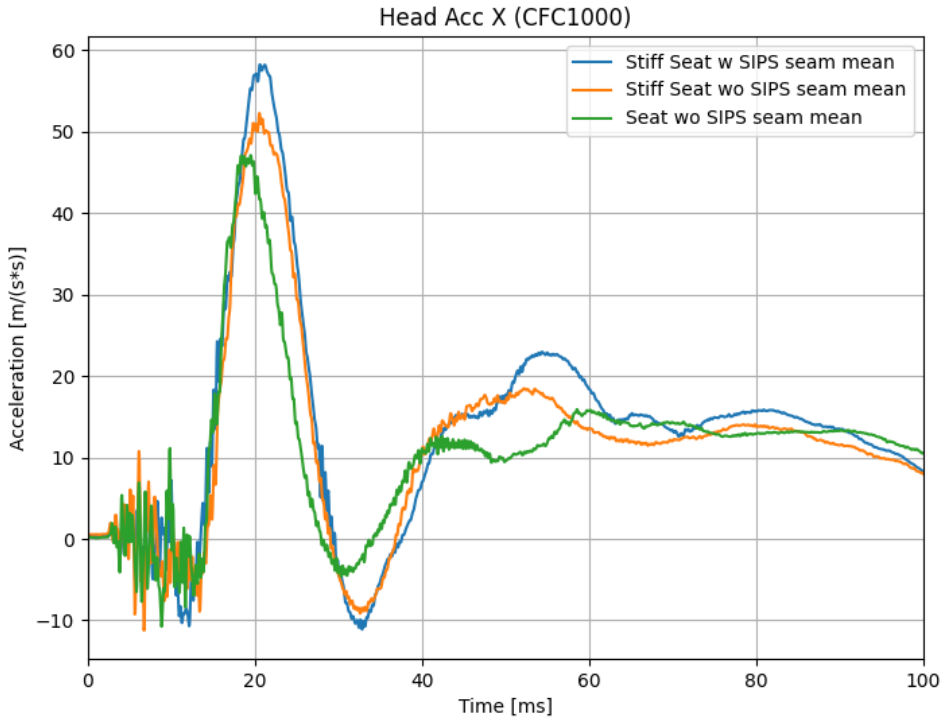
```python

    else:
        file_pattern = os.path.join(source_folder, 'Channel/246095*')

    matching_files = glob.glob(file_pattern)[:41]
    response_dataframes = []

    for file_path in matching_files:
        file_name = os.path.splitext(os.path.basename(file_path))[0]
        file_content = open(file_path, 'r')
        lines = file_content.readlines()
        df = pd.read_csv(io.StringIO('\n'.join(lines[43:])), delimiter='\t', header=None)
        df = df.apply(pd.to_numeric, errors='raise')
        measurement_name = lines[1].split(':')[1].strip()
        unit = lines[6].split(':')[1].strip()

        if ((
                    'Acc' in measurement_name or 'Acceleration' in measurement_name) and 'Spine' not in measurement_name) or 'Force' in measurement_name:
            CFC_filter = CFC1000
            filter_type = 'CFC1000'
        elif 'Moment' in measurement_name or 'Deflection' in measurement_name:
            CFC_filter = CFC600
            filter_type = 'CFC600'
        elif 'Spine' in measurement_name:
            CFC_filter = CFC180
            filter_type = 'CFC180'


        custom_column_name = f"{measurement_name} ({filter_type})"
        df.columns = [custom_column_name]

        df_smoothed = pd.DataFrame(signal.sosfiltfilt(CFC_filter, df, axis=0), columns=df.columns)
        response_dataframes.append(df_smoothed)

    if response_dataframes:
        source_df = pd.concat(response_dataframes, axis=1)
        source_dataframes[file_name] = source_df
    else:
        print(f'No DataFrames created for source: {source_folder}')
```

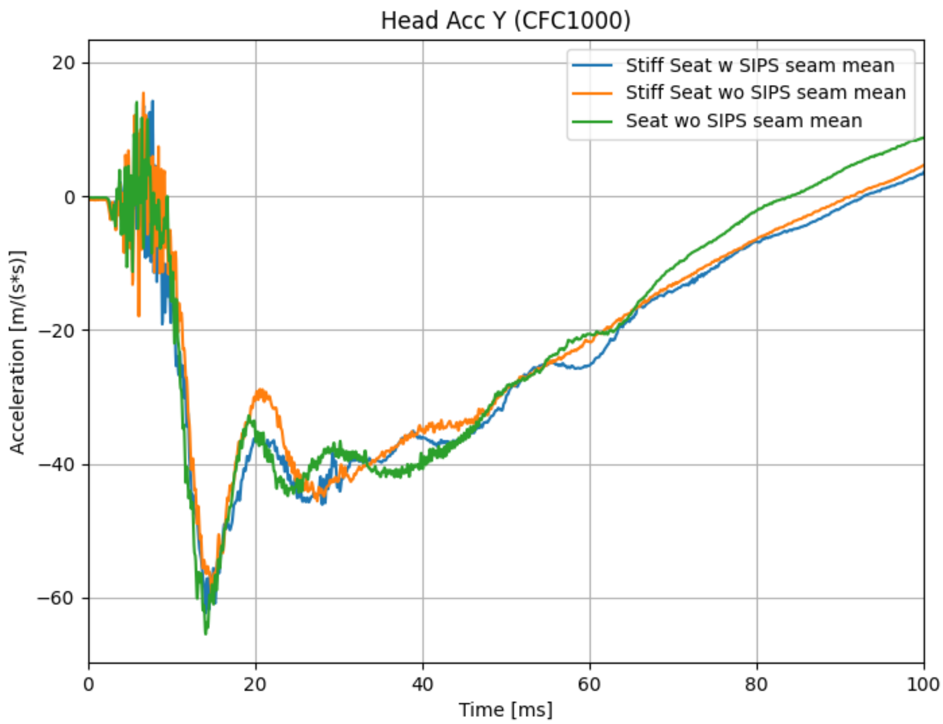
```python

# ------------------------------------------------------------------------------------------------------------------
# Debug
if not source_dataframes:
    print("No DataFrames were created. Check file paths.")

else:

    groups = {
        'Stiff Seat w SIPS seam': ['24609501', '24609503', '24609505'],
        'Stiff Seat wo SIPS seam': ['24609502', '24609504', '24609506'],
        'Seat wo SIPS seam': ['24609507', '24609508', '24609509']
    }

    # Dictionary to store dfs and means for each group
    group_data = {}

    for group_name, keys in groups.items():
        concatenated_df = pd.concat([source_dataframes[key] for key in keys])
        concatenated_df_numeric = concatenated_df.apply(pd.to_numeric, errors='coerce')

        # Group by row index and calculate the mean
        by_row_index = concatenated_df_numeric.groupby(concatenated_df_numeric.index)
        group_mean = by_row_index.mean()
        group_median = by_row_index.median()

        group_data[group_name] = {
            'concatenated_df': concatenated_df,
            'mean': group_mean,
            'median': group_median
        }



    for group_name, data in group_data.items():
        # Extract the mean dataframe for the group
        mean_df = data['mean']
        num_steps = mean_df.shape[0]
        time_vector = np.linspace(-100, 500, num_steps)
        # Plot the first column of the mean dataframe
        plt.plot(time_vector, mean_df.iloc[:, 16], label=
```

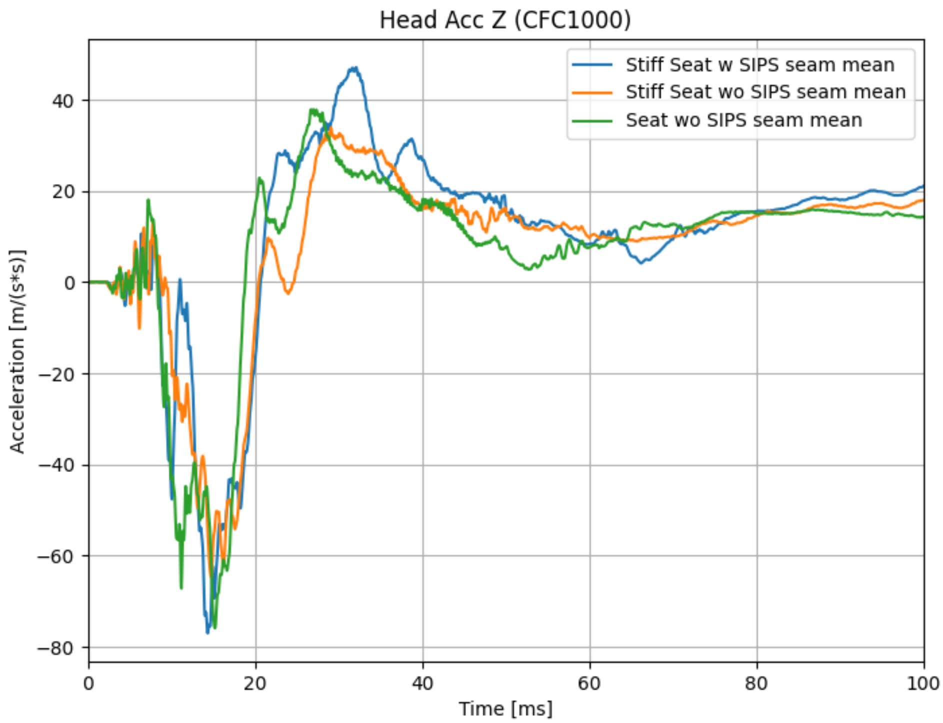
```
group_name)

        # Get the column name for the first column
        custom_column_name = data['concatenated_df'].columns[0]
        if "Acc" in custom_column_name:
            label_y = "Acceleration [m/(s*s)]"
        if "Force" in custom_column_name:
            label_y = "Force [kN]"
        if "Moment" in custom_column_name:
            label_y = "Moment [Nm]"
        if "Deflection" in custom_column_name:
            label_y = "Deflection [mm]"


    plt.title(custom_column_name)
    plt.legend()
    plt.xlim(0, 200)
    plt.xlabel('Time [ms]')
    plt.ylabel(label_y)
    plt.grid(True)


    plt.show()

##-----------------------------------------------------------------------------------------------------------------------


figure_names = []

# Iterate over each column in the mean DataFrame
for column_index in range(mean_df.shape[1]):
    # Create a new figure for each column
    plt.figure(figsize=(8, 6))

    # Iterate over each group
    for group_name, data in group_data.items():
        mean_df = data['mean']
        median_df = data['median']
        num_steps = mean_df.shape[0]
        time_vector = np.linspace(-100, 500, num_steps)

        # Plot the data for the current column and group
        plt.plot(time_vector, mean_df.iloc[:, column_index], label=f'{group_name} mean')

    custom_column_name = mean_df.columns[column_index]
```

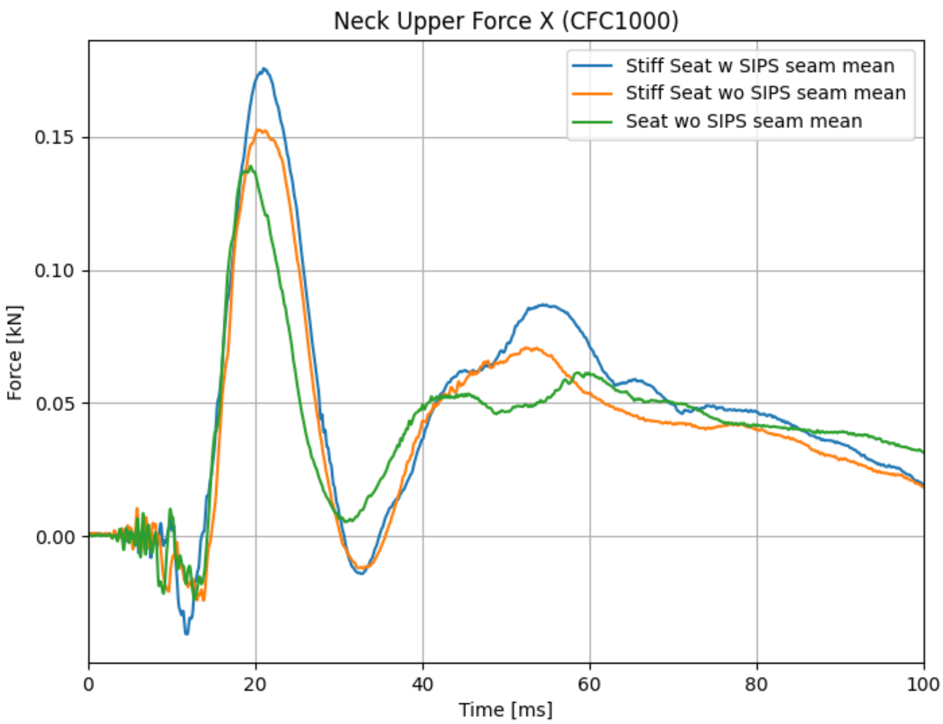
```
    if "Acc" in custom_column_name:
        label_y = "Acceleration [m/(s*s)]"
    if "Force" in custom_column_name:
        label_y = "Force [kN]"
    if "Moment" in custom_column_name:
        label_y = "Moment [Nm]"
    if "Deflection" in custom_column_name:
        label_y = "Deflection [mm]"

    plt.title(custom_column_name)


    plt.legend()
    plt.xlim(0, 100)
    plt.xlabel('Time [ms]')
    plt.ylabel(label_y)
    plt.grid(True)

    figure_name = f"figure_{column_index + 1}.png"
    plt.savefig(figure_name)
    plt.close()
    figure_names.append(figure_name)



# Create a PDF
with PdfPages('combined_figures_means.pdf') as pdf:
    for i in range(0, len(figure_names), 2):
        fig, axes = plt.subplots(1, 2, figsize=(14, 6))
        for j, ax in enumerate(axes):
            if i + j < len(figure_names):
                img = plt.imread(figure_names[i + j])
                ax.imshow(img)
                ax.axis('off')

        pdf.savefig(fig)

# Delete the figure files
for figure_name in figure_names:
    os.remove(figure_name)

