

Department of Construction Science

Solid Mechanics

TFHF - 5256

# **A Methodology for Evaluating the Performance of Material Models Under Biaxial Loads**

Master's Dissertation by

**Emmie Salomonsson**

**Ina Ögren**

**Supervisors:**

Björn Stoltz, IKEA Components  
Jonas Engqvist, Div. of Solid Mechanics

**Examiner:**

Stephen Hall, Div. of Solid Mechanics

# Abstract

The objective of this thesis is to develop a methodology for evaluating the performance of material models during biaxial loads. This is done by executing identical punch tests, one in a simulation and one in a physical experiment, and then comparing the results from the two. The material model that is to be evaluated is used in the simulation and a specimen of the corresponding material in the physical experiment. The more the results resemble each other, the more accurate the material model is considered to be.

A physical test jig is designed using a concept development process. Results from the experiment are acquired using digital image correlation and then compared to data from the simulation. Three comparisons are then made. First, the global force-displacement curves are compared. Second, a field analysis where local displacements and in-plane strains are compared. Third, the distribution of major vs. minor strains is compared. The mentioned comparisons result in a number of graphs and figures where the differences between the simulation and the experiment are represented both graphically and numerically.

The results from using this methodology can be used to calibrate and compare different material models. In addition, the material behavior can be analyzed qualitatively. The results can also reveal in which deformation range the model performs best.

**Keywords:** Material Model, Biaxial Test, Punch Test, Material Test, POM, Simulation, FEA.

# Acknowledgements

We would like to express our gratitude and thank all who have been a part of completing this thesis project. Their support and guidance throughout the entire project have been of great value.

First, we would like to thank the ones supporting us on a daily basis, our industry supervisors at IKEA, Björn Stoltz and Marko Kokkonen, and our university supervisor, Jonas Engqvist. Their expertise and continuous guidance throughout this project have been a key role in forming the final outcome. We would also like to thank Stefan Bertilsson and IKEA of Sweden for providing us with the opportunity to conduct our thesis project at IKEA Test Lab, it has been inspiring to work in such a motivating environment.

During different parts of this project, we have received help and support from people across IKEA's organization that has provided us expertise in different areas. We would therefore like to thank Kristian Nilsson at IKEA Components for his support during the product development phase and Peter Johansson at Pattern Shop for constructing a prototype and manufacturing the final product with such high quality. We would also like to thank David Svensson, a consultant at Sigma Industry AB positioned at IKEA, who came over to chat about horses during a coffee break which happened to result in him solving one of our main problems by proposing the use of a first surface mirror.

We have received great feedback from our opponent Olle Faritzon and would like to thank him for his valuable inputs on this thesis. Finally, we want to direct our gratitude towards our examiner Stephen Hall for contributing with final feedback on the project.

This master thesis is a result of great teamwork between the two authors who have complimented each other, both with their different areas of expertise, and with their different strategies of solving problems. Ina Ögren has had the main responsibility for making the CAD-model and writing the script for post-processing the data. Emmie Salomonsson has had the main responsibility for performing the finite element analyses and the data extraction.

**Lund, June 2023**

*Emmie Salomonsson*

*Ina Ögren*

# Contents

<b>1</b>	<b>Introduction .....</b>	<b>1</b>
1.1	<i>Background.....</i>	1
1.2	<i>About IKEA.....</i>	1
1.3	<i>Purpose .....</i>	2
1.4	<i>Objectives.....</i>	2
1.4.1	<i>Limitations.....</i>	2
1.5	<i>Report Structure.....</i>	3
<b>2</b>	<b>Theory .....</b>	<b>4</b>
2.1	<i>Punch Testing.....</i>	4
2.2	<i>Digital Image Correlation.....</i>	6
2.3	<i>Iterative Closest Point Algorithm .....</i>	8
<b>3</b>	<b>Designing the Test Setup.....</b>	<b>9</b>
3.1	<i>Methodology .....</i>	9
3.1.1	<i>Concept Development Process.....</i>	9
3.1.2	<i>Finite Element Analysis of Test Jig.....</i>	11
3.2	<i>Preparatory Work.....</i>	13
3.2.1	<i>Determine Preconditions .....</i>	13
3.2.2	<i>Identify Users .....</i>	14
3.3	<i>Identify User Needs.....</i>	14
3.4	<i>Establish Product Requirements.....</i>	15
3.5	<i>Concept Generation.....</i>	16
3.5.1	<i>Decomposition into Subproblems.....</i>	16
3.5.2	<i>Benchmarking .....</i>	17
3.5.3	<i>Brainstorming.....</i>	19
3.6	<i>Concept Selection.....</i>	21
3.6.1	<i>Choice of Overall Concept .....</i>	21
3.6.2	<i>Dimensioning .....</i>	23
3.7	<i>Concept Testing .....</i>	24
3.7.1	<i>Physical Prototype.....</i>	24
3.7.1	<i>Results from Finite Element Analysis.....</i>	24
3.8	<i>Final Design .....</i>	26
<b>4</b>	<b>Evaluating Material Models .....</b>	<b>27</b>
4.1	<i>Methodology .....</i>	27
4.1.1	<i>The Physical Punch Test.....</i>	27
4.1.2	<i>The Simulated Punch Test .....</i>	29
4.1.3	<i>Data Extraction.....</i>	30
4.1.4	<i>Striker Force-Displacement .....</i>	32

4.1.5	Field Analysis.....	32
4.1.6	Major vs. Minor In-Plane Strains .....	36
4.2	<i>Results</i> .....	37
4.2.1	Striker Force-Displacement .....	37
4.2.2	Field Analysis.....	38
4.2.3	Major vs. Minor In-Plane Strains .....	42
<b>5</b>	<b>Discussion .....</b>	<b>43</b>
5.1	<i>Designing the Test Setup</i> .....	43
5.1.1	Reflections on the Methodology.....	43
5.1.2	Reflections on the Design.....	43
5.2	<i>Evaluating Material Models</i> .....	44
5.1.1	Interpreting the Results .....	44
5.1.2	The Effectiveness of the Methodology .....	45
5.3	<i>Sources of Error</i> .....	46
5.4	<i>Future Work</i> .....	47
<b>6</b>	<b>Conclusion.....</b>	<b>48</b>
	<b>References .....</b>	<b>49</b>

# 1 Introduction

This section is an introduction to the thesis project. First, the background to why this research is relevant is presented as well as some information about IKEA. Second, both purpose and objectives, including limitations, are listed. Lastly, the structure of this report is explained.

## 1.1 Background

Traditionally, when designing products, prototypes are manufactured and tested to evaluate their functionality. This is costly in more than one way. Not only does it slow down the product development process, but it also requires money and resources. Due to this, many companies have started using simulations to test their products instead, most commonly by doing finite element analysis (FEA).

In order to obtain reliable results from the simulations, it is necessary to have accurate material models. Extensive research has been done on metals due to their use in many prominent industries, such as the automotive industry, military industry, and so on. In comparison, far less research has been done on polymers. For this reason, prototyping has been the most cost-efficient approach for testing thermoplastic products, but this is starting to change.

To enable high-quality simulations on thermoplastics, material models that can capture their complex behavior are essential. Plastic materials can exhibit non-linear, time-dependent, and viscoelastic behavior such as creep, stress relaxation, and hysteresis. In order to account for these phenomena accurately, further research has to be made.

## 1.2 About IKEA

IKEA is a multinational retail company specializing in furniture and interior. It was founded in Älmhult, Sweden by Ingvar Kamprad in 1943. IKEA strives to offer well-designed, functional, and affordable products for everyday life. The company's mission is to create a better everyday life for the vast majority of people. It is mainly known for its distinctive concept of flat-pack furniture, where products are efficiently packaged in flat boxes for easy transportation and customer assembly. This approach allows for

cost savings in manufacturing, storage, and transportation, which are then passed on to customers in the form of competitive prices.

IKEA engages in various types of research within material theory. The company especially focuses on exploring new materials that align with its sustainability goals, while still meeting the quality standards. IKEA aims to only use renewable and environmentally friendly materials in its products by 2030. Further, the company aims to eliminate the need for assembly tools in consumer packages. For this, new types of components need to be developed.

### **1.3 Purpose**

The purpose of the thesis is to help further strengthen IKEA's simulation capabilities. The company uses FEA simulations for both development and optimization purposes. Furniture, as well as its components, experience a wide range of external loads during their lifetime, which creates the need to accurately simulate complex load cases. Improved simulations will also help IKEA achieve its two goals mentioned in the previous section.

### **1.4 Objectives**

This thesis aims to develop a methodology for evaluating the performance of material models during biaxial loads. This is done in two steps. The first step consists of designing a physical setup for a punch test and constructing a corresponding digital model using computer-aided design (CAD) so that FEA also can be done. The second part consists of extracting data from both the physical experiment and the simulation and developing a method for comparing the results from the two.

#### **1.4.1 Limitations**

While the objective of this thesis does not revolve around the assessment of any particular material model, the development of the test jig is based on the properties of the thermoplastic material polyoxymethylene (POM). Test specimens of materials with very different properties may not be possible to use in the test.

## **1.5 Report Structure**

The report is organized into six sections, each serving a specific purpose. Chapter 2, titled “Theory”, provides a theoretical framework necessary for understanding the subject matter. The report further progresses with two distinct chapters dedicated to the two steps of the thesis. Chapter 3 explains the process used for designing the test setup and its result. Chapter 4 is dedicated to presenting the methodology developed for the evaluation of material models and its results. This chapter includes graphs to visually as well as numerically present the findings.

These chapters are followed by the Discussion, Chapter 5, where both the test jig and the evaluation method employed are discussed. The applicability of the evaluation method is discussed together with limitations and potential sources of errors. Lastly, the final chapter of the report is Chapter 6, the Conclusion, which provides a summary of the main findings and key insights.



## 2 Theory

In this section, key concepts necessary for understanding the project are presented. This includes explaining what a punch test is and what it is used for, how digital image correlation works, and presenting the iterative closest point algorithm. Digital image correlation is used in the experiment and the iterative closest point algorithm is used when performing the analysis of the results.

### 2.1 Punch Testing

Punch testing was first developed as a tool to evaluate material properties for components in service. It came from the radiation industry needing to evaluate material deprivation in components exposed to high levels of radiation [1]. This type of punch test is referred to as a *small punch test* since it enabled testing of component pieces not larger than a couple of millimeters.

What was first developed as a quality tool, later become a widely used test method in material research. Since punch tests induce more complex deformations, compared to traditional uniaxial tensile tests, it plays an important role in understanding material behavior when exposed to multiaxial stress states. Today, it is a valuable tool to improve material models and obtain well-performing simulations. [1]

#### Test Setup

A basic punch test setup uses a striker to punch a test specimen through a hole and measures punching force and displacement. The material can either be placed freely or clamped between two dies, see Figure 1.

The setup can vary depending on the desired outcome. Specimen size, striker and hole geometries, and the type of clamping are all factors that can impact deformation characteristics. Figure 1 shows an example where a punch, together with a loose ball is used as a striker, in Figure 2, three other common strikers are presented. The stress state in the

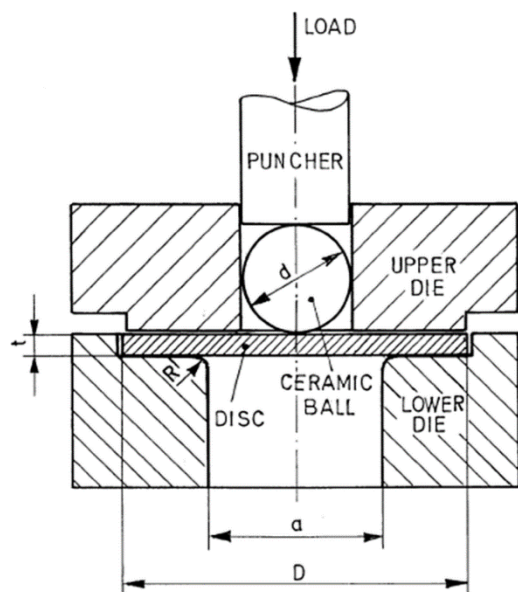


Figure 1. A punch test setup where a punch and a loose ball are used as a striker. [2]

specimen can be changed by using different striker shapes. When changing from conical (a) and hemispherical (b) strikers to a blunt (c) striker the stress state changes from biaxial tension to shear [3]. By clamping the specimen, deformations in the outer region of the specimen are avoided. Such deformations can lead to an unwanted increase in puncture energy. [4]

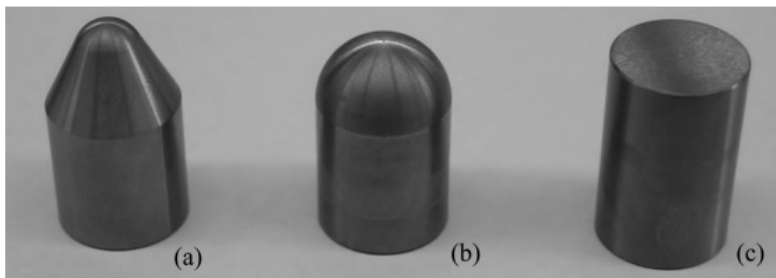


Figure 2. Three different types of strikers - (a) conical striker, (b) hemispherical striker, (c) blunt striker. [3]

The tests range from low-rate quasi-static tests, using for example a tensile testing machine, to high-rate dynamic tests using drop towers or pneumatically driven projectiles. The variety of punch test setups enables a large spectrum of analyses to be performed. When solely using a testing machine and setup as described above, striker force and displacement are usually the recorded measurements. Combining it with, for example, digital image correlation enables full-field measurements of the strain field on the rare surface of the specimen. These are used for a deeper analysis of the material behavior. Phenomena such as creep and stress relaxation in a biaxial stress state can also be analyzed. [3]

There are standards for executing different kinds of punch tests. These standards contain guidelines for experimental procedures, specimen dimensions, and data analysis methods. Aspects such as clamping the specimen and friction management are addressed, and certain guidelines for handling these challenges are specified. [4]

### **Advantages and Limitations**

The punch test is a simple technique that can induce complex stress states. It is possible to execute with numerous testing machines and setups making it possible for companies and researchers to use equipment they might already utilize, making punch testing a cost-effective testing method. However, some limitations arise due to the size and geometry of the specimen. The behavior of material may vary depending on its geometry and size. Furthermore, there are challenges in accurately simulating real-

world loading conditions due to its limitation in replicating a wide enough range of different stress states.

## **2.2 Digital Image Correlation**

Digital image correlation (DIC) is a non-contact experimental measurement technique to perform full-field measurements of objects undergoing deformation. There are different types of DIC; 2D- and 3D- surface DIC, and 3D volume DIC. 2D DIC measures in-plane deformation on a surface while 3D-surface DIC in addition can measure out-of-plane deformations on a surface. 3D volume DIC can also measure events inside of the material, using for example x-ray tomography. In this project, 3D-surface DIC is used, and the focus will therefore be on explaining the main concept of 2D and 3D- surface DIC since they have similar procedures.

### **2D and 3D- Surface DIC**

2D DIC requires one camera, and the observed object needs to have a flat surface throughout the measuring sequence. Since 2D DIC only measures in-plane deformations, any deformation in depth will cause incorrect measurements. 3D-surface DIC requires two cameras (that need calibration) to perform measurements in depth. It can be used to analyze non-planar objects and measure out-of-plane deformations of surfaces.

### **The Basic Principles of Digital Image Correlation**

To enable the correlation, a speckle pattern is created on the specimen using spray paint (if not already having a natural irregular pattern). A sequence of images of the specimen undergoing deformation is then acquired. The irregular pattern enables the formation of unique regions of the surface, called subsets. The displacement and deformation of these subsets are then traced throughout the sequence of images. These subsets are also referred to as facets. In Figure 3 some subsets are displayed. As can be seen, they usually overlap which enables a more efficient tracing of each subset.

The subset size is based on the irregular pattern; each subset needs to contain enough information for it to form a unique image in relation to nearby subsets. Once the subsets are selected, they are traced from the reference image to the deformed image,

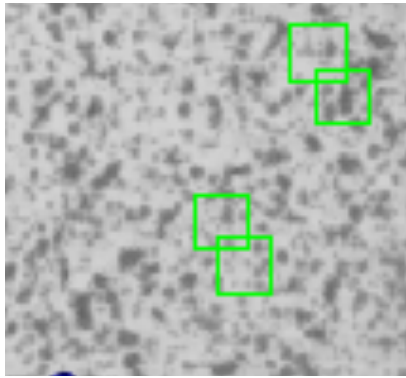


Figure 3. A speckle-patterned test specimen. The green squares are examples of subsets/facets.

determining the displacement of each subset. Subset tracing is performed using a correlation algorithm, comparing subset-image intensities. Tracing is restricted to a smaller region around the subset, with a size suitable for deformations occurring between the reference and the deformed image. A search region too large will not provide an effective algorithm, since it enables tracing in irrelevant areas. It also increases the risk of finding irrelevant subsets with high correlations,

too far away from the reference subset. On the other hand, a region too small might not include the whole deformation. The tracing results enable calculations of the displacements of each subset.

This method only enables displacement calculations of an integer number of pixels, while in reality, displacements measure values of in-between pixels, so-called, subpixel values. Therefore, a subpixel algorithm is used to treat the data and obtain more realistic values. Further, the displacement can be used together with continuum assumptions to calculate strain fields. Figure 4 shows the general procedure of surface DIC. The 3D-surface DIC requires calibration of the camera setup to enable accurate measurement of out-of-plane deformations [5].