```

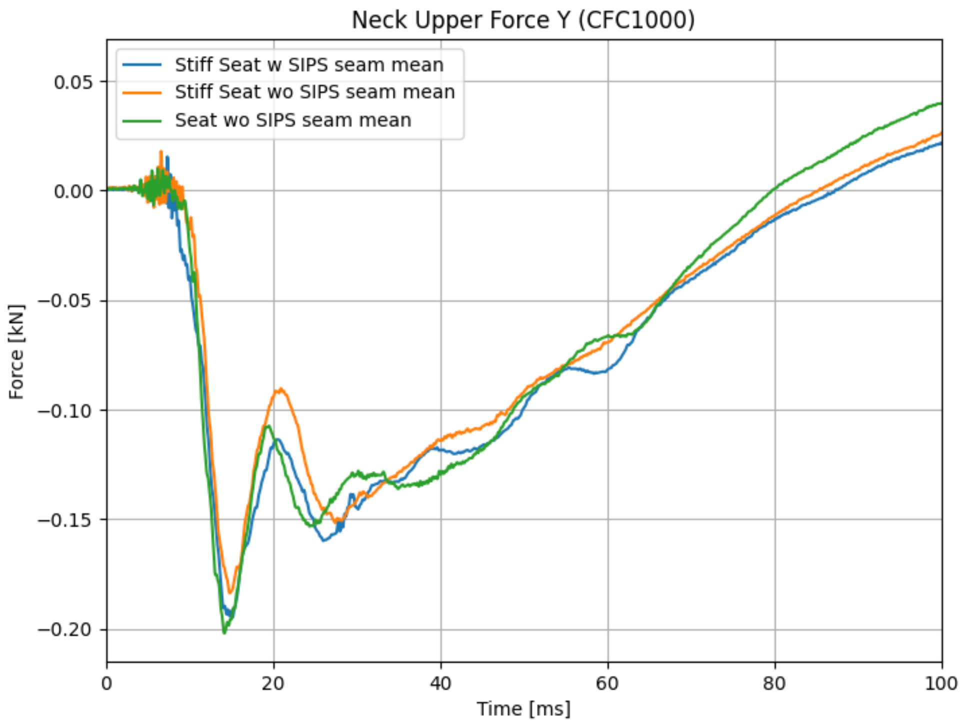
A.2 Graphs From Physical Testing



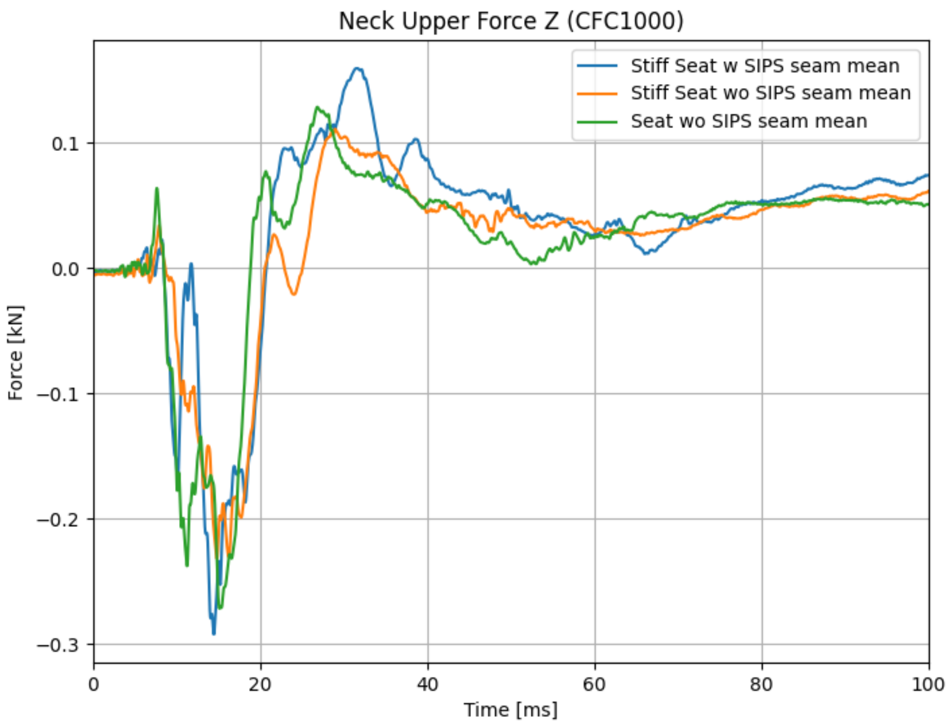



Head Acc Z (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Acceleration [m/(s*s)]
Time [ms]
40
20
0
−20
−40
−60
−80
0
20
40
60
80
100

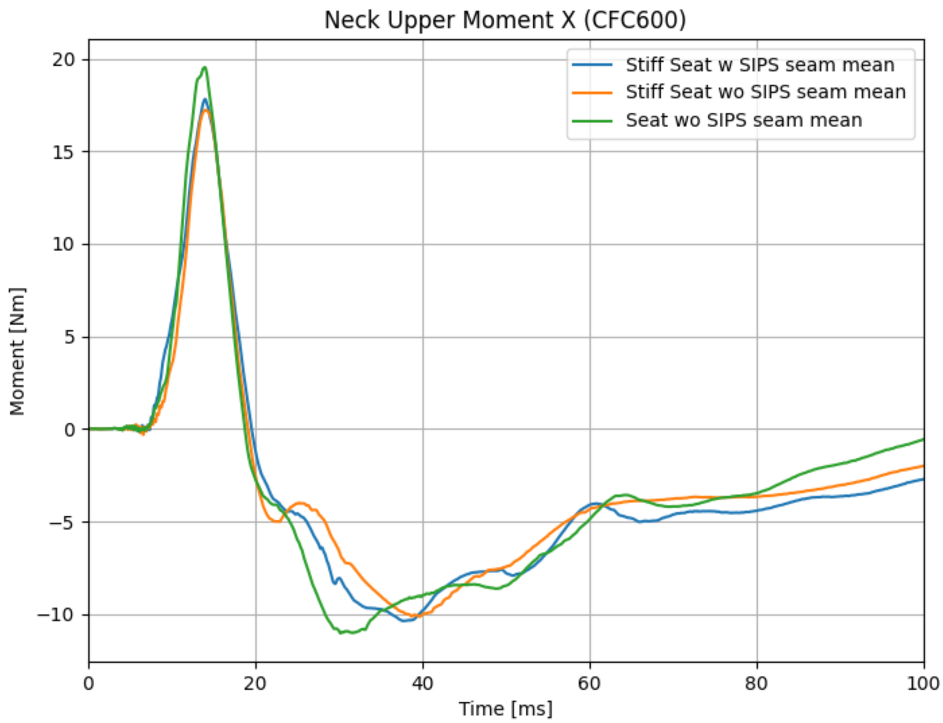

Neck Upper Force X (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Force [kN]
Time [ms]
0.15
0.10
0.05
0.00
0
20
40
60
80
100

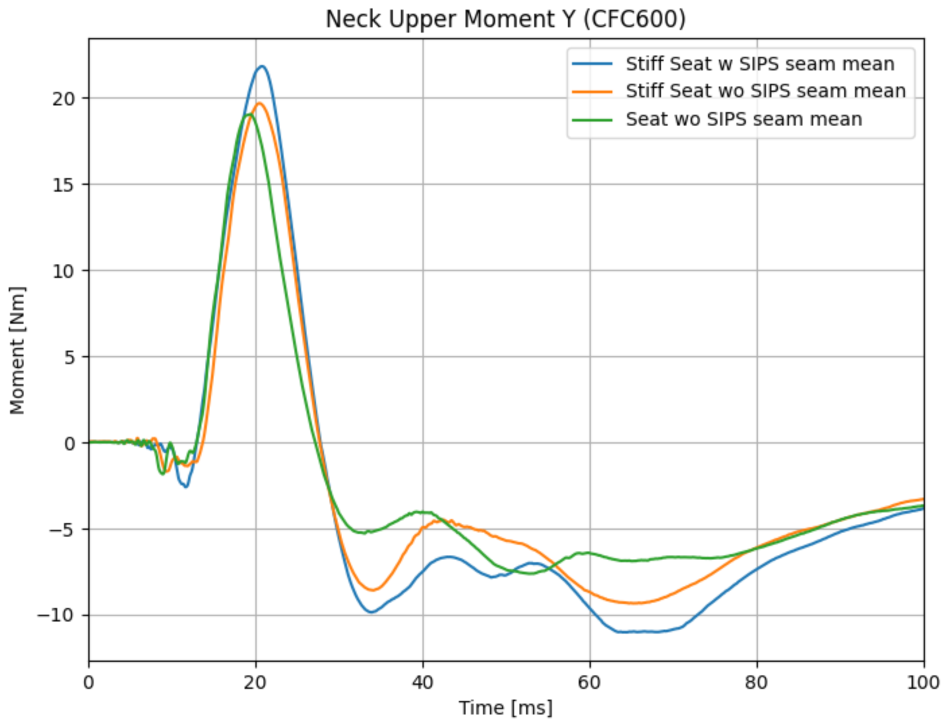


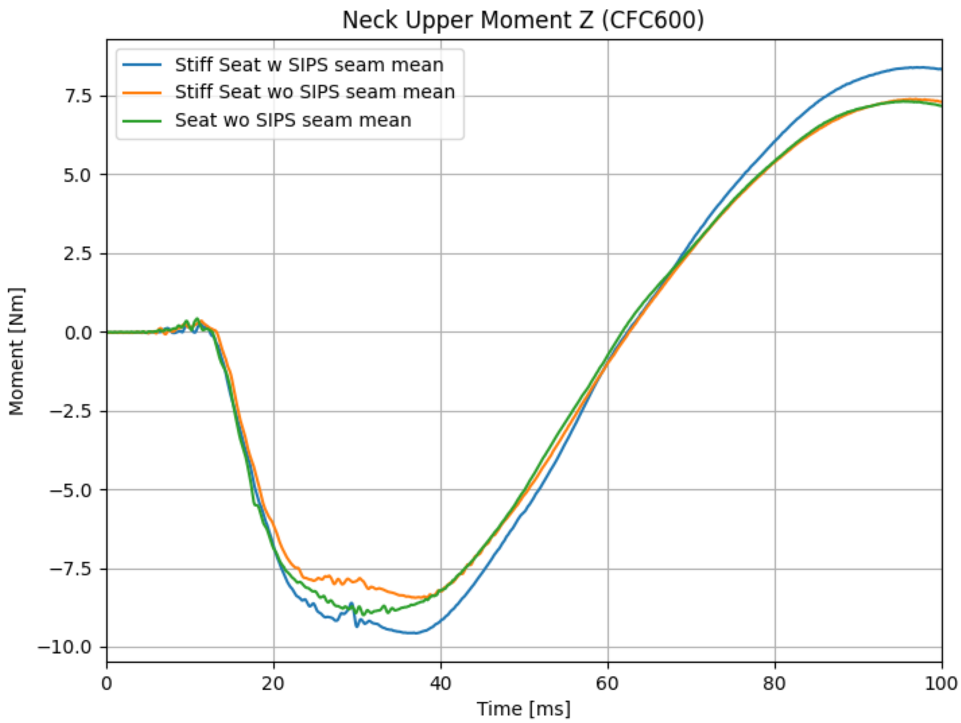
Neck Upper Force Y (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Force [kN]
Time [ms]
0.05
0.00
−0.05
−0.10
−0.15
−0.20
0
20
40
60
80
100

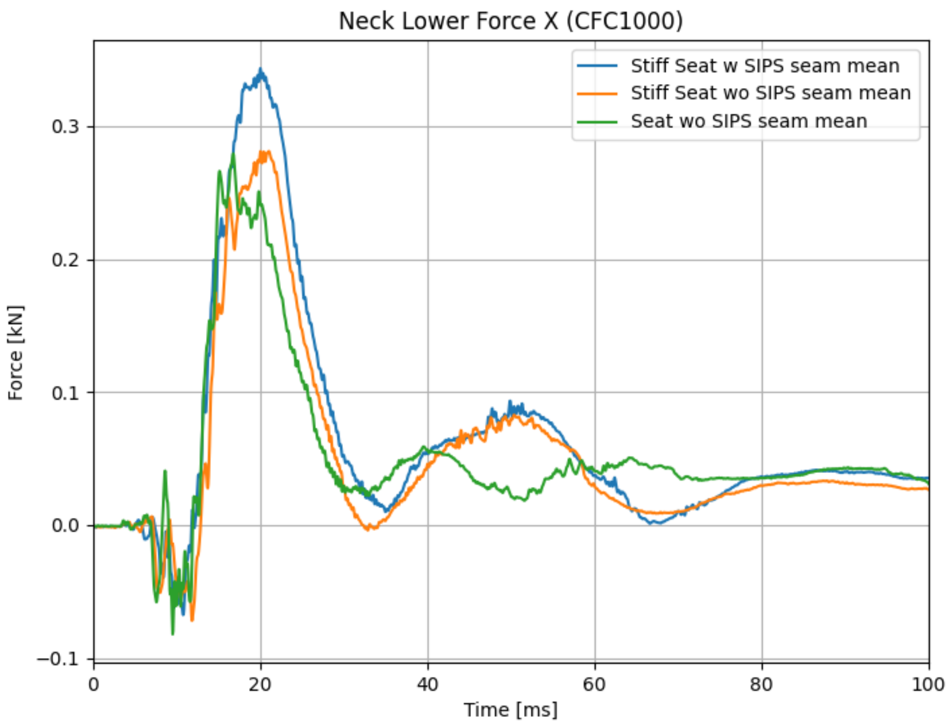


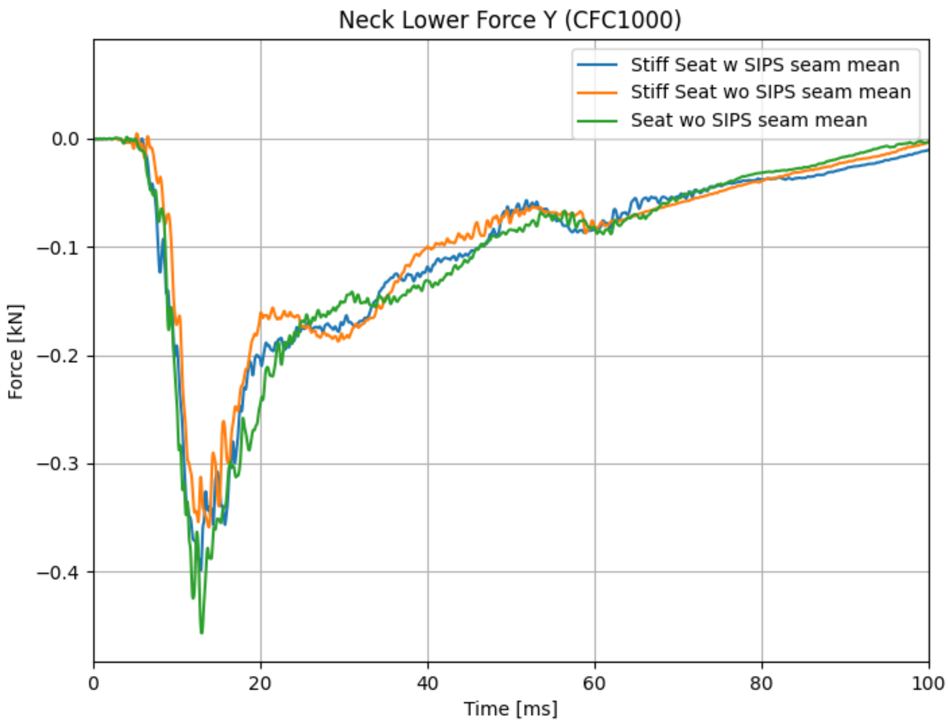
Neck Upper Force Z (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Force [kN]
Time [ms]
0.1
0.0
−0.1
−0.2
−0.3
0
20
40
60
80
100