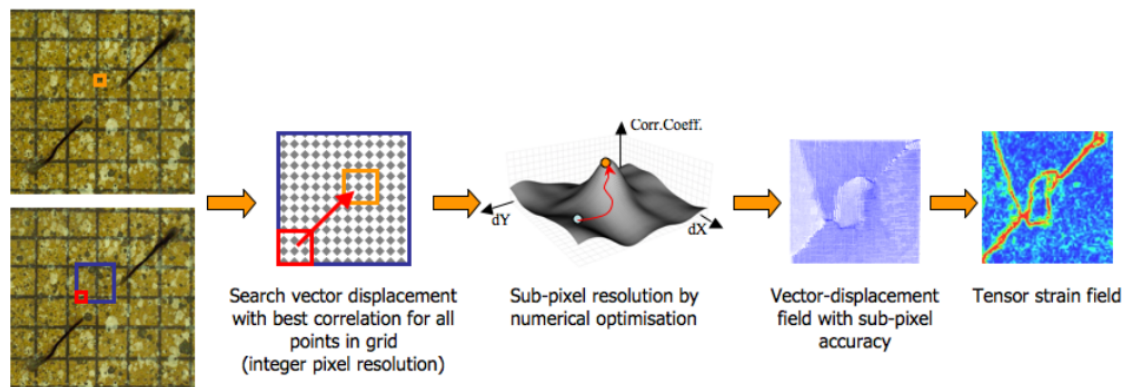


Figure 4. The general procedure of surface DIC. [5]

## 2.3 Iterative Closest Point Algorithm

The iterative closest point (ICP) algorithm is, in this project, used in the post-processing of the extracted data. Its purpose is to align data points and enable a comparison between the experimental and simulated punch tests. Why this is needed is explained in Section 4.1.5 Field Analysis.

The ICP algorithm is commonly used for aligning three-dimensional data sets (point clouds). Given two 3D point sets L (loose) and F (fixed), the task is to find the rigid transformation that brings L into the best possible alignment with F. It can be broken down into five steps, as shown in Figure 5:

1. Selection
2. Matching
3. Rejection
4. Minimization
5. Transformation

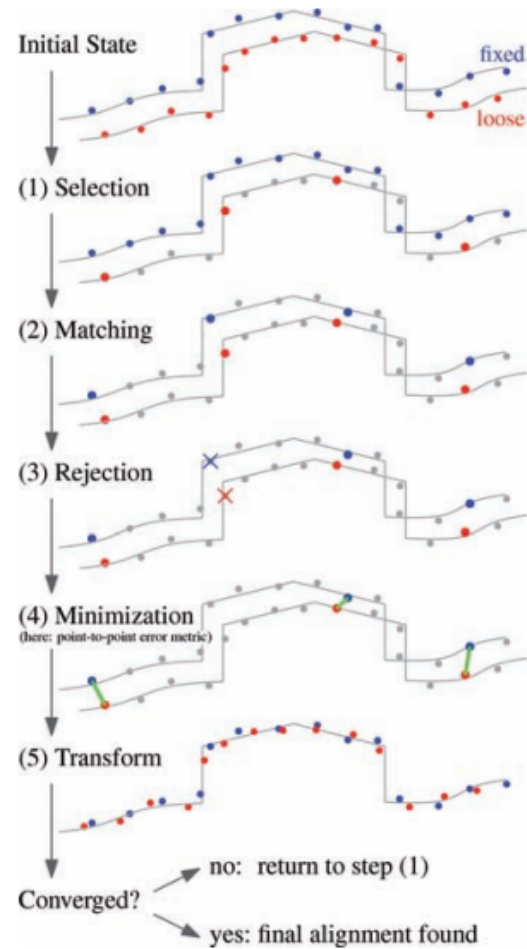


Figure 5. Schematic figure of the ICP algorithm procedure. [6]

During the selection, a subset of points is selected within the overlap area in one point cloud. Then matching is done by finding the corresponding points for the selected subset in the other point cloud. An estimation of transformation parameters for the moving point cloud is done by minimizing the distances between corresponding points. The distance between the points is called the point-to-point error. One can also minimize this by using the point-to-plane error. This is done by calculating the distance between the moving point and the plane that is defined by the corresponding fixed point's neighbors. Lastly, the moving point cloud is transformed. These steps are performed iteratively until the sum of the errors converges. When convergence is achieved, the final alignment is found [6].

# 3 Designing the Test Setup

This section of the report contains the first phase of the thesis project; designing the test setup. First, the methodology for designing is described. After this, all steps of the design process and their results are documented. Lastly, the final concept as well as reflections on its efficiency are presented.

## 3.1 Methodology

The methodology for designing the test jig is inspired by the concept development process that Ulrich & Eppinger present in their book *Product Design and Development* [7]. Further, finite element analysis is used to ensure that the test jig can endure the expected loads as well as to explore how varying certain parameters affects the test.

### 3.1.1 Concept Development Process

Concept development is the second step of Ulrich & Eppinger’s generic product development process, illustrated in Figure 6. The concept development process in turn consists of several steps, see Figure 7.



Figure 6. The generic product development process by Ulrich & Eppinger.

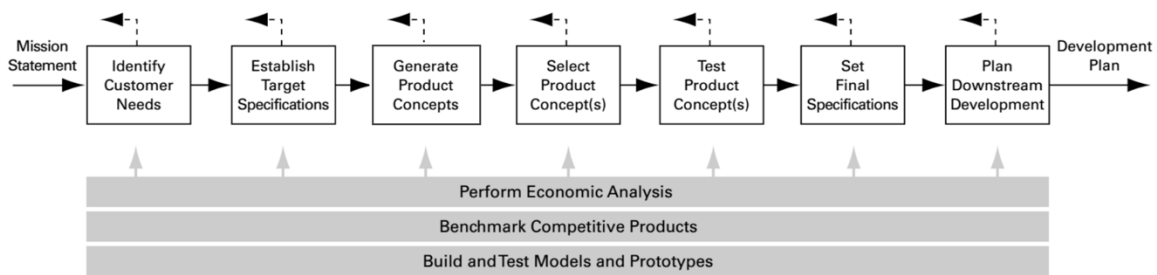


Figure 7. The concept development process by Ulrich & Eppinger. [7]

Ulrich & Eppinger’s process is aimed at products that are designed for commercial use [7, p. 12]. Since the test jig will not be commercialized, some of the steps are not applicable and/or necessary. Since there are no customers, the intended users and their needs are the focus during the process. Before the concept development process

is started, all information needed to determine preconditions, such as the specifications of the machine used and the size of the test specimens, are collected and the prerequisites are listed. Next, the users of the test are identified.

The first step is to *Identify User Needs*, using the following three steps from Ulrich & Eppinger's process:

1. Gather Raw Data from Users
2. Interpret Raw Data in Terms of User Needs
3. Organize Needs into a Hierarchy

[7, p. 75]

The raw data is gathered by having continuous conversations with the intended users as well as observing the test personnel executing tests using the same equipment that is to be used for the punch test. According to Ulrich & Eppinger, observing a similar product in use can reveal important details about user needs. [7, p. 77] After this, the raw data is used to list the user needs. These needs in turn are organized into primary and secondary needs.

The second step in the process is to *Establish Product Requirements*. The requirements are determined by considering the user needs and what is required of the test jig in order to fulfill them. This is done by discussing the user needs one by one as well as considering the information that is found through the discussion with the users and observing the test execution.

After the target specifications are established, the *Concept Generation* is started. This is done using the following steps from Ulrich & Eppinger's process:

1. Decompose the Problem into Subproblems
2. Benchmark Similar Products
3. Brainstorming

[7, p. 120]

The test jig design needs to solve several different subproblems, such as how to make the test specimen visible to the DIC cameras and how the test specimen should be fastened. These are all considered individually to simplify the process. Solutions to each subproblem are then found by exploring existing punch- and puncture tests

through a literature study. In the literature study, both testing standards, as well as scientific reports, are considered.

After generating a sufficient number of solutions to each subproblem, the next step is *Concept Selection*. Ulrich & Eppinger suggest a rather intricate process for concept selection using concept rating and ranking [7, p. 149-150]. It was determined that doing all these steps is not necessary, but that the best solution to each subproblem can be found through discussion. Each subproblem and its most suitable solution is discussed individually. These discussions result in a combination of concepts, that results in the final overall concept. When the final overall concept is selected, the measurements of the test jig are determined. This is done using the benchmarking of existing test jigs and considering the existing preconditions determined before the concept development process.

After determining the preliminary final design, the concept is tested. First, FEA is used to ensure that the test jig can endure the expected loads and that the test specimen exhibits the desired behavior. This process is described more in detail in Section 3.1.2 Finite Element Analysis of Test Jig. After this, a simplified prototype is manufactured and tested. This testing does not involve applying any loads onto the test specimen. Its sole purpose is to make sure that the desirable parts, with sufficient margin, of the specimen are visible using the DIC equipment. Necessary alterations are made, then the final specifications are set. After the test jig has been manufactured, it is tested.