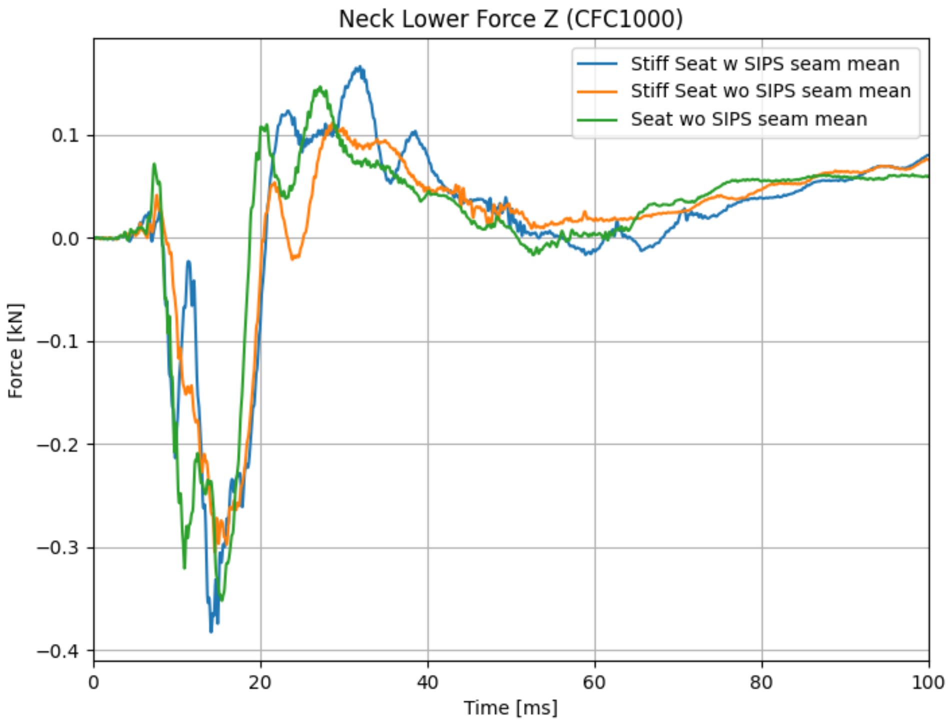

Neck Upper Moment X (CFC600)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Moment [Nm]
Time [ms]
20
15
10
5
0
−5
−10
0
20
40
60
80
100

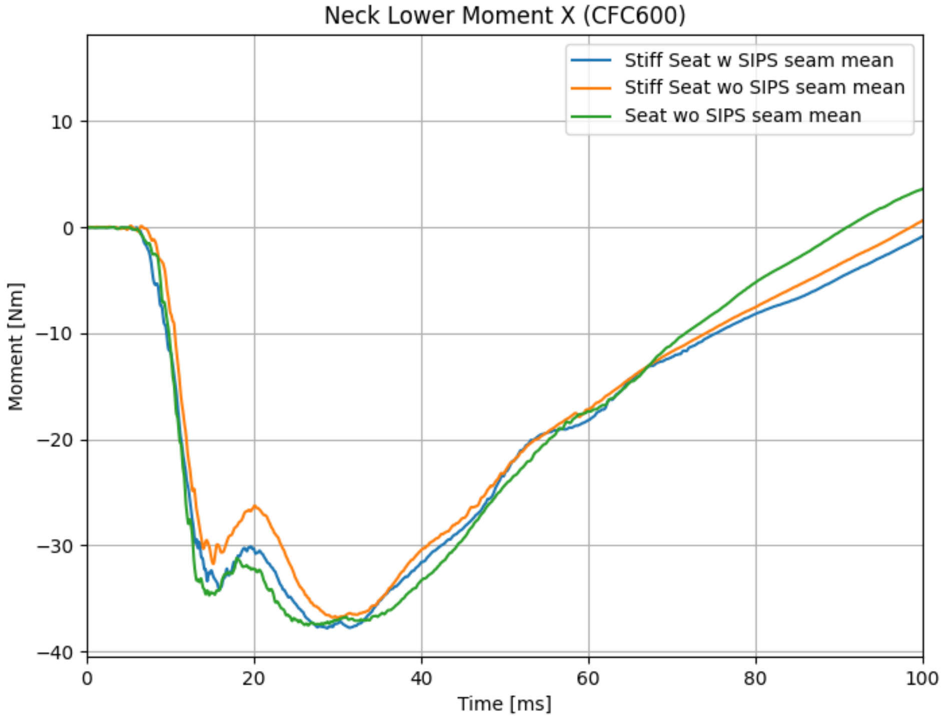

Neck Upper Moment Y (CFC600)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Moment [Nm]
Time [ms]
20
15
10
5
0
−5
−10
0
20
40
60
80
100

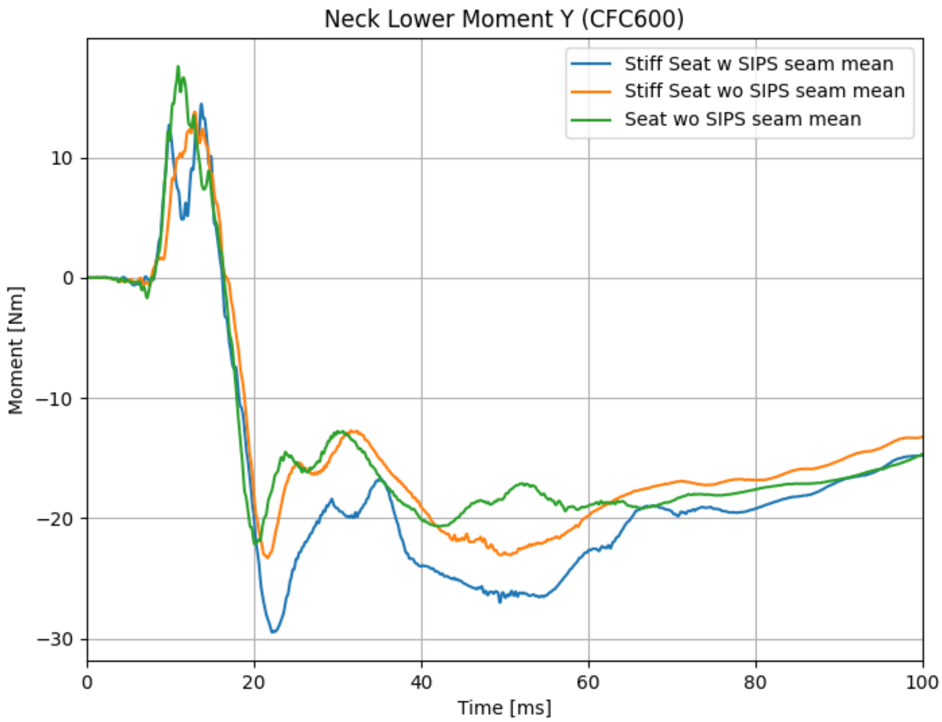

Neck Upper Moment Z (CFC600)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Moment [Nm]
Time [ms]

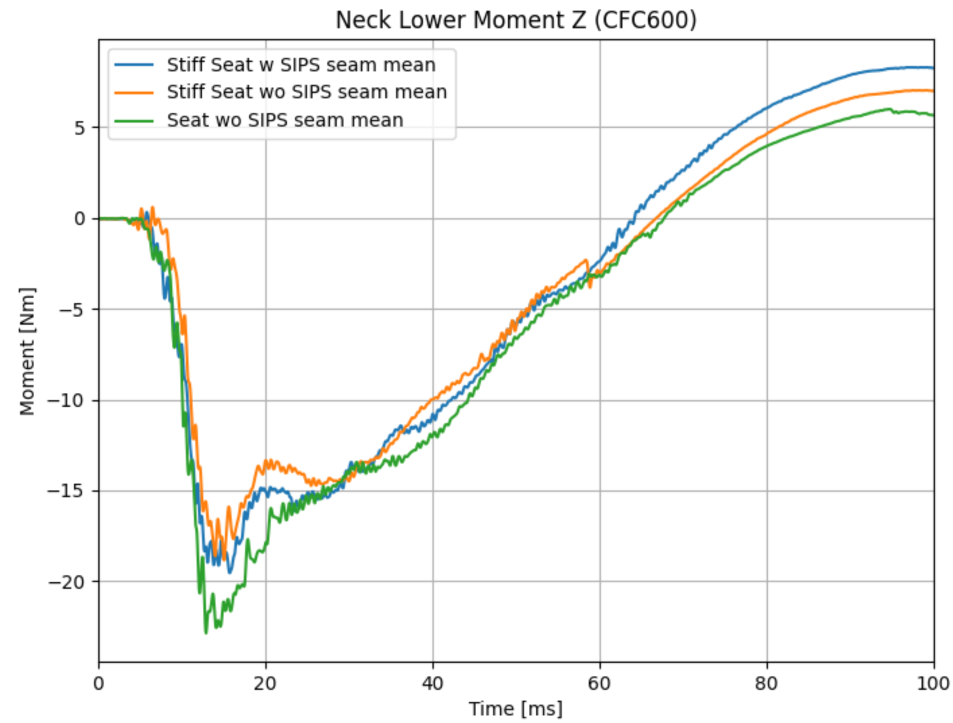

Neck Lower Force X (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Force [kN]
Time [ms]

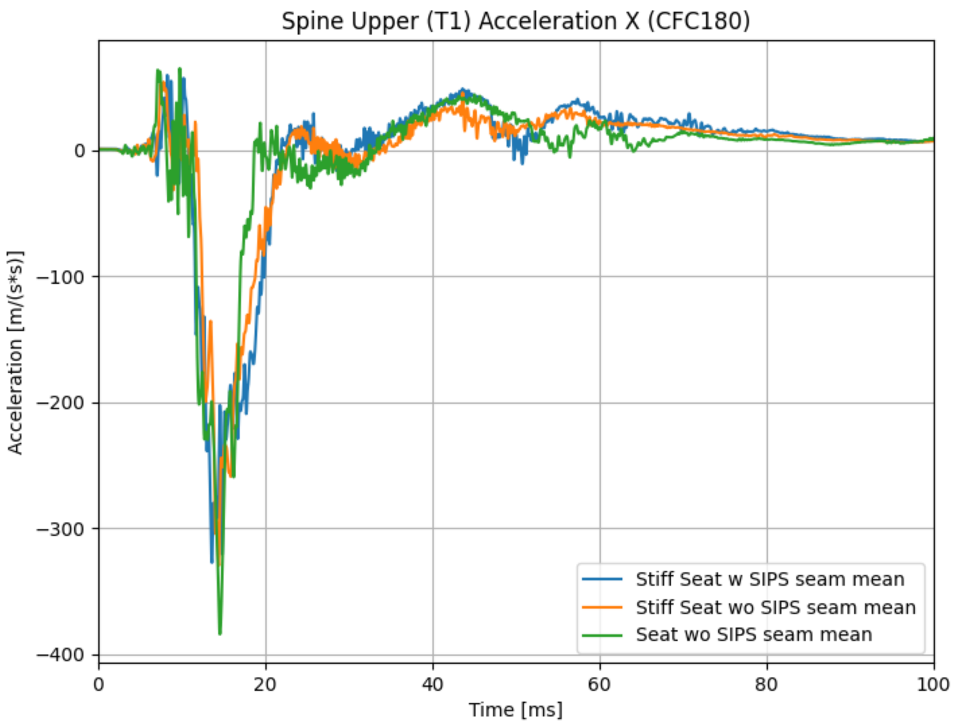

Neck Lower Force Y (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Force [kN]
Time [ms]
0.0
−0.1
−0.2
−0.3
−0.4
0
20
40
60
80
100

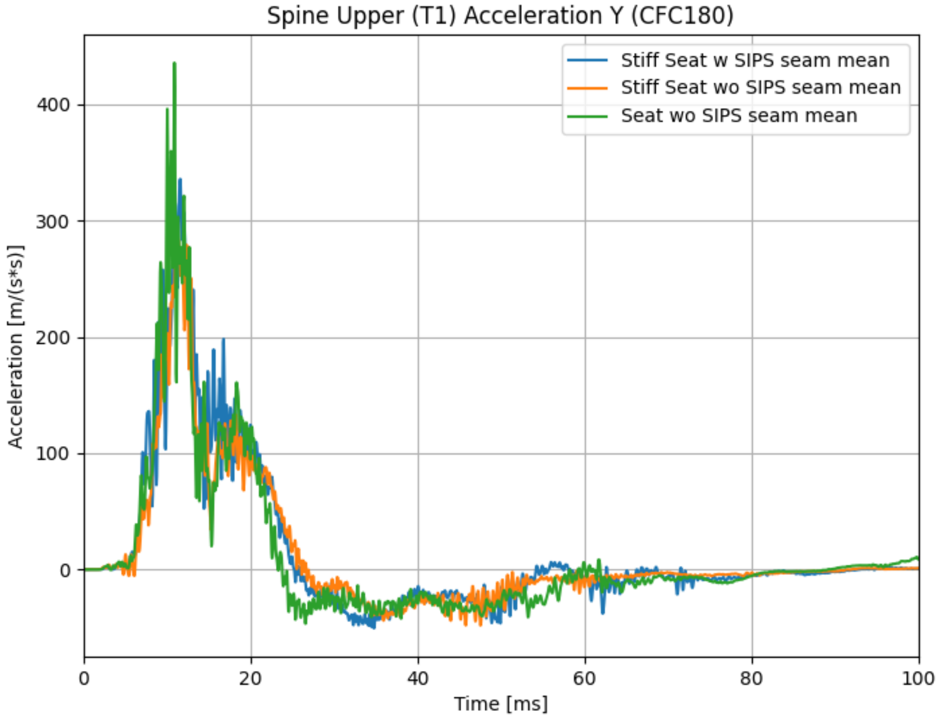

Neck Lower Force Z (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Force [kN]
Time [ms]
0.1
0.0
−0.1
−0.2
−0.3
−0.4
0
20
40
60
80
100


Neck Lower Moment X (CFC600)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Moment [Nm]
Time [ms]
10
0
−10
−20
−30
−40
0
20
40
60
80
100