### **3.1.2 Finite Element Analysis of Test Jig**

A finite element analysis is performed to evaluate the robustness of the final design. Further, the effect of the friction between the specimen and its neighboring surfaces (the striker and the clamping dies) is examined. Apart from this, a general observation of the simulation is performed in order to see if the test produces desirable results.

Altair HyperMesh is used as the preprocessor and Altair HyperWorks as the postprocessor, with LS-Dyna as the solver. Material models for steel and POM are used in the analyses. For steel, a bilinear material model with kinematic hardening is used, and for POM, a piecewise linear material model with isotropic hardening, that does not consider damage or failure. Both models are available in LS-Dyna. Due to symmetry conditions, the analyses are done on a quarter of the geometry.



## Robustness Analysis

The robustness of the structure is tested by applying a load concentrated at the edge of the punching hole, see Figure 8. This replicates a worst-case scenario and is used to evaluate how much the structure deforms at different load levels. If the test jig is deformed during testing, it results in inaccurate measurements. Therefore, the deformations of the jig itself must be neglectable. The deformation is measured at a point at the edge of the punching hole marked as a black cross in Figure 8.

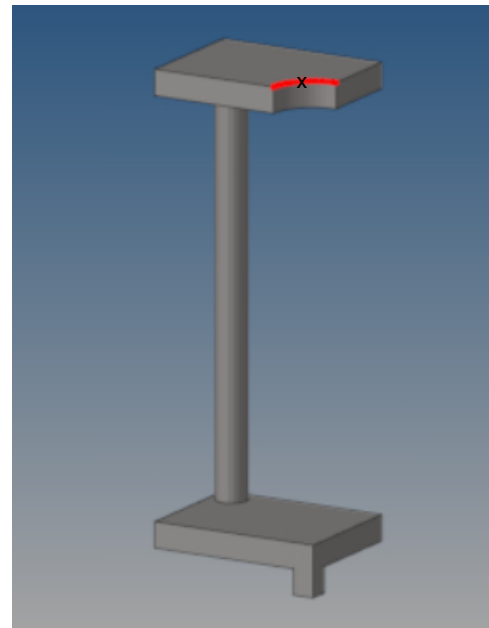


Figure 8. The geometry that was used for the robustness analysis. The red line shows where the load was applied, and the cross mark shows where the deformation is measured.

Three load levels are analyzed, 5 kN reflecting the expected load level for POM, and 10 kN and 30 kN to evaluate the deformations for higher loads.

## Friction Analysis

The effect of the friction between the specimen and its neighboring surfaces (the striker and the clamping dies) is examined. The striker force-displacement curve is analyzed for the striker friction and the sliding movement of the specimen for the friction of the striker dies. The sliding movement is analyzed by measuring the in-plane displacement of an edge node on the specimen. The tests are performed using the geometry in Figure 9. Two extreme scenarios are tested, one high friction scenario with a friction coefficient of 0.3 together with a preload force of 3 kN and a low friction scenario with a friction coefficient of 0.001 with no preload.

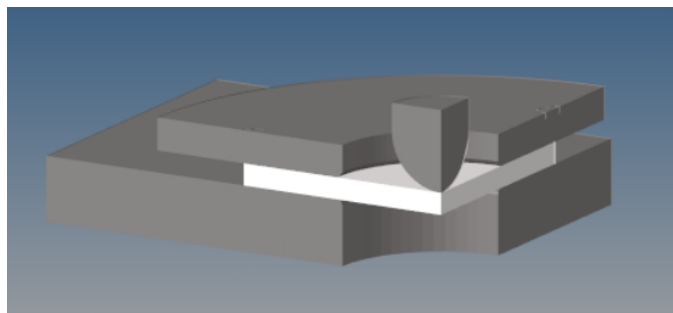


Figure 9. The model that was used for the friction analysis.

For both the robustness and the friction analysis, the structures are meshed with tetrahedral elements. The sizes of the elements are chosen so that each part has five elements throughout the thickness.

## **3.2 Preparatory Work**

The preparatory work, necessary to perform before starting the concept development process, consists of determining the preconditions and identifying the users of the test.

### **3.2.1 Determine Preconditions**

The preconditions given by IKEA are the following:

1. The test jig can be used in two testing machines that IKEA has in its testing lab.
2. The deformations of the test specimen can be measured by digital image correlation, using the DIC setup in IKEA's test lab.
3. The test can be executed on IKEA's standard test specimens of POM. In addition, the test can be executed on test specimens of various thicknesses.
4. The piston stroke of the test does not need to be larger than 100 mm.

### **The Testing Machines**

IKEA has two machines in which the punch test is to be performed in: INSTRON 5982 and Zwick Roell LTM 3. Thus, the test jig needs to be able to fit into both machines **and** have fastening devices for both. Further, the specifications of these machines, such as their maximum forces and velocities are limiting factors when executing the test. The main differences between the two machines are the load capacity and the operating velocity. The INSTRON machine has a load cell size of 100 kN, and the Zwick Roell of 3 kN. The maximum velocities are 0.017 m/s and 1 m/s respectively.

### **DIC Equipment**

IKEA has the DIC camera GOM ARAMIS 3D CAMERA 2.3M, which consists of two angled cameras, positioned so that the same area of the specimen is visible for both. The DIC setup is too large to record from underneath, thus the test specimen needs to be visible from the side. Further, the test jig needs to have a geometry that allows both cameras to see the test specimen, without any parts of it concealing the desirable field of view. The DIC camera has a focal length of 700 mm and a resolution of 2.3 megapixels which allows a frame rate of 130 fps.

### **Test Specimens**

The standard test specimens used at IKEA have the size 80 mm × 80 mm × 2 mm. IKEA also wishes for the ability to test specimens of various thicknesses, varying from thin fabrics to plastics with a thickness of up to mm.

### 3.2.2 Identify Users

The users of the testing device and its results are defined as everyone across IKEA's organization that uses the test jig or the test results. The testing is executed by employees at IKEA Test Lab, thus they are users of the physical test jig. The results of the tests are then used to verify the material models that are used in simulations. Therefore, the users of the test results are the employees developing new material models, as well as all employees who perform simulations.

In summary, the users are determined to be the following:

- Employees at IKEA Test Lab
- Employees at IKEA developing material models
- Employees at IKEA performing simulations

### 3.3 Identify User Needs

The interpreted user needs are listed below in Table 1. The primary needs are displayed in bold, and the secondary needs in plain text. Every need has its own need number.

Table 1. The user needs. Primary needs are written with bold text and secondary needs with plain text.

No.	User Need
<b>1</b>	<b>The test produces reliable results</b>
2	The test is repeatable.
3	The deformations in the test jig are much smaller than in the test specimen.
<b>4</b>	<b>The test captures the desired material characteristics.</b>
5	The test specimen is deformed in a desirable way.
6	The desirable quantities can be measured using the existing equipment, including the DIC setup, at IKEA Test Lab.
<b>7</b>	<b>The boundary conditions of the test are known.</b>
<b>8</b>	<b>The test is easy for the employees at IKEA Test Lab to execute.</b>
9	The test jig is easy to mount onto the machine.
10	It is easy to ensure that the test specimen is fastened in a consistent (repeatable) way.
11	The test is safe to execute.
<b>12</b>	<b>The test allows for flexibility according to IKEA's needs.</b>

13	The test jig can be mounted onto both the Instron and the Zwick machines.
14	The test allows for testing specimens of various materials.
15	The test can be executed on specimens with the size 80 x 80 x 2 mm.
16	The test has a piston stroke of 100 mm.

### 3.4 Establish Product Requirements

The requirements of the test jig are listed below in Table 2.

Table 2. The product requirements.

No.	Product Requirement	Satisfies User Need(s) No.
1	The pretension force and/or the clamping distance are known.	7
2	The test jig can test specimens with the dimensions 80 x 80 x 2 mm.	15
3	The piston stroke of the punch test is 100 mm.	16
4	The clamping device prevents deformations in the outer region of the test specimen.	1, 4, 5
5	No stress concentrations occur in the edge of the hole of the test jig.	4, 5
6	Stress concentrations occur in the center of the test specimen, where it is hit by the tip of the striker.	4, 5
7	When testing, the deformations in the test jig are significantly smaller than the deformations in the test specimen.	1, 3, 4
8	The test jig ensures a consistent, centered, placement of the test specimen.	1, 2, 8, 10
9	The clamping device ensures a constant pretension force and/or distance.	1, 2, 7, 8, 10
10	The test executor can ensure that the test jig is placed correctly into the machine.	1, 2, 8, 9, 11
11	The test jig has fastening devices for both testing machines.	6, 12, 13

12	The test jig has dimensions that allow it to fit into both testing machines.	6, 12, 13
13	The desirable part of the test specimen is visible to the DIC from the side of the testing machine.	4, 6
14	The test allows for testing specimens of thicknesses varying from very thin up to 4 mm.	12, 14
15	The weight of the test jig is light enough so that it can be carried by one person alone.	8, 9, 11
16	Preparing the test does not take an excessive amount of time.	8

### 3.5 Concept Generation

The concept generation is done in three steps. First, the problem is decomposed into smaller subproblems. Second, benchmarking is done by exploring existing punch test setups. Third, brainstorming is done systematically to identify possible solutions to each subproblem.