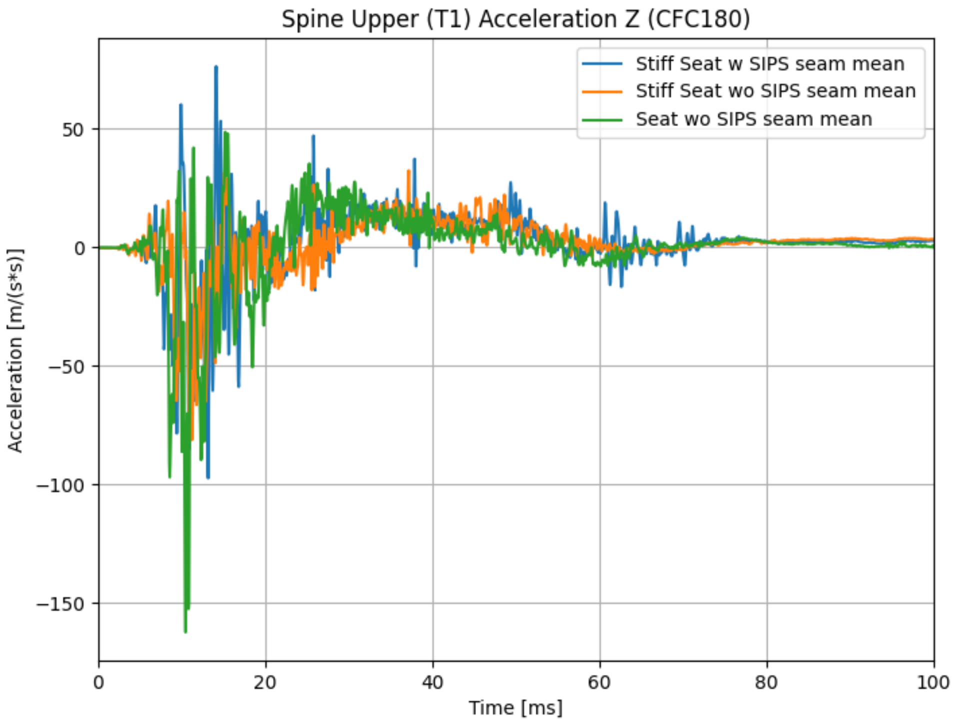

Neck Lower Moment Y (CFC600)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Moment [Nm]
Time [ms]
10
0
−10
−20
−30
0
20
40
60
80
100


Neck Lower Moment Z (CFC600)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Moment [Nm]
Time [ms]
5
0
−5
−10
−15
−20
0
20
40
60
80
100

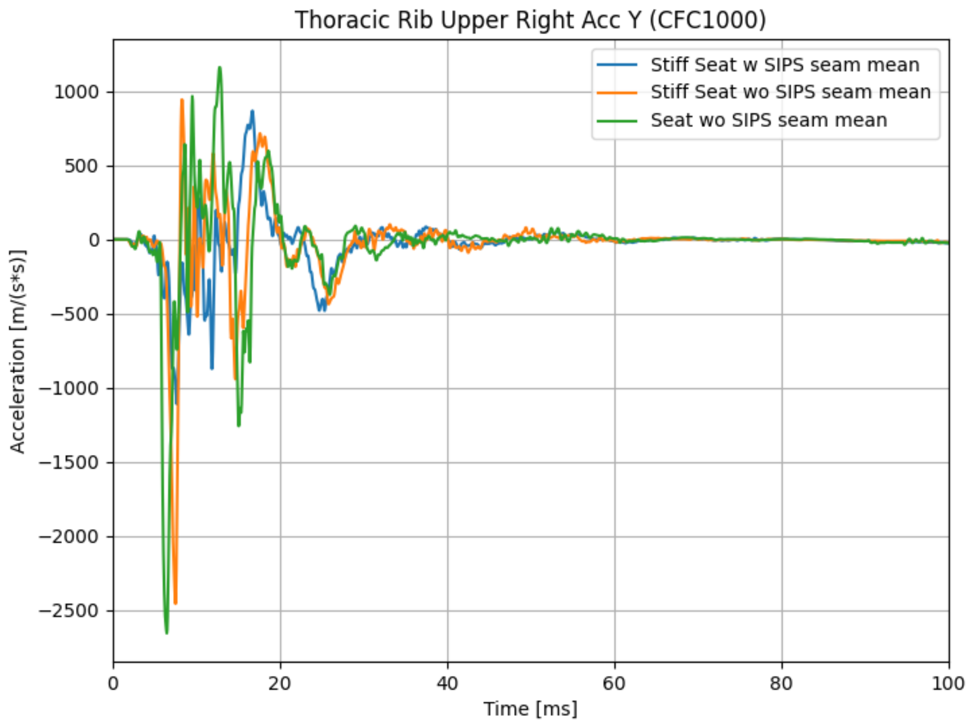

Spine Upper (T1) Acceleration X (CFC180)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Acceleration [m/(s*s)]
Time [ms]
0
−100
−200
−300
−400
0
20
40
60
80
100

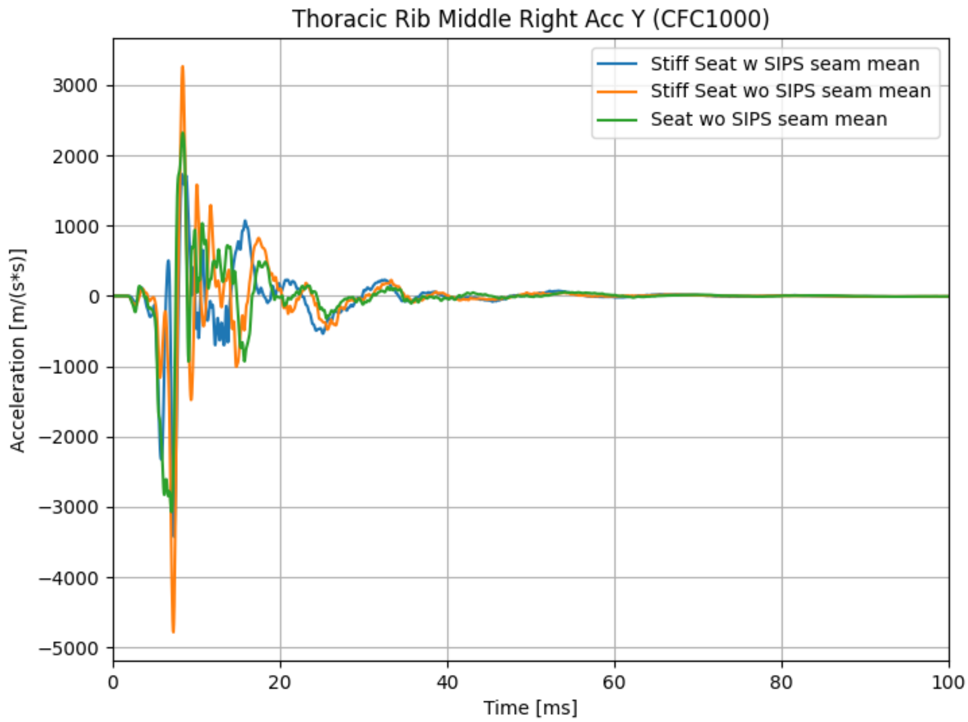


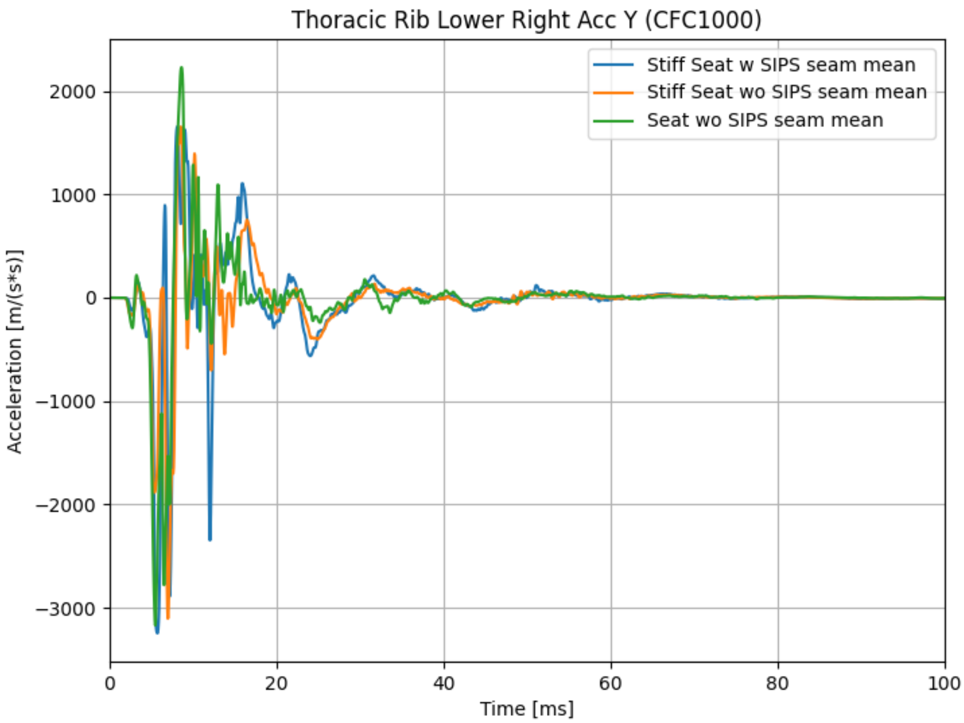
Spine Upper (T1) Acceleration Y (CFC180)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Acceleration [m/(s*s)]
Time [ms]

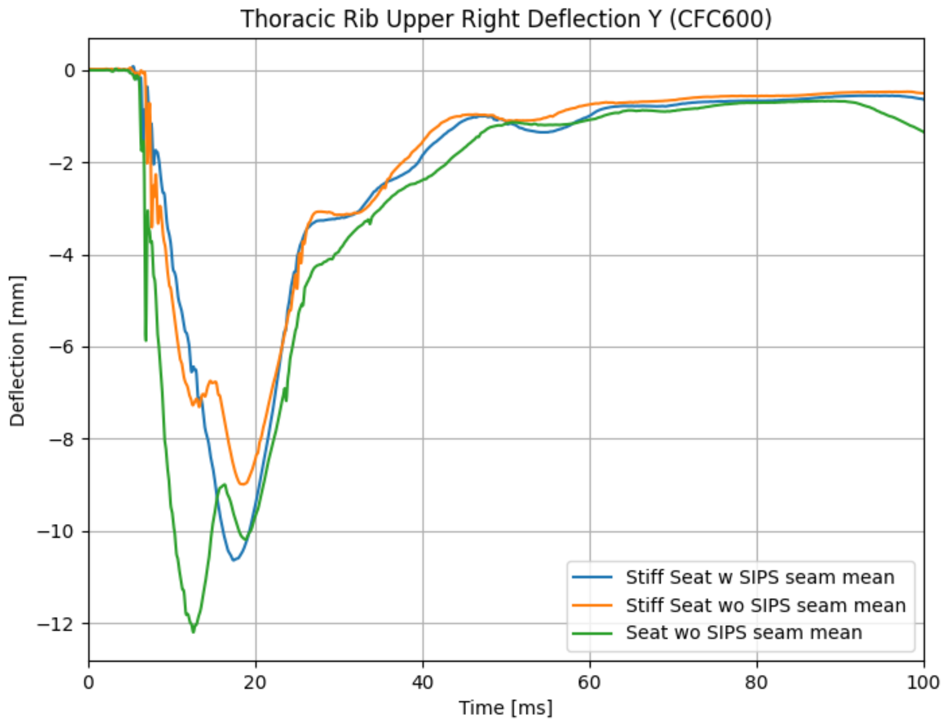


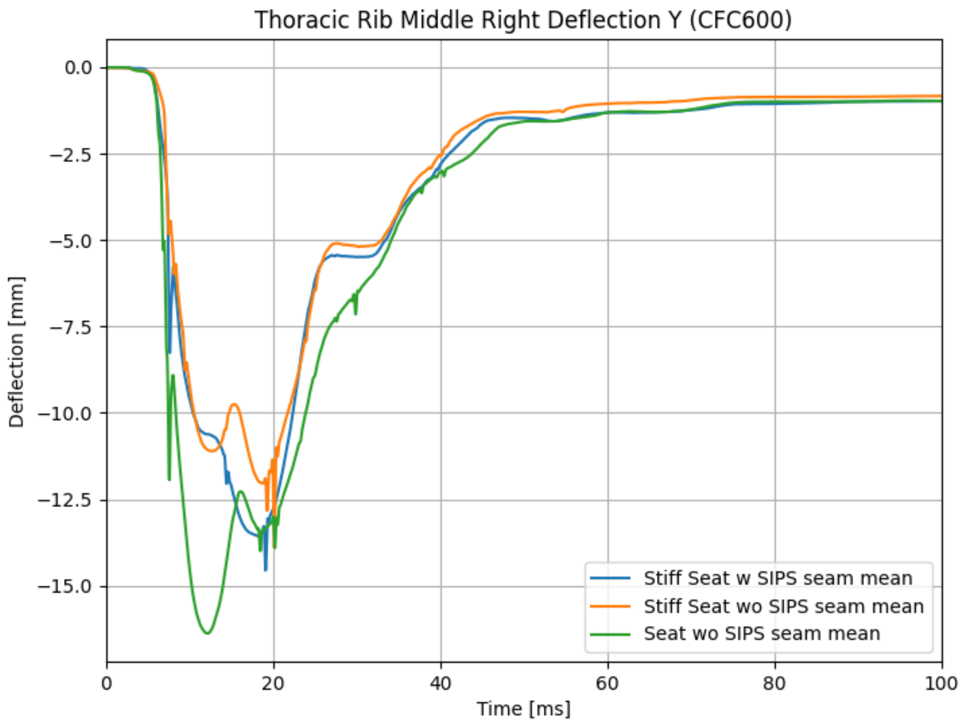
Spine Upper (T1) Acceleration Z (CFC180)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Acceleration [m/(s*s)]
Time [ms]

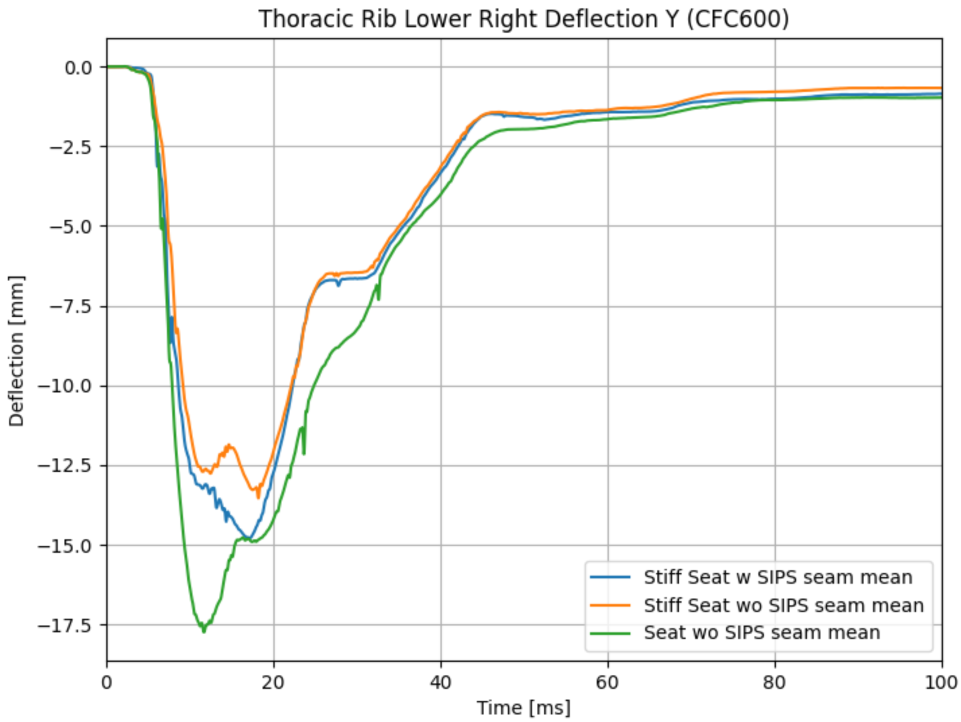

Thoracic Rib Upper Right Acc Y (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Acceleration [m/(s*s)]
Time [ms]
1000
500
0
−500
−1000
−1500
−2000
−2500
0
20
40
60
80
100

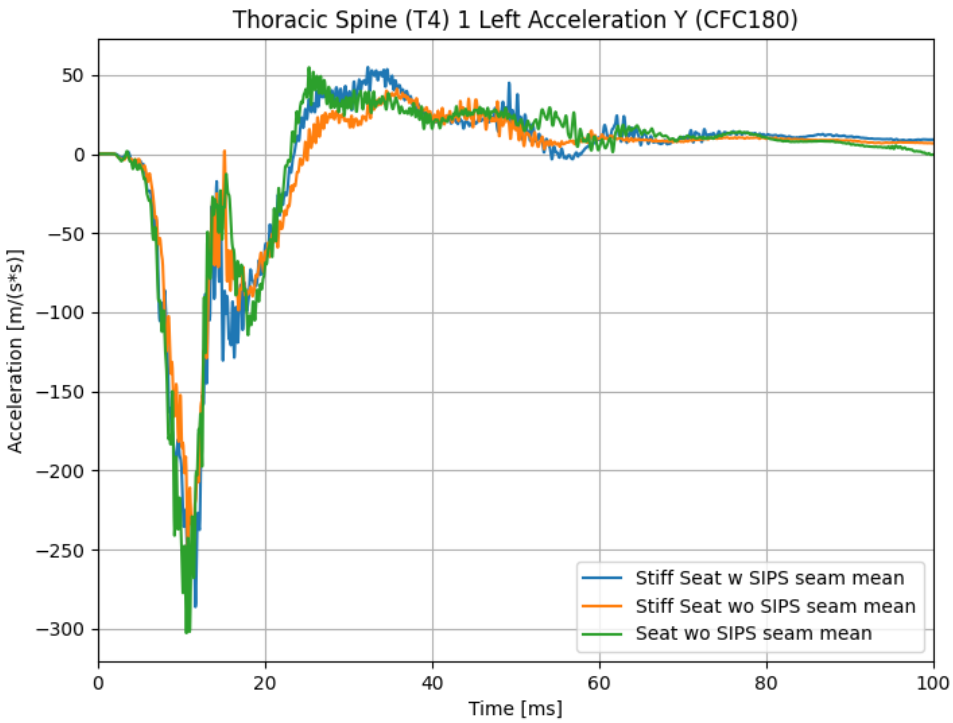

Thoracic Rib Middle Right Acc Y (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Acceleration [m/(s*s)]
Time [ms]
3000
2000
1000
0
−1000
−2000
−3000
−4000
−5000
0
20
40
60
80
100

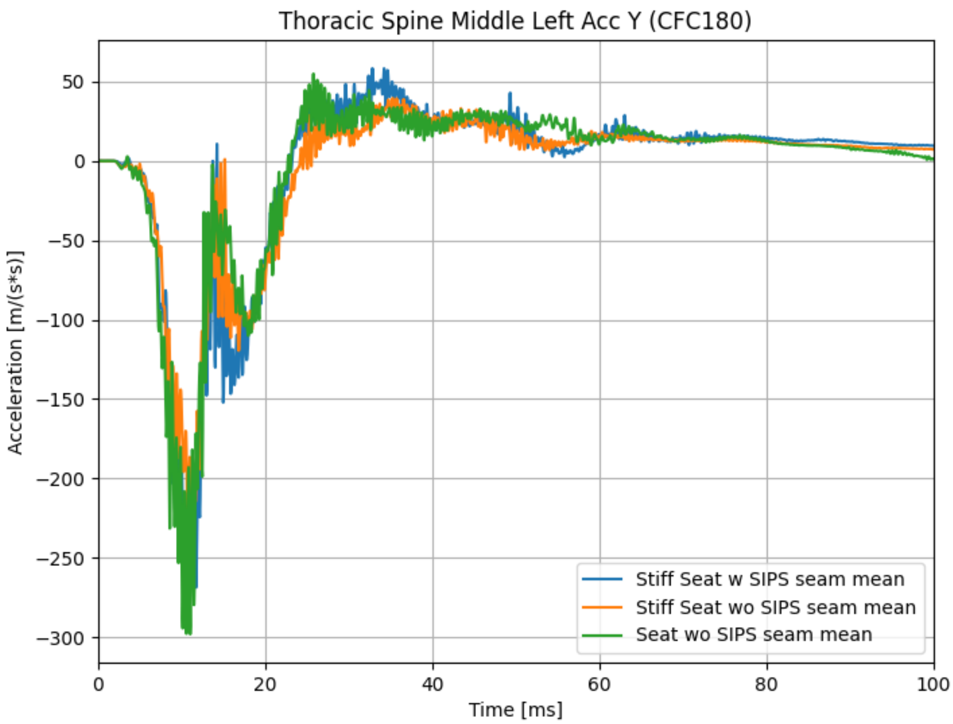

Thoracic Rib Lower Right Acc Y (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Acceleration [m/(s*s)]
2000
1000
0
−1000
−2000
−3000
0
20
40
60
80
100
Time [ms]

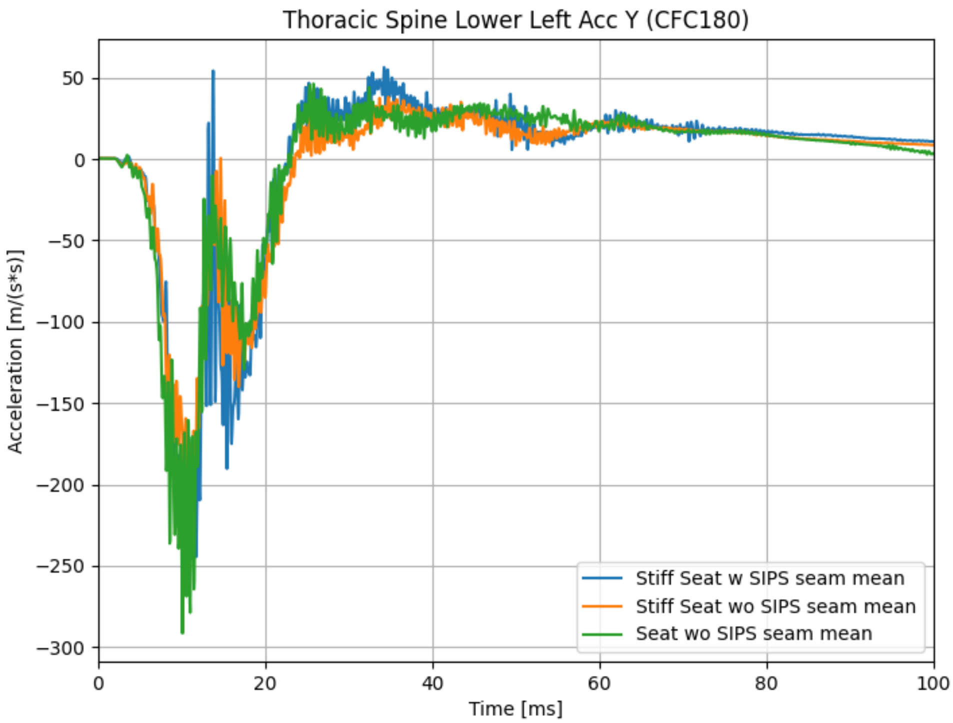

Thoracic Rib Upper Right Deflection Y (CFC600)
Deflection [mm]
0
−2
−4
−6
−8
−10
−12
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
0
20
40
60
80
100
Time [ms]

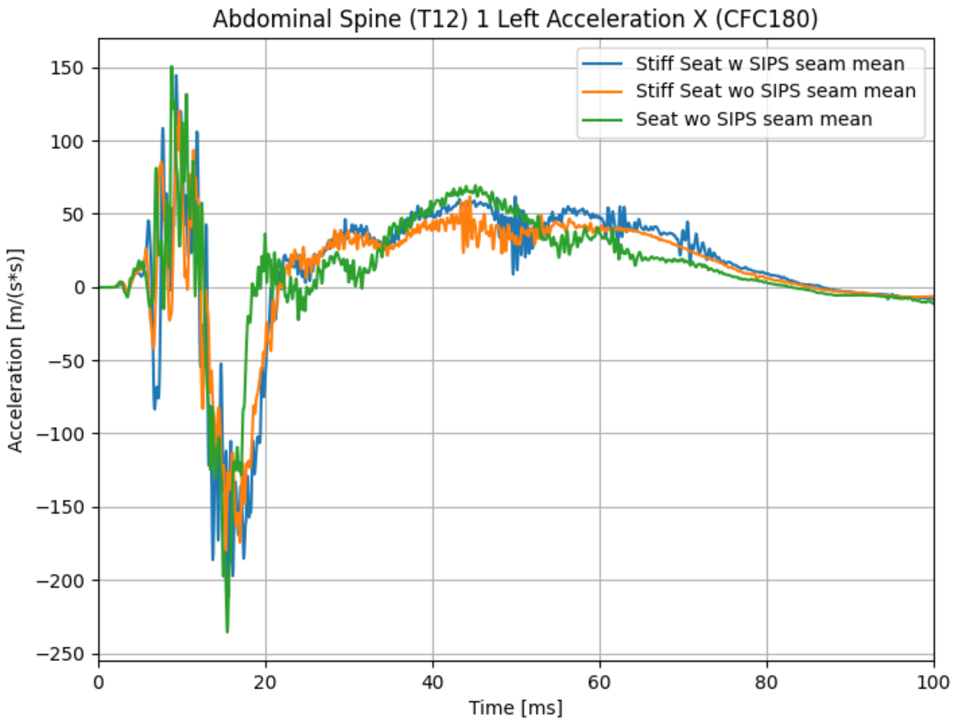

Thoracic Rib Middle Right Deflection Y (CFC600)
Deflection [mm]
Time [ms]
0.0
−2.5
−5.0
−7.5
−10.0
−12.5
−15.0
0
20
40
60
80
100
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean

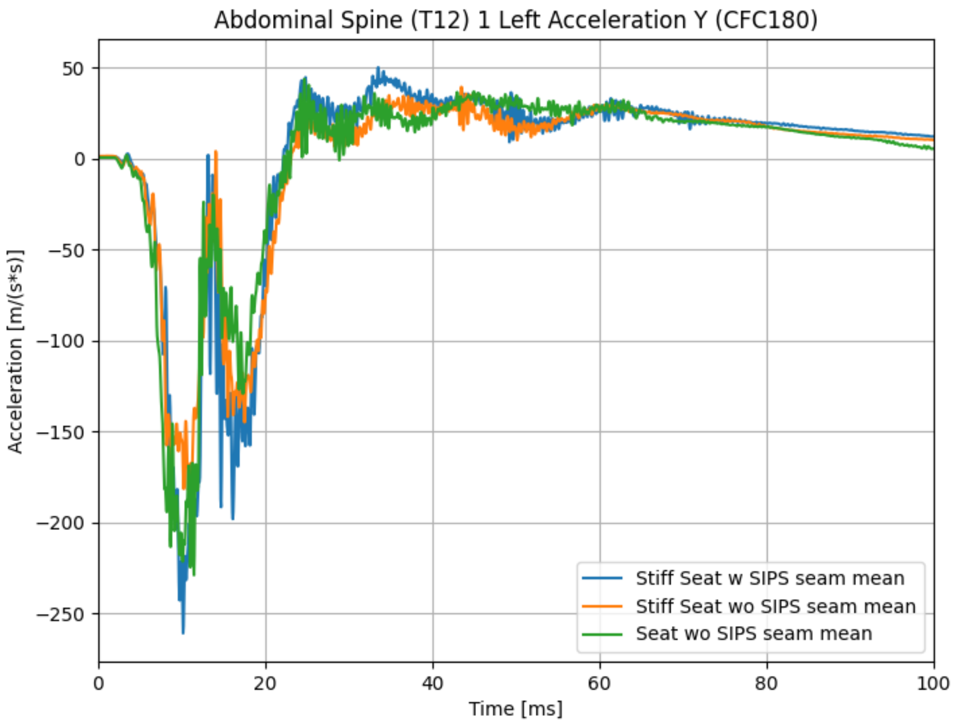

Thoracic Rib Lower Right Deflection Y (CFC600)
Deflection [mm]
Time [ms]
0.0
−2.5
−5.0
−7.5
−10.0
−12.5
−15.0
−17.5
0
20
40
60
80
100
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean

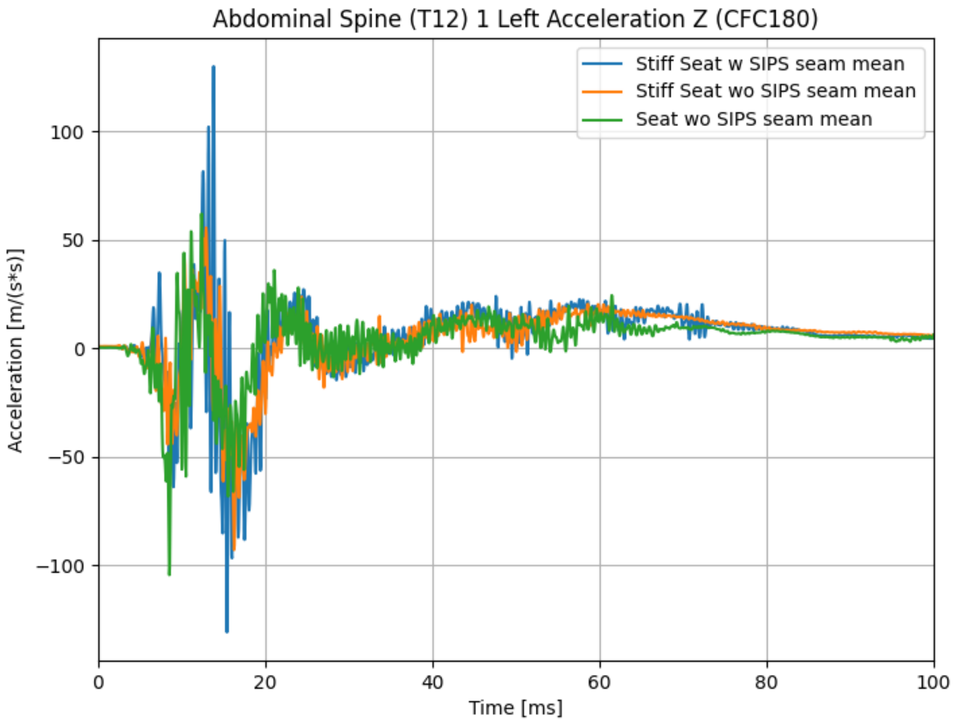

Thoracic Spine (T4) 1 Left Acceleration Y (CFC180)
Acceleration [m/(s*s)]
Time [ms]
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean

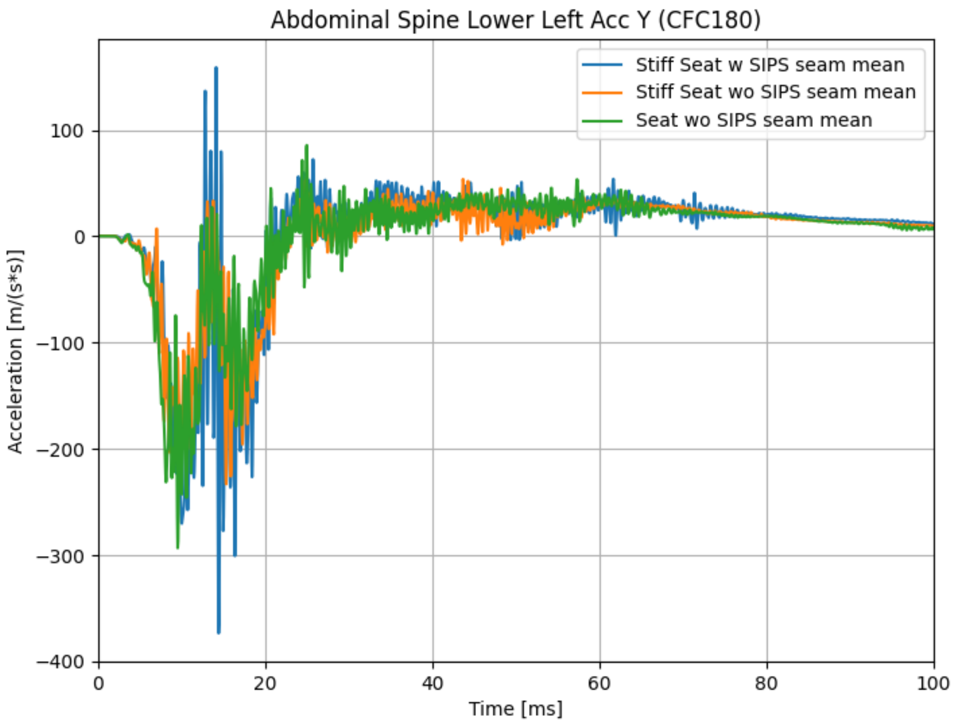

Thoracic Spine Middle Left Acc Y (CFC180)
Acceleration [m/(s*s)]
Time [ms]
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean

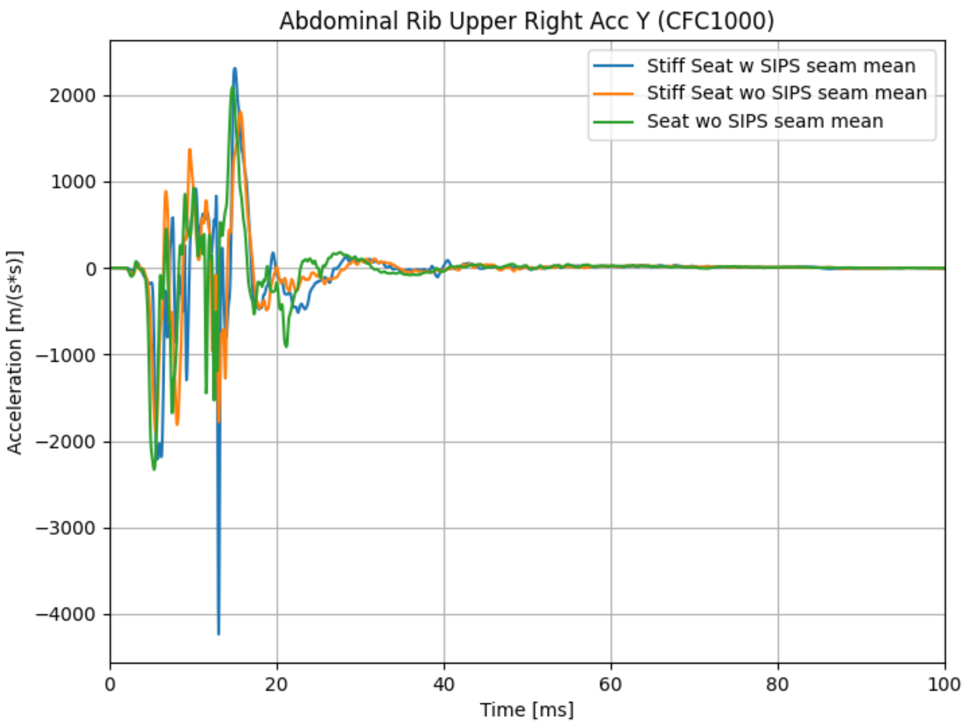

Thoracic Spine Lower Left Acc Y (CFC180)
Acceleration [m/(s*s)]
Time [ms]
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean

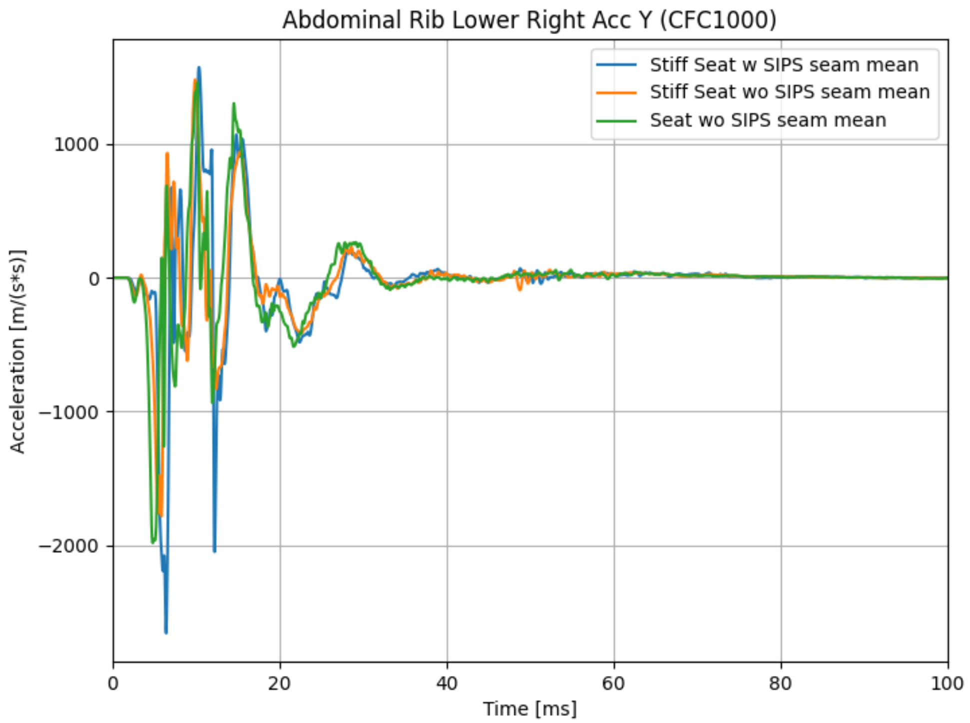

Abdominal Spine (T12) 1 Left Acceleration X (CFC180)
Acceleration [m/(s*s)]
Time [ms]
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean

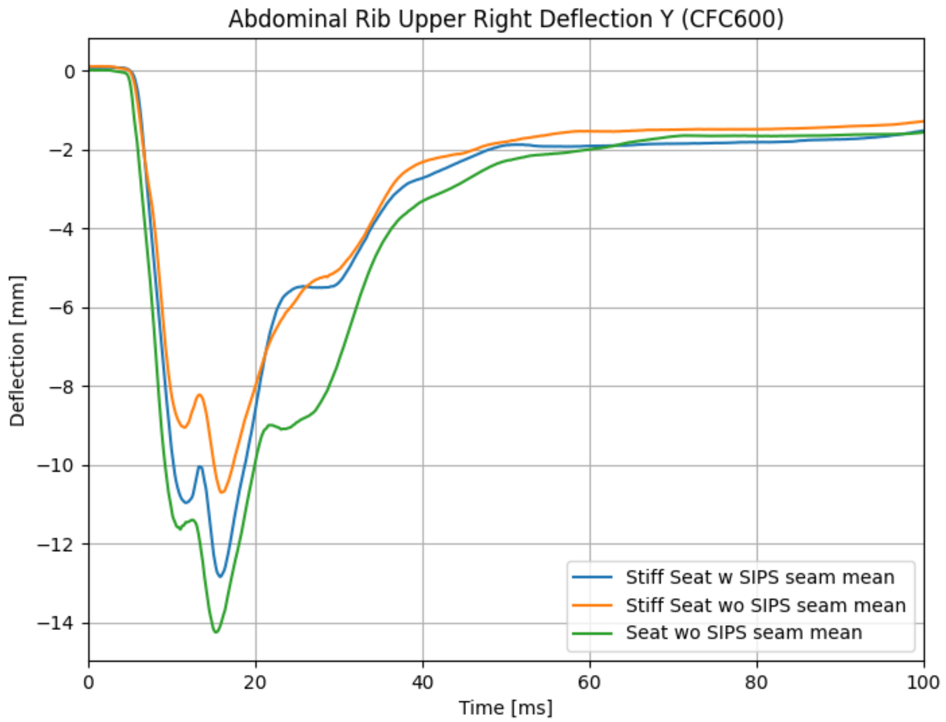

Abdominal Spine (T12) 1 Left Acceleration Y (CFC180)
Acceleration [m/(s*s)]
Time [ms]
50
0
−50
−100
−150
−200
−250
0
20
40
60
80
100
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean

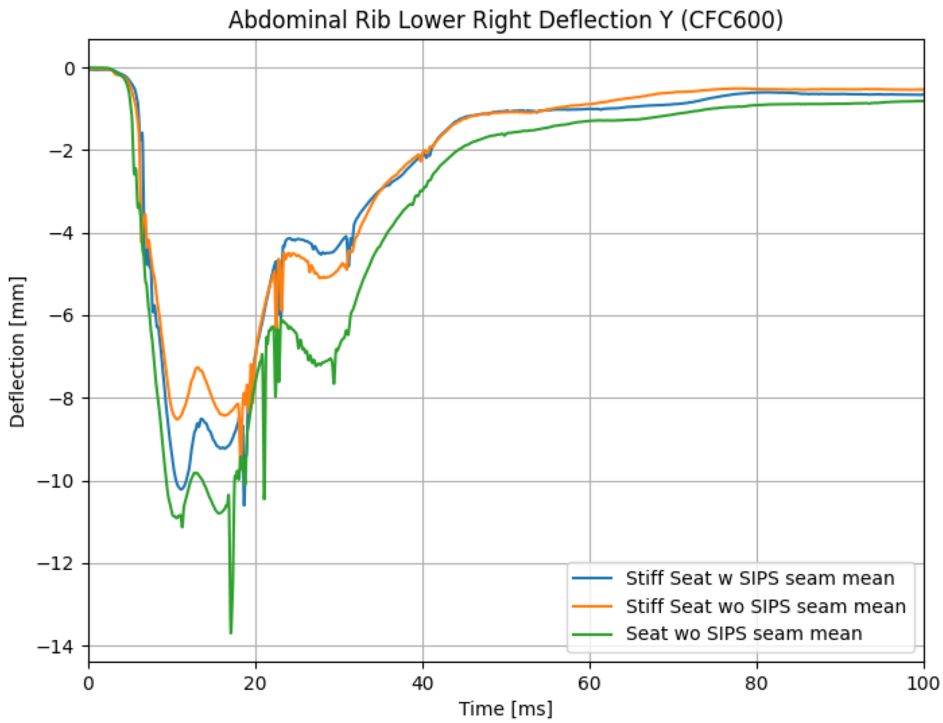

Abdominal Spine (T12) 1 Left Acceleration Z (CFC180)
Acceleration [m/(s*s)]
Time [ms]
100
50
0
−50
−100
0
20
40
60
80
100
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean

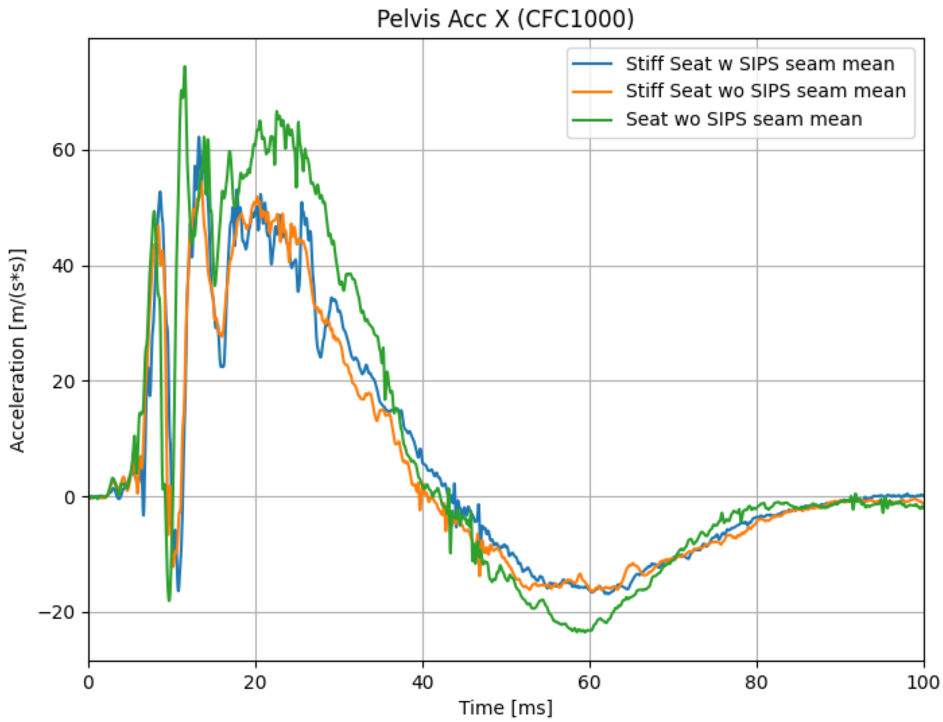

Abdominal Spine Lower Left Acc Y (CFC180)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Acceleration [m/(s*s)]
100
0
−100
−200
−300
−400
0
20
40
60
80
100
Time [ms]