#### 3.5.1 Decomposition into Subproblems

The problem is decomposed into smaller subproblems in order to make the concept generation more systematic. Two types of subproblems were identified: designing subproblems and dimensioning subproblems. The designing subproblems are considered when selecting the overall design. The dimensioning subproblems are considered when dimensioning the test jig, after choosing the final overall design.

#### Designing Subproblems

1. How can the design ensure that the desirable part of the test specimen is visible from the side of the testing machine?
2. How can the design ensure that the test specimen is fastened with sufficient clamping force?
  - a. How can the design ensure that the pretension force and/or the clamping distance is known?
  - b. How can the design ensure that the pretension force and/or the clamping distance is constant?

3. What shape should the striker have?
4. How can the design enable the fastening of the striker and the test jig into the two machines?
5. How can the design help ensure that the test jig is placed correctly into the machine?
6. How can the design help ensure a consistent, correct, placement of the test specimen?
7. How can the design enable the testing of specimens with various thicknesses?

### **Dimensioning Subproblems**

1. The dimensions of the test jig allow the desirable part of the test specimen to be measured with the DIC cameras from the side of the testing machine.
2. The dimensions of the test jig allow it to fit into both of the testing machines.
3. The dimensions of the test jig allow testing of specimens with the size 80 x 80 x 2 mm.
4. The dimensions of the test jig allow a piston stroke of 100 mm.
5. The dimensions of the test jig are large enough to prevent the test jig from deforming when testing.
6. The dimensions of the test jig are small enough to ensure that the test jig is light enough so that it can be carried by one person alone.

### **3.5.2 Benchmarking**

When benchmarking for similar punch test setups that fulfill the stated problems, three sources targeting different problems are found. One ISO standard, one setup using a horizontal deformation mechanism together with DIC and one setup using a mirror together with DIC.

#### **ISO Standard for Punch Test - ISO6603-2:2000**

The ISO standard address three main aspects of a punch test: the dimensions of the setup, striker, punching hole, jig, and specimen, the clamping force, and the friction between striker and sample. Two different setups are specified, one for a larger test specimen and one for a smaller test specimen, where the larger specimen includes the following dimensions: hole diameter and edge radiuses of 40 mm and 1 mm respectively, and a hemispherical striker with a diameter of 20 mm.

A clamping force of at least 3 kN is recommended to avoid any unwanted deformations on the outer parts of the specimen. Clamping can be done either by force or by shape. Regarding friction, it is not necessary to use lubrication for rates lower than 10 mm/s. Analyzing the crack can indicate whether lubrication might be necessary or not, whereas a crack shaped like a round cap indicates too high friction and lubricant might be necessary, see Figure 10 [4].

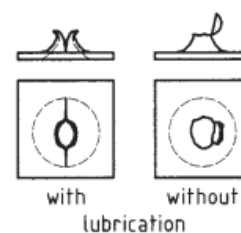


Figure 10. Failure characteristics when testing with and without lubrication. [4]

### Small Punch Test with First Surface Mirror

In a study by Vijayanand in 2020, a punch test is performed using a testing machine in combination with DIC. The challenge of making the specimen visible for the cameras is solved by using a first surface mirror, see setup in Figure 11. A first surface mirror is used to remove the unwanted so-called “ghosting effect” that occurs when using a regular mirror with a glass coverage.

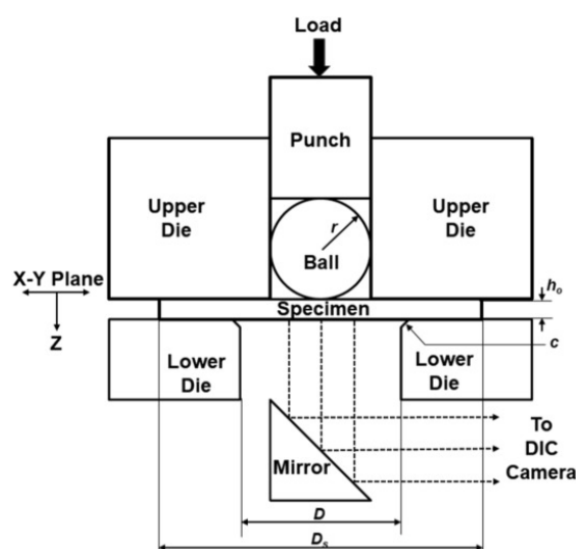


Figure 11. The punch test setup used in the study. [1]

The angle of the mirror causes parts of the specimen to be out of the focus depth of the camera, this is due to the lenses and mirror not being parallel. This error is quantified and shows a deviation of  $\pm 0.07$  mm for displacements up to 2.7 mm, larger deviations are observed for larger displacements but are not quantified in the study. The striker is a loose spherical ball being punched down on the specimen, see Figure 11. Advantages with this solution is that the ball can easily be replaced and thereby avoiding wear. Detailed dimensions of the setup are not specified. [1]

## Evaluation of Striker Geometries in Horizontal Setup

In a study by Hammer in 2015, a horizontal test setup is used, enabling free space to place the cameras. To make the specimen visible for the DIC, holes are made in the clamping dies, see Figure 12. Different striker shapes are also evaluated: one conical, one hemispherical, and one blunt. The results show that the punching force and the deformation are sensitive to the striker geometry. The highest force and deformation are both obtained using the blunt shape, followed by the hemispherical, and lastly the conical shape. A specimen with a 50.8 mm diameter and thickness of 5.08 mm is used and clamped mechanically with screws [3].

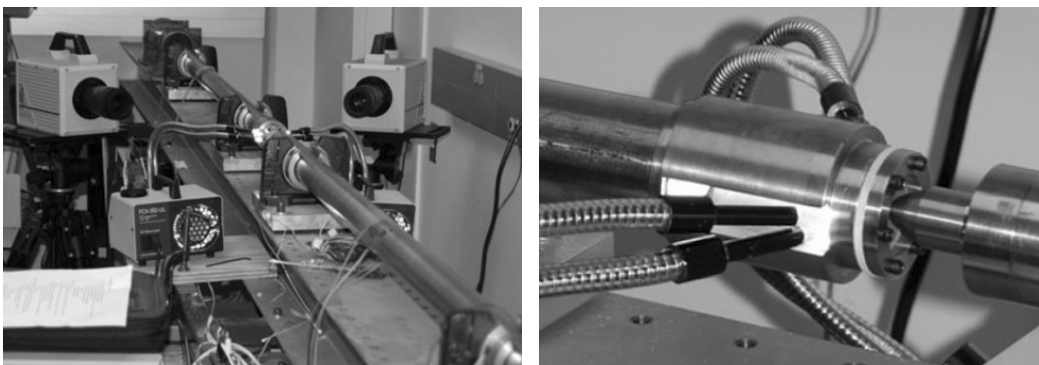


Figure 12. The test setup used in the study. Left: An image of the camera setup. Right: A close up view of the holes displaying the specimen. [3]

### 3.5.3 Brainstorming

Possible solutions to each designing subproblem are found through brainstorming and are then listed below.

#### 1. How can the design ensure that the desirable part of the test specimen is visible from the side of the testing machine?

- Transmitting the vertical motion of the machine to a horizontal motion.
- Placing a first surface mirror below the test specimen at a 45° angle.
  - *Additional problem: How can the first surface mirror be protected against damage from scatter from the punctured test specimen?*
    - *Tempered glass*
    - *Compressed air blower*



**2. How can the design ensure that the test specimen is fastened with sufficient clamping force (that is both known and constant)?**

- Using bolts and a torque wrench.
- Using clamps
- Using a pneumatic solution
- Using a hydraulic solution
- Using the force of the machine to press onto the clamping device

**3. What shape should the striker have?**

- Cylindrical
- Hemispherical
- Conical

**4. How can the design enable the fastening of the striker and the test jig into the two machines?**

- Striker:
  - Manufacture two different strikers with different fastening devices
  - Have a fastening device for one of the machines on the striker and manufacture an adapting device for the other machine
- Test jig:
  - Manufacture two different test jigs with different fastening devices
  - Have a fastening device for one of the machines on the test jig and manufacture an adapting device for the other machine
  - Have fastening devices for both devices on the test jig

**5. How can the design help ensure that the test jig is placed correctly into the machine?**

- Using marks on the machine
- Using a guide tool, which has a hole for the striker

**6. How can the design help ensure a consistent, correct, placement of the test specimen?**

- Using marks on the test jig that matches the size of the test specimen
- Milling a hole the same size as the test specimen, acting as a guide

## **7. How can the design enable the testing of specimens with various thicknesses?**

- Using insertions with known thicknesses
- Using a clamping device with adjustable height

## **3.6 Concept Selection**

First, the overall design is chosen by considering all the designing subproblems individually. Second, dimensioning is done by considering the dimensioning subproblems and using the information found through benchmarking. Inspiration was taken from the ISO standard for punch testing, ISO 6602, since the size of specimens that are available at IKEA are similar to the size of the specimens that the ISO standard recommends.

### **3.6.1 Choice of Overall Concept**

A discussion of each subproblem is made, resulting in a selection of a solution.

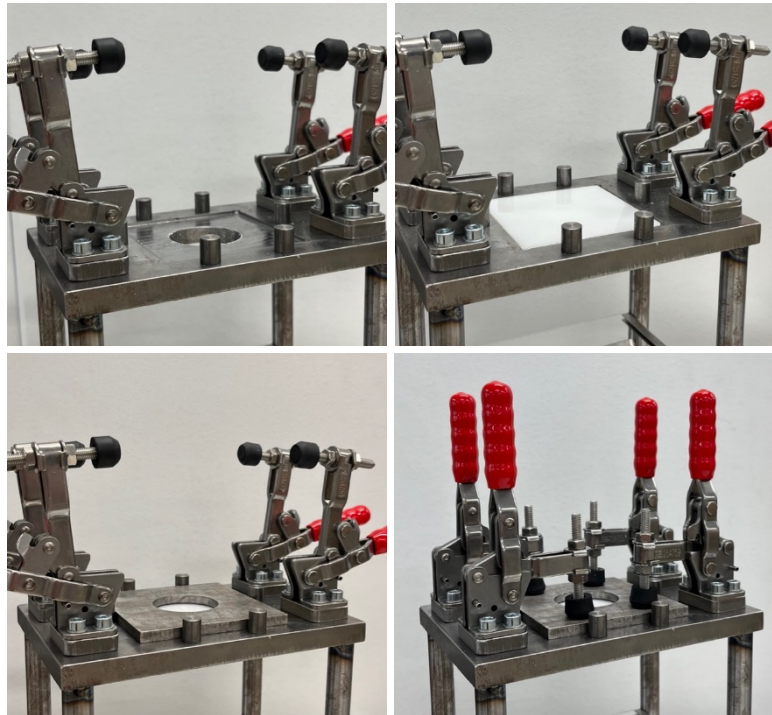
#### **1. How can the design ensure that the desirable part of the test specimen is visible from the side of the testing machine?**

The testing machines that are used operate vertically and transmitting to horizontal motions is rather complex, using a mirror is a much simpler solution. Therefore, it is selected to use a first surface mirror, placed below the test specimen at a 45° angle. The mirror is protected using a plate of tempered glass, placed parallel to the test specimen to avoid refraction of the image captured by the DIC camera.

#### **2. How can the design ensure that the test specimen is fastened with sufficient clamping force (that is both known and constant)?**

Through discussion, the options for clamping solutions are quickly narrowed down to clamps or bolts since these are the simplest to implement. Using bolts with a torque wrench, the pretension force can become known. However, mounting bolts each time a test is executed takes a lot of time for the test lab personnel. Further, the threads get easily worn out when mounted repeatedly. By using clamps, preparing for the test becomes quicker and easier for the personnel. However, it is difficult to find clamps with a known and accurate clamping force, making the use of clamps together with a boundary condition of a known pretension force unfitting.

Since clamps are much more user-friendly, it is decided to find a solution where they can be used together with a boundary condition of a known clamping distance. The clamping distance is decided to be the same as the specimen thickness, in this case, 2 mm. A square milling, that is 2 mm deep and has a size of 80 mm is made. On top of the specimen, a plate is placed and then the system is fastened using four toggle clamps with a combined force of 6 kN. Since the clamping force is so large, the plate can be considered rigidly placed right on top of the specimen. Figure 13 illustrates this mechanism.



*Figure 13. The clamping mechanism in use. The specimen is placed in the milled square, the clamping placed on top of it and the toggle clamps fastened.*

### **3. What shape should the striker have?**

The striker is chosen to have a hemispherical shape. This is the most commonly used shape, and it is also used in the ISO standard that was used as inspiration for the design.

### **4. How can the design enable the fastening of the striker and the test jig into the two machines?**

For the striker, it is decided to manufacture two different strikers with different fastening devices for the two machines. For the test jig, it is decided to have two fastening devices on the same jig. Both testing machines have two types of fastening opportunities on the bottom: one cylindrical hole as well as T-shaped tracks. The T-shaped tracks are utilized. Holes for fastening T-shaped blocks are made on the test jig, the blocks are fastened and then the whole jig is slid into the tracks.

## 5. How can the design help ensure that the test jig is placed correctly into the machine?

In order to ensure a correct placement of the test jig into the machine, a guiding tool is made. The tool has a hole with the same diameter as the striker. When mounting the

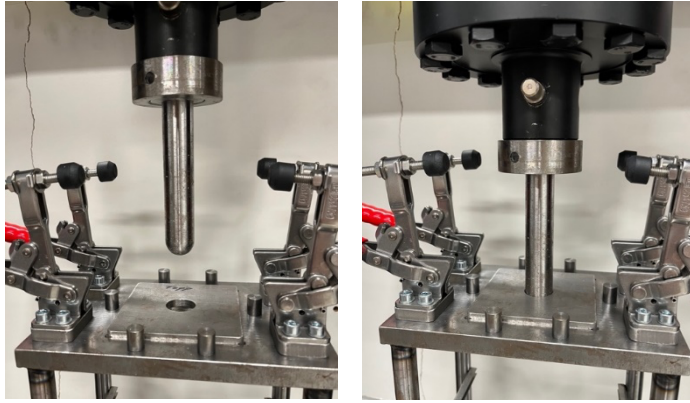


Figure 14. The procedure of positioning the test jig using the guiding tool.

test jig, the tool is placed in the milling for the specimen. The striker is then lowered, and the position of the test jig is adjusted so that the striker hits the hole. This ensures correct placement of the test jig, and that the striker hits the center of the hole. The procedure is illustrated in Figure 14.

## 6. How can the design help ensure a consistent, correct, placement of the test specimen?

The milled square, which originally was made to achieve the clamping distance, also solves this problem, since it acts as a guide for placing the specimen.

## 7. How can the design enable the testing of specimens with various thicknesses?

If specimens of other thicknesses are to be tested in the future, distance insertions need to be used. If the specimen is thinner than 2 mm, the insertion is placed between the clamping plate and the specimen. If the specimen is thicker than 2 mm, the insertion is placed outside of the milled hole, between the base plate and the clamping plate.

### 3.6.2 Dimensioning

The detailed parts of the jig, such as striker and punching hole geometries, and the thickness of the top plate, are dimensioned based on the ISO standard. Since the ISO standard is designed for a test specimen with similar dimensions as the specimens used in this project, it serves as a suitable base for initial dimensioning. The remaining parts are determined based on piston stroke and the focal length of the DIC cameras. With the use of optic calculations, it is ensured that no parts of the jig interfere with

the camera view. Recalculations are made iteratively with optimizations of the jig dimensions.

### 3.7 Concept Testing

The concept is tested, both by testing a simplified physical prototype and by conducting FEA on a digital prototype.

#### 3.7.1 Physical Prototype

A simplified physical prototype of the test jig is manufactured and then tested, see Figure 15. The testing does not involve applying any loads onto the prototype; its sole purpose is to ensure that the desirable parts of the test specimen are visible using the DIC camera and the mirror. Therefore, the prototype is made lighter, and details that are not necessary for this test are removed. The testing shows that the specimen is visible, however with very little margin. Therefore, it is decided to increase the width of the mirror on the final test jig.



Figure 15. The physical prototype.

#### 3.7.1 Results from Finite Element Analysis

In this section, the results from the robustness analysis of the jig are presented, and the results from the friction analysis regarding both the analysis of striker friction and clamping friction.

##### Robustness Analysis

Table 3 shows minimal deformations in the structure at both expected load levels of 5 kN, and also when the load is increased to 10 kN. The measured deformation corresponds to the displacement of a point on the edge of the punching hole, see Figure 8 in Section 3.1.2 Finite Element Analysis of Test Jig. Since the tests are performed using loads replicating worst-case scenarios, the deformations would be even smaller in reality.

Table 3. The deformations of the structure when exposed to different types of loads.

Force [kN]	Deformation at the edge of the punching hole [mm]
5	0.19
10	0.37
30	1.11

### Friction Analysis Striker-Specimen

Figure 16 shows the striker force-displacement curves for the test using friction coefficients of 0.3 and 0.001 respectively between the striker and specimen. At a level of 10 mm displacement the force increases by approximately 670 N, an increase of about 8%.