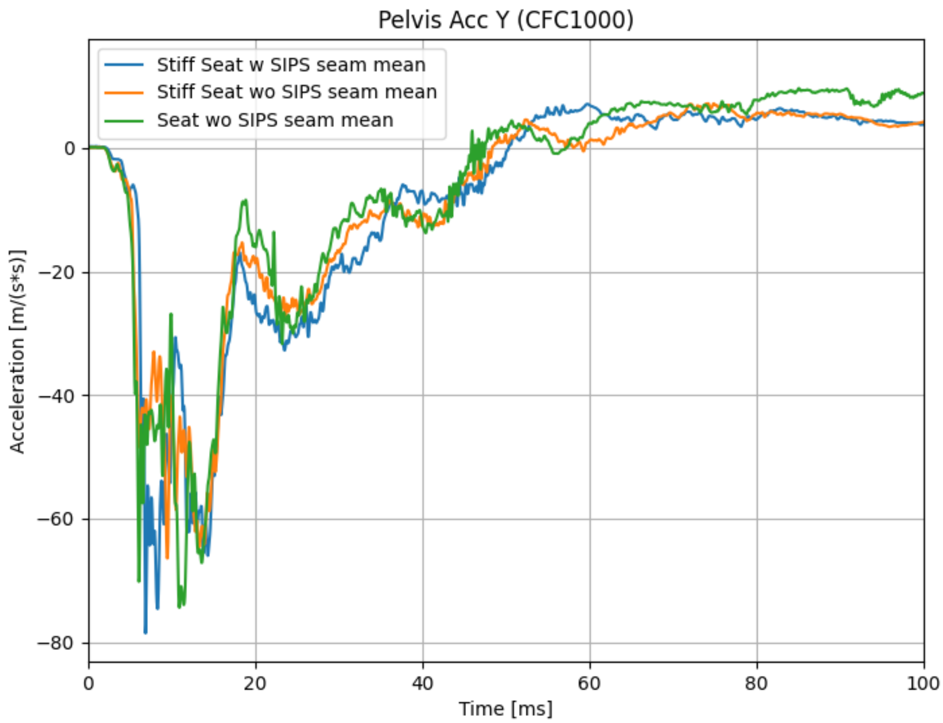

Abdominal Rib Upper Right Acc Y (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Acceleration [m/(s*s)]
2000
1000
0
−1000
−2000
−3000
−4000
0
20
40
60
80
100
Time [ms]

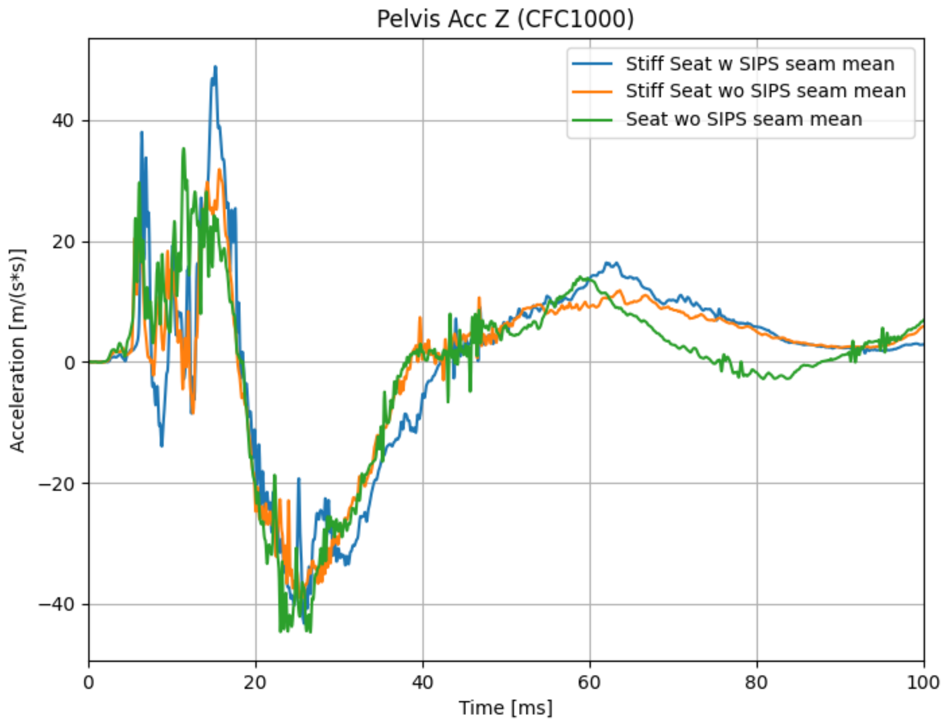

Abdominal Rib Lower Right Acc Y (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
1000
0
−1000
−2000
Acceleration [m/(s*s)]
0
20
40
60
80
100
Time [ms]

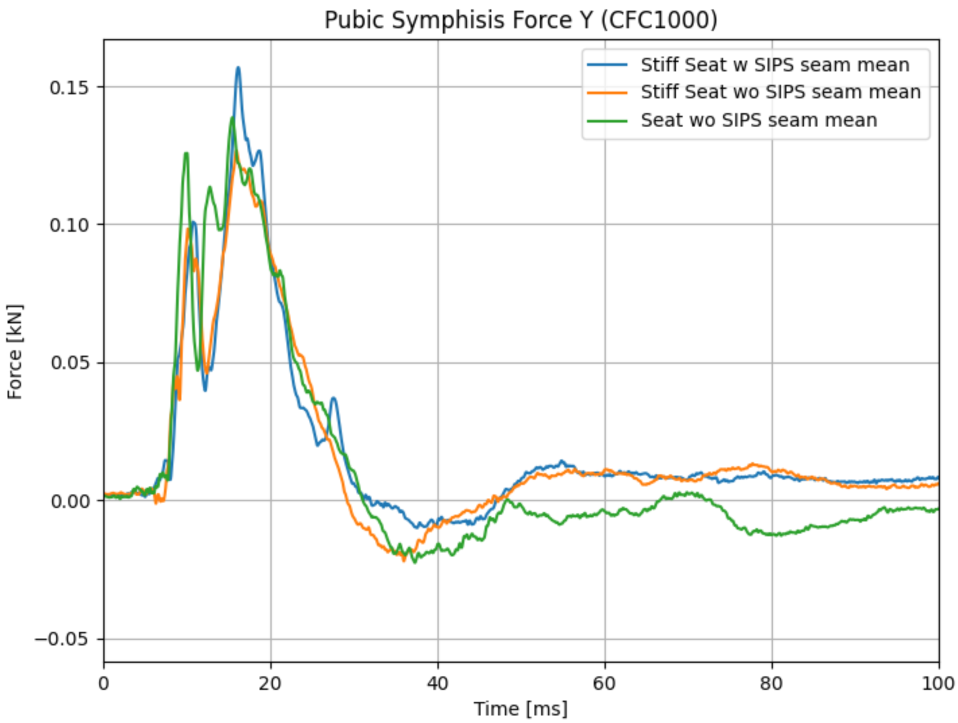

Abdominal Rib Upper Right Deflection Y (CFC600)
0
−2
−4
−6
−8
−10
−12
−14
Deflection [mm]
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
0
20
40
60
80
100
Time [ms]

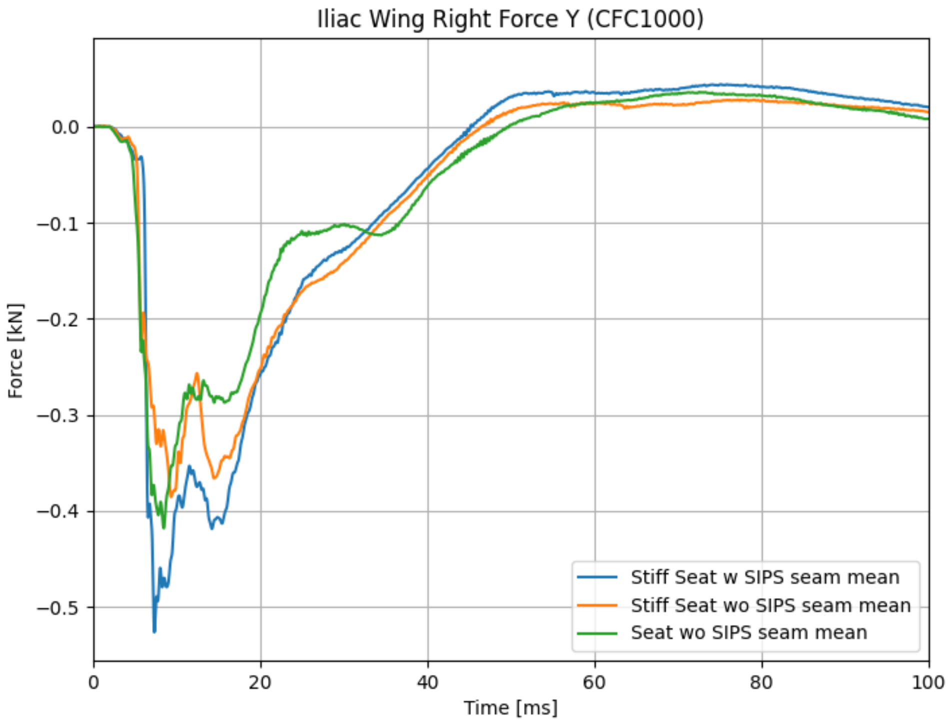

Abdominal Rib Lower Right Deflection Y (CFC600)
Deflection [mm]
Time [ms]
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
0
−2
−4
−6
−8
−10
−12
−14
0
20
40
60
80
100

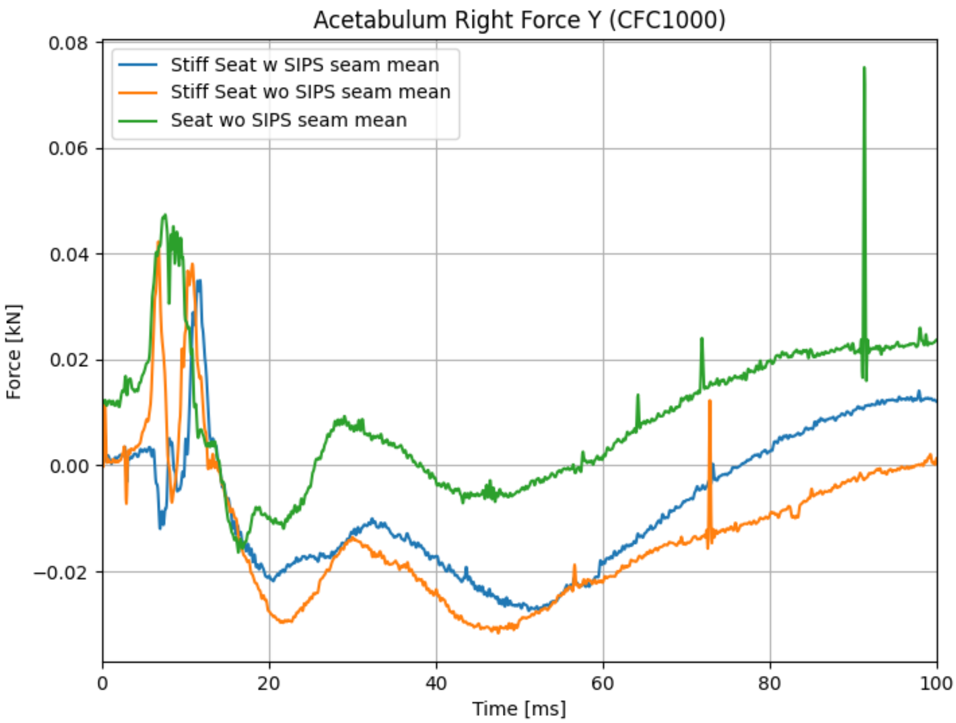

Pelvis Acc X (CFC1000)
Acceleration [m/(s*s)]
Time [ms]
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
60
40
20
0
−20
0
20
40
60
80
100


Pelvis Acc Y (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Acceleration [m/(s*s)]
Time [ms]
0
−20
−40
−60
−80
0
20
40
60
80
100


Pelvis Acc Z (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Acceleration [m/(s*s)]
Time [ms]
40
20
0
−20
−40
0
20
40
60
80
100


Pubic Symphisis Force Y (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Force [kN]
Time [ms]
0.15
0.10
0.05
0.00
−0.05
0
20
40
60
80
100


Iliac Wing Right Force Y (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Force [kN]
Time [ms]
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
0
20
40
60
80
100


Acetabulum Right Force Y (CFC1000)
Stiff Seat w SIPS seam mean
Stiff Seat wo SIPS seam mean
Seat wo SIPS seam mean
Force [kN]
Time [ms]
0.08
0.06
0.04
0.02
0.00
−0.02
0
20
40
60
80
100

A.3 Requirement Specification

Chalmers	Document type		Requirement specification			
Volvo Cars	*Project*		Front seat rig			
Author: Johannes Lindholm, Jonathan Viktorsson			*Created: 2024-02-12*			
			Modified: 2024-05-21			
Criteria		*Target value*		*R/D*	*Weight*	*Verification method*	*Justification*
1 Cost and material usage reduction							
1.1	Seat or parts of seat that lasts for multiple airbag deployments (forces and heat)	Minimum 5 deployments, preferably for the entire testing of a specific car model	R		Assesment, testing	Needs to last longer than what one seat can withstand
1.2	Possibilty to replace only the broken components	Modular design	D	2	Assesment	Only damaged parts need to be replaced
1.3	Low cost rig	- 50% cost reduction over 100 tests	R		LCC	Has to be a big enough saving for the time and resources used to develop a rig to be worth
1.4	Reduce resource usage	- 50% co2 eqvivalents compared to current way over 100 tests	D	3	LCA	It's a company target to reduce emissions
1.5	Efficient use of weight rig	<40kg	D	3	Check CAD	Shipping costs and manual handling
2 Compatible with existing testing equipment and design guidelines						
2.1	Rig must fit within design space	TRUE	R		Check CAD	Must fit into the use-case to have value
2.2	Rig must be compatible with existing mounting points	TRUE	R		Check CAD	Must fit into the use-case to have value
2.3	No stiff (structural) elements in front of airbag (overlap in x)	TRUE	R		Check CAD	Must follow same design guidelines as the seats themselves
2.4	No sharp corners in direction of airbag	R>3,2 mm	R		Check CAD	Must follow same design guidelines as the seats themselves
2.5	No protruding elements that may interfere with airbag deployment	TRUE	R		Check CAD	Must follow same design guidelines as the seats themselves
3 Accurate testing - Similar behaviour to real seat						
3.1	Same surface geometry	A-surface needs to be same	R		Check CAD	Dummy interaction, Needs to be similar enough to a real seat in order for the test results to be useful
3,2	Same seating foam stiffness	Same as real seat	R		Assesment	Dummy interaction, Needs to be similar enough to a real seat in order for the test results to be useful
3,3	Geometrically same airbag mounting points as seat	Same coordinates	R		Check CAD	Needs to be similar enough to a real seat in order for the test results to be useful
3,4	Similar surface friction between dummy and seat upholstery	In the same realm (similar type of material)	D	1	Assesment	Needs to be similar enough to a real seat in order for the test results to be useful