### Friction Analysis Clamping-Specimen

The tests show neglectable differences in the characteristics of the specimen behavior when using different coefficients of friction. Some sliding of the specimen can be observed for both high and low frictions, measuring horizontal movements of 0.14 mm and 0.15 mm respectively at a striker displacement of 10 mm.

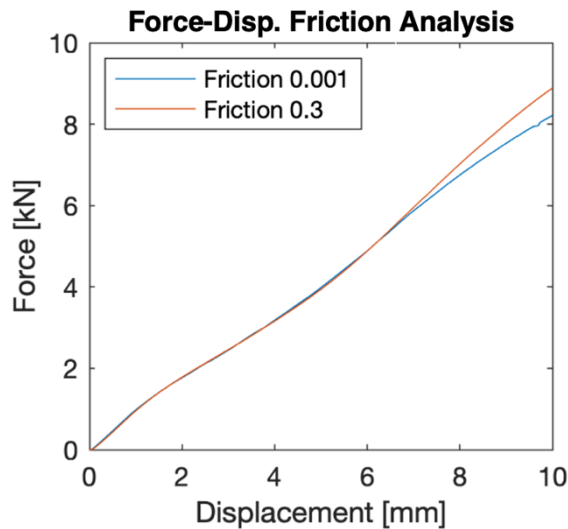


Figure 16. The force-displacement curves for different friction coefficients.

### 3.8 Final Design

A CAD model of the final design and the physical product is presented below in Figure 17, included parts are marked in the figure.

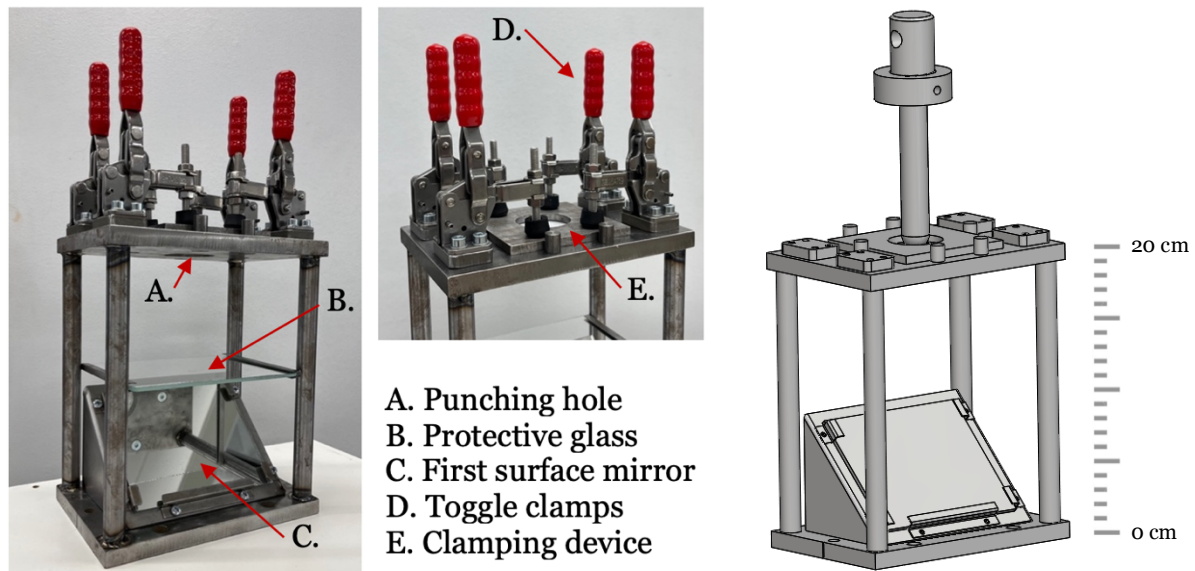


Figure 17. Left: The final design of the test jig with references to the different parts. Right: A CAD model of the final design (without clamps).

Overall, the test jig works as expected. It is easy to mount both the jig and the striker into the machine, as well as use the guide tool to ensure the correct placement. The milling easily ensures that the specimen is placed correctly onto the jig and the toggle clamps are closed quickly to fasten the clamping device. The desired parts of the test specimen are visible through the mirror and the images captured by the DIC camera are of good quality.

However, there are a few things that do not work as expected. First, the handles of the toggle clamps are vertical, which significantly reduces the available stroke of the piston. The desired piston stroke was 100 mm, but due to the clamps, it results in around 30 mm. When testing POM, it does not matter since the material is brittle and fracture occurs quickly. However, it will be problematic for testing of more ductile materials. Further, the color that is used to create the speckle pattern falls off the specimen and gets stuck on the hardened glass plate that is installed to protect the first surface mirror. After only a few tests, the glass becomes so stained that it can affect the quality of the DIC.

## 4 Evaluating Material Models

This section of the report contains the second phase of the thesis project; evaluating material models. First, the methodology used for the evaluation is described. The aim of this thesis is not to evaluate any specific material model, however, the methodology is demonstrated on a commonly used material model for POM. The purpose of this is to demonstrate the process as well as enable evaluation of the methodology employed in the study. Results from this evaluation are reported.

### 4.1 Methodology

In order to evaluate the material model, a punch test is performed both in a physical experiment and in a simulation. The simulated test is done using geometry and boundary conditions that correspond to the physical test. The material model that is to be evaluated is used in the simulation and a specimen of the corresponding material is used in the experiment. In this project, a piecewise linear material model was used in the simulation and the physical test specimen was made of POM.

The results from the two tests are then compared. The more the results from the simulation resemble the results from the physical test, the more accurate the material model is considered to be. Data containing information about the force, the displacements, and the strains are extracted from both the experiment and the simulation results. This data is then processed so that the results from the two can be compared. First, the global force-displacement curves for the strikers are compared. Second, the local displacements and strains of the bottom surfaces of the test specimens are compared. Finally, the major strains are plotted against the minor strains for comparison and to ensure that the specimen is deformed biaxially.

#### 4.1.1 The Physical Punch Test

The purpose of the physical punch test is to record how the material behaves when exposed to biaxial loads. By performing the following experiment, data can be extracted and used in the comparison with the simulated punch test. This section provides information about the utilized equipment, the test specimen, and the experimental procedure.



## Equipment

In the experiment, a tensile testing machine and a DIC setup are used. The tensile testing machine (Instron 5982) and is used with the test jig that is developed in the first phase of the project. The Instron machine uses the software Bluehill Universal. The DIC camera is the GOM ARAMIS 3D Camera 2.3M, and its software is GOM ARAMIS.

## Test Specimen

The test specimen consists of POM plates measuring 80 mm × 80 mm, with a thickness of 2 mm. To enable deformation measurements using digital image correlation, a speckle pattern is applied to the specimen along with a non-shine coating to avoid light reflections into the cameras. The direction of the inlet is also marked, to ensure that the orientation of the specimens is consistent throughout the testing process. Before testing, the specimen is acclimatized at a temperature of 23°C. Since POM is not sensitive to humidity changes, acclimatization is only needed for the temperature.

## Experimental Procedure

The experiment is performed at IKEA Test Lab, in a climate-controlled room with a temperature of 23°C and relative humidity of 50%. The test jig is mounted in the testing machine, using a guiding tool to align the striker and the jig. This is done to ensure that the striker hits the center of the puncture hole. The test specimen is placed in the jig and locked with the clamping device at a distance of 2 mm. Once the specimen is in place, the DIC system is set up to acquire images with a frequency of 20 Hz, and the testing machine is set to move the striker at a constant rate of 50 mm/min. The testing machine and the DIC system are then started simultaneously to record the

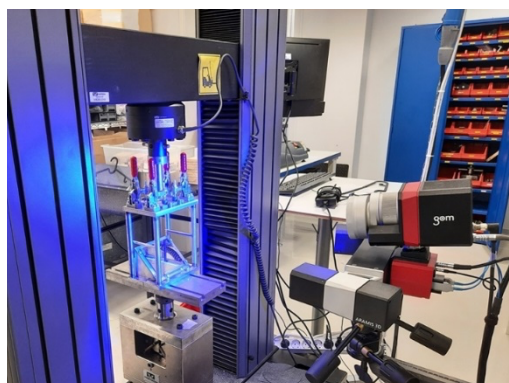
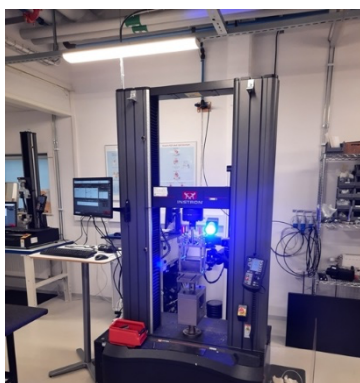


Figure 18. Left: the testing machine with the test jig mounted. Right: close-up view of the test jig with the DIC cameras.

deformations of the specimen. The experiment is performed five times to ensure statistically correct results. The setup is illustrated in Figure 18.