Figure A.1: Requirement specification part 1

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3,5	Similar surface friction between airbag and expansion points of contact	Within reason	R		Assesment	Needs to be similar enough to a real seat in order for the test results to be useful
3,6	Similar breakthrough resistance to airbag deployment	The closer the better	D	2	Physical test	Needs to be similar enough to a real seat in order for the test results to be useful
3,7	Not affect deployment direction	Same direction	R		Check CAD	Needs to be similar enough to a real seat in order for the test results to be useful
3,8	Consistent & predictable test result	Measurable and predictable deviation	R		Assesment	Makes it easier to trust the results
3,9	Adjustable angle of seat back	Must be able to maintain design angle regardles of set height	R		Check CAD	Height mech might affect angl. + minor adjustments allowed
3,10	Adjustable in x	Continous through full range	R		Check CAD, assesment	OOP 3.3.5.2 require it, and desire from test engineers
3,11	Adjustable in z	Highest and lowest setting corresponding to seat travel box	R		Check CAD, assesment	Tests performed at min & max
4	Easy handling and setup					
4,1	Adjustable angle of seat back	Toolless and/or electric operation	D		Check CAD	Height mech might affect angl. + minor adjustments allowed
4,2	Adjustable in z	Toolless and/or electric operation	D	3	Check CAD	It is hard to get dummy in correct position relative to car interior without continous
4,3	Adjustable in x	Toolless and/or electric operation	D	3	Check CAD	It is hard to get dummy in correct position relative to car interior without continous
4,4	Easy manual handling	Good grips that allow two people to carry	D	3		The seats are quite awkward to lift by hand because of shape, size and lack of handles
4,5	Easy access to airbag module	No fixtures in the way of airbag installation	D	3	Check Cad and do physical test	Would be unessesary and or time consuming
4,6	Easy to find correct test setup positions	Intuitive position markings	D	2		Helps with setup time and decreases chance of handling error
5	General desires					
5.1	Possibility to test upholstery concepts	Has upholstery	D	1		It would be benficial for "seat" department to be able to test fullscale upholstery concepts in a seat rig
5.2	Should be able to be adapted to fit new generations of design	Not too specific solution to XC40	D	3		Goal is to be able to re use concept for different designs or platforms

Figure A.2: Requirement specification part 2

A.4 Function Means Modelling

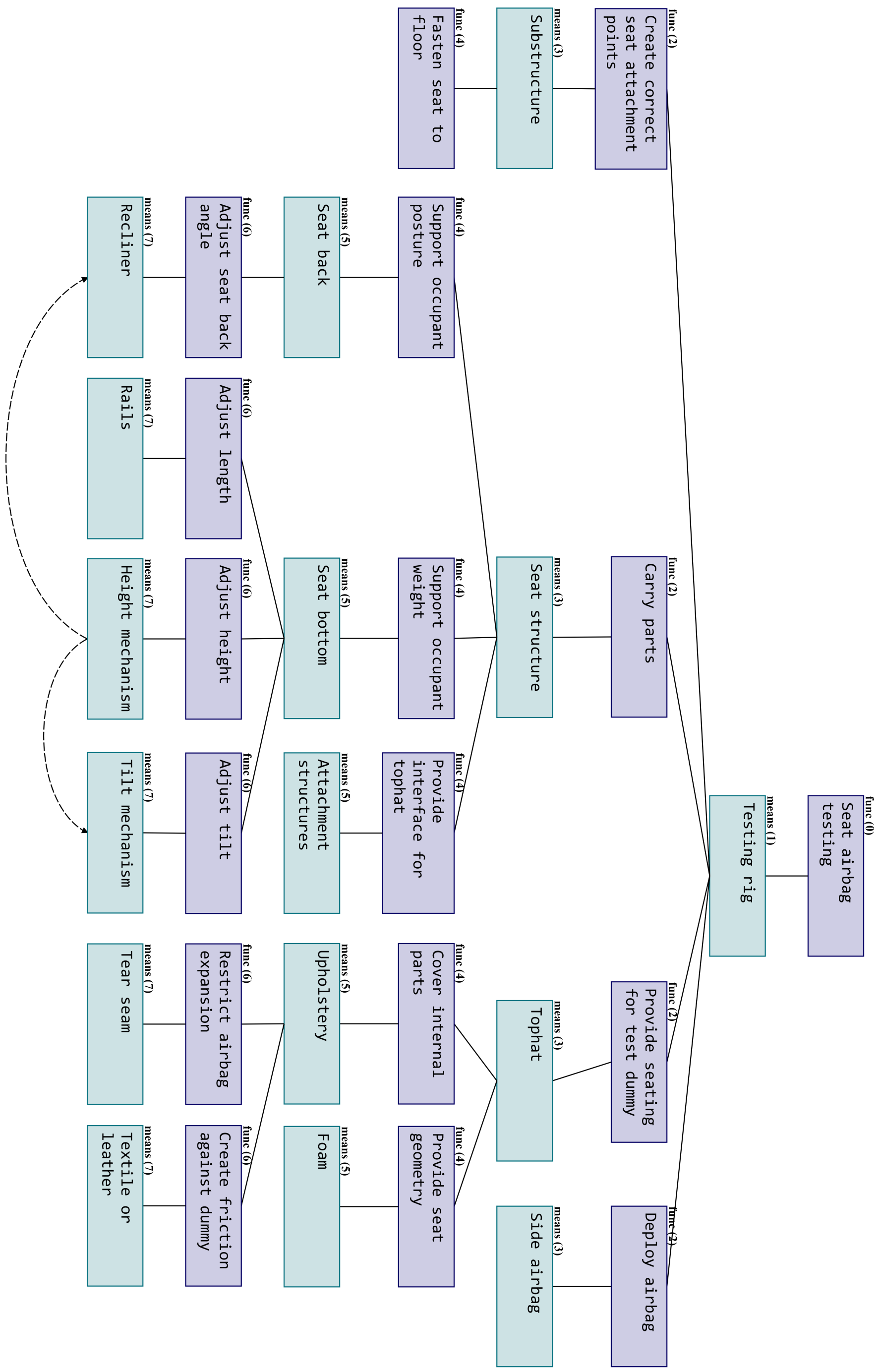


Figure A.3: Function means tree

A.5 Elimination Matrix

Criteria fullfillment:

(+)	Yes
(-)	No
(?)	More info needed
(!)	Check with specification

Decision:

(+)	Continue
(-)	Remove
(?)	More info needed
(!)	Check with specification

Solution alternative	Solves main problem	Fulfills all demands	Compatible/Realizable	Reasonable cost	Safe	Enough Information	Comment	Decision
1	+	+	+	+	+	+	Likely to work but simple	+
2	+	?	+	+	+	?	Merged with 3	+
4	+	+	+	?	+	?	Needs further development	+
5	+	+	+	?	+	?	Variation of 4	+
6	+	+	+	+	+	+	Likely to work but simple	+
7	+	+	+	+	+	?	Variation of 18	+
8	+	?	?	?	+	?	Difficult due to A-surface	-
9	+	+	+	+	+	+	Sourcing of mech parts	+
10	+	+	+	+	+	?	Potential for merge	+
11	+	?	?	+	+	?	Difficult due to A-surface	-
12	+	+	-	-	+	+	Too different from reference	-
13	+	-	+	+	+	+	Differs from foam softness	+
14	+	+	?	+	+	+	Could be difficult to implement	+
15	+	+	+	+	+	+	Merged with 1 & 3	+
16	+	+	+	?	+	?	Variation of 4 & 5	+
17	+	-	+	+	+	-	Not better than origional	-
18	+	+	+	+	+	+	Merge with 1, 3 & 15	+
19	+	+	+	+	+	+	Needs two separate seat frames	+
20	+	+	+	?	+	?	Variation of 4 & 5 & 16	+
21	+	+	+	+	+	+	Relatively heavy & complex rig	+

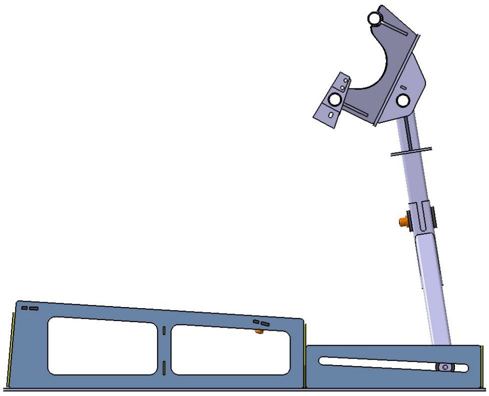
Figure A.4: Elimination matrix

A.6 Checklist

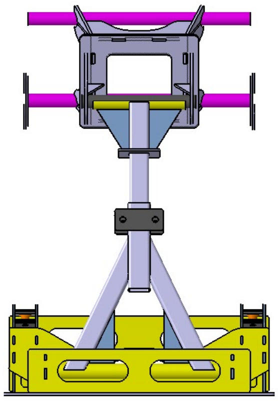
Table A.1: Embodiment design checklist

Headings	Examples
Function	Is the stipulated function fulfilled? What auxiliary functions are needed?
Working principle	Do the chosen working principles produce the desired effects and advantages? What disturbing factors may be expected?
Layout	Do the chosen overall layout, component shapes, materials and dimension provide: Adequate durability (strength) Permissible deformation (stiffness) Adequate stability Freedom from resonance Unimpeded expansion Acceptable corrosion and wear
Safety	Have all factors affecting the safety of the components, function, operation, user and environment been taken into account?
Ergonomics	Have the human-machine relationships been taken into account Avoidance of unnecessary human stress or injury factors
Production	Has there been a technological and economic analysis of the production processes?
Quality control	Do we have the necessary checks to be applied during and after production or at any other time?
Assembly	Can all the internal and external assembly processes be performed simply in the correct order
Transport	Have the internal and external transport conditions and risks been examined?
Operation	Have all the factors influencing the operation, such as noise, vibration, handling, etc been considered?
Maintenance	Can maintenance, inspection, and overhaul be easily performed and checked?
Recycling	Can the product be reused or recycled? What measures may be taken to enable efficient recycling? Material tagging
Costs	Have the stipulated cost limits been observed? What additional costs may arise?
Schedules	Can the delivery dates be met?

A.7 Proposed Solution

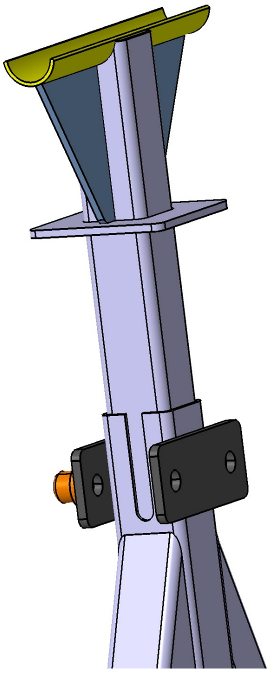


(a) Rig from side

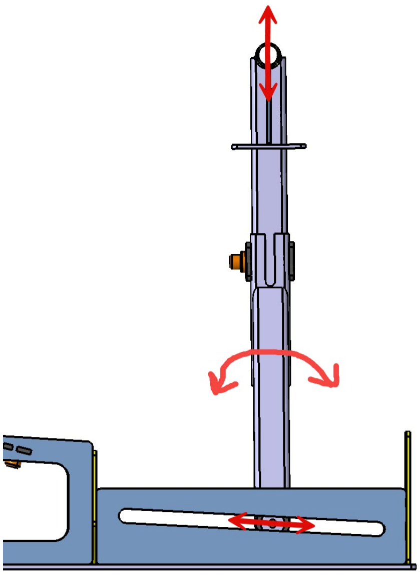


(b) Rig from behind

Figure A.5: Side and rear views of rig



(a) Detail view of strut and clamp mechanism



(b) Strut from side with degrees of freedom marked in red arrows

Figure A.6: Side and ISO views of telescopic strut

A.8 Breakthrough Concept Use Case & Evaluation

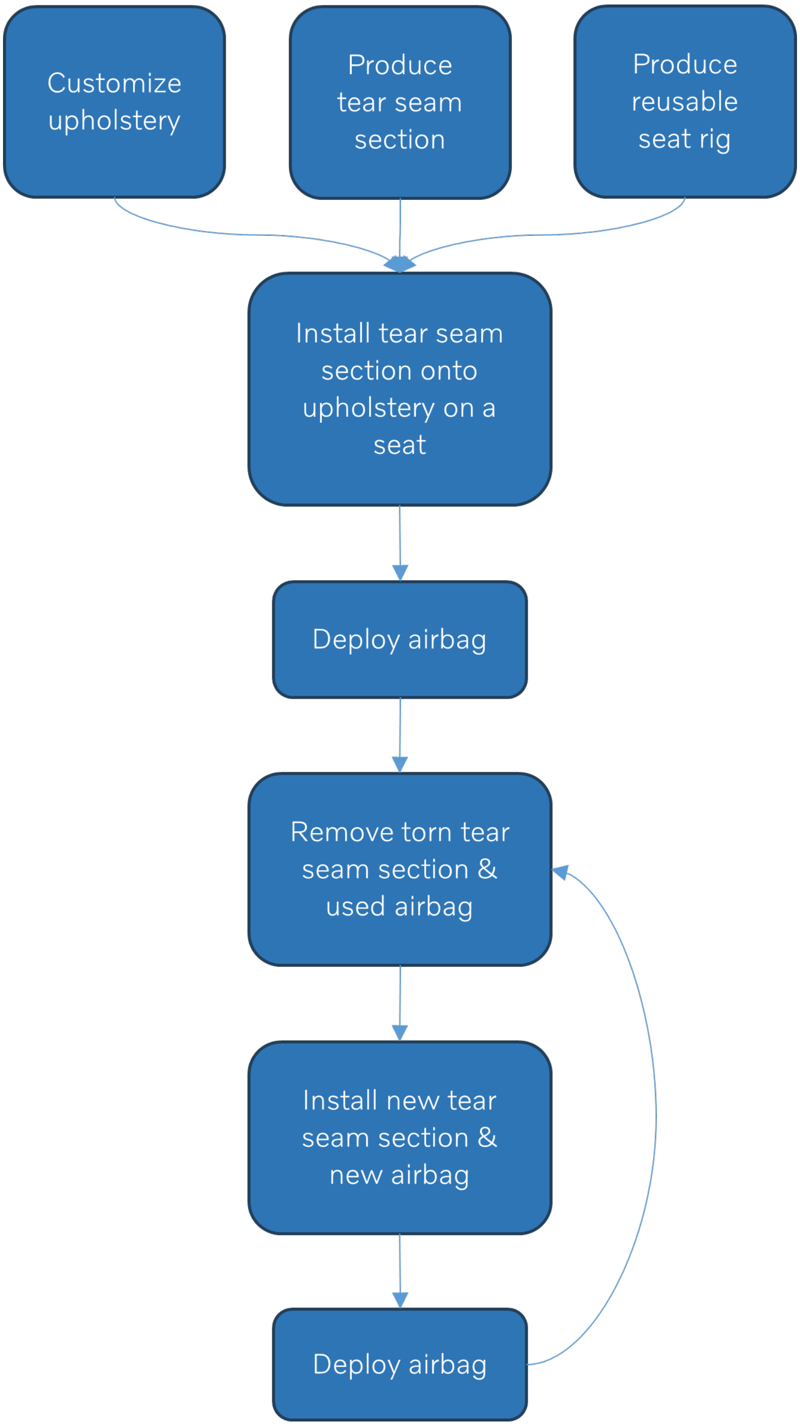


Figure A.7: Flowchart over implementation of the replaceable tear seam solution

(a) Closed tear seam

(b) Tear seam beginning to rupture

(c) Tear seam completely open

(d) Airbag in position

Figure A.8: Stages of zipper concept tear seam opening

(a) Closed tear seam

(b) Tear seam beginning to rupture

(c) Tear seam completely open

(d) Airbag in position

Figure A.9: Stages of button concept tear seam opening

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CHALMERS UNIVERSITY OF TECHNOLOGY
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www.chalmers.se

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