### 4.1.2 The Simulated Punch Test

The objective of this section is to describe the procedure used to simulate the punch test, replicating the physical experiment to enable a comparison between the two.

A CAD model is used as a base geometry in the simulation. It is simplified to a quarter of the original geometry by using symmetry conditions, and by removing small, detailed parts. This procedure does not affect the quality of the simulation, it is done to reduce the number of elements and thereby reduce the computational costs. The final geometry is shown in Figure 19. Altair HyperMesh is used as the preprocessor and Altair HyperWorks as the postprocessor, with LS-Dyna as the solver.

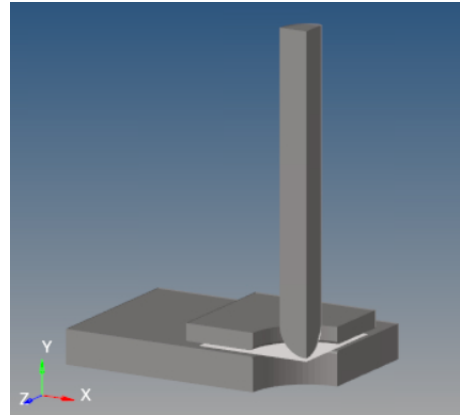


Figure 19. The geometry of the simulated punch test.

Since the test specimen has a large length-thickness ratio, it is more efficient to model it as a surface component. This is done with nine integration points throughout the thickness. All other components are modeled as solid parts and meshed with tetrahedral elements. The sizes of the elements are chosen by taking the smallest dimension of the solid part and dividing it by five. On the striker, finer elements are chosen to preserve the roundness of the tip. Boundary conditions are used to restrict unwanted movements and to ensure a realistic behavior of the structure. Figure 20 displays in which directions each component is restricted.

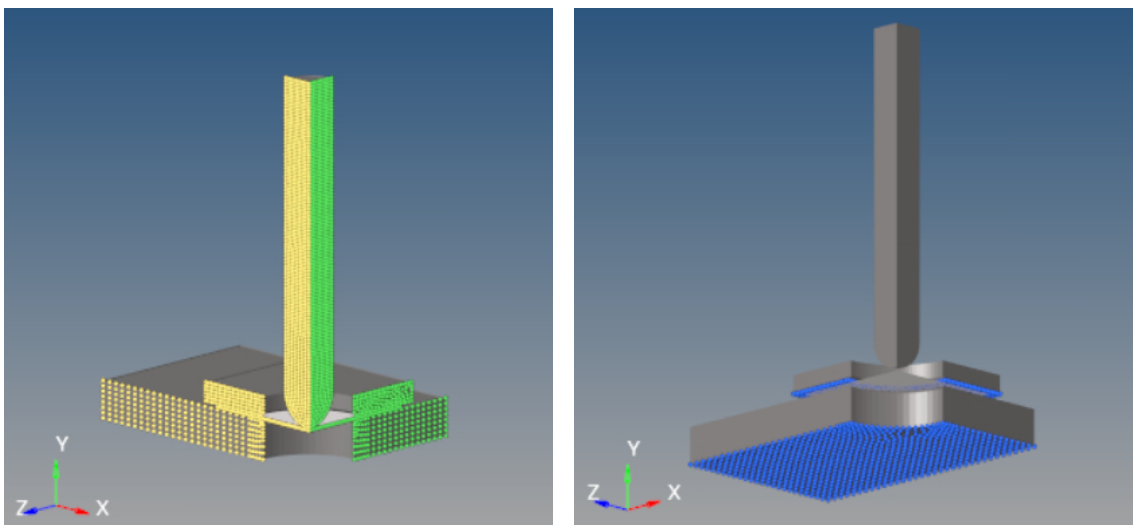


Figure 20. An illustration of the boundary conditions of the test setup. The yellow surfaces are locked in the z-direction, the green in the x-direction and the blue in the y-direction.

The highlighted vertical surfaces in Figure 20 (yellow and green) are restricted due to symmetry conditions. The bottom surface of the clamp (blue) is locked to replicate a clamping distance of 2 mm, the same clamping distance that is used in the physical experiment. Lastly, the bottom surface of the base plate (also blue) is restricted to keep the structure in place. The striker is prescribed a displacement of 15 mm, starting from when the striker tangents the test specimen. Since the material model used in this simulation have no time dependency and is done implicitly, the velocity of the striker is unimportant in this case, but it is worth noting that it needs to be controlled in case another material model is evaluated.

The clamp, base plate, and striker are modeled as rigid bodies since their deformations are neglectable in comparison to the test specimen. The test specimen is assigned a piecewise linear material model for POM with isotropic hardening. It does not account for damage or failure. Contact relations are assigned to the contact surfaces between the components. The relations are established with the test specimen as the part being deformed and the striker, clamping, and bottom plate as the parts driving the deformation. All contact relations are between steel and POM and therefore have the same coefficient of friction, 0.2, both for dynamic and static friction. This value is found in a friction study, where it is stated that the friction coefficient between POM and stainless-steel start at about 0.2 [8].

### **4.1.3 Data Extraction**

This section outlines the procedure for extracting data for the comparisons between the simulated punch test and the experimental punch test. Data for the striker force-displacement, the local behaviors throughout the fields, and the major- and minor in-plane strains is extracted.

The results are extracted using three different systems: results from the simulation using Altair HyperWorks, results from the digital image correlation analysis using GOM ARAMIS, and results from the Instron testing machine using Bluehill Universal. The process of the data extraction for each comparison is explained below.

#### **Striker Force-Displacement**

Data for the striker force-displacement comparison is extracted from the simulation results and the data acquired by the testing machine. The force-displacement curve for

the experiment is directly extracted from Bluehill Universal. As mentioned in Section 4.1.1 The Physical Punch Test, five tests are performed, meaning five results are extracted. For the simulation results, Altair HyperWorks is used to create and extract a corresponding force-displacement curve.

### Field Analysis

For the field analysis, out-of-plane displacements, true major and minor in-plane strains are compared between the simulation and the experiment. Data for the simulation is extracted from Altair HyperWorks and for the experiment, the data acquired using DIC is extracted from GOM ARAMIS. Data is extracted for five stages, defined by the striker displacement. It is done for the displacements 2, 4, 6, 8 and 10 mm, where zero is defined as when the tip of the striker tangents the top of the test specimen.

The necessary data is gathered from data points in both software. In the simulation, the data points correspond to element nodes and in the experiment to the facets created in the DIC analysis. This is illustrated in Figures 21 and 22. Each node/facet carries all information necessary; node/facet coordinates, out-of-plane displacements, and true major and minor in-plane strains. The strains are selected as in-plane since the DIC cameras cannot measure the thinning of the specimen.

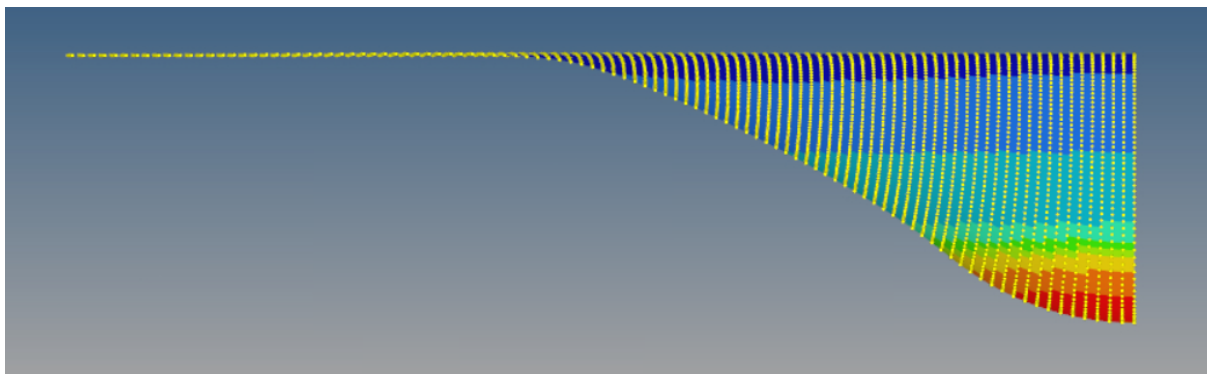


Figure 21. The nodes from which the data is extracted from the simulation results.

In the DIC software, a so-called surface component is constructed to extract the desired data from the experiment, see Figure 22. The distance between the facet center points is put to 19 pixels and the facet size to 21 pixels. In this case, a user-defined filter is also necessary to achieve a high-quality surface component with as few non-measurable regions as possible. Data for each facet in the surface component is then exported. For the simulated punch test, the nodes on the bottom surface of the

specimen are selected and used to extract the corresponding data. Since the nodes and facets are located differently in relation to each other, the raw data is not comparable. Therefore, the node- and facet coordinates are used to interpolate the data. This is explained in Section 4.1.5 Field Analysis. The data for the plot of major vs. minor in-plane strains are found in the same files that are exported for the field analysis.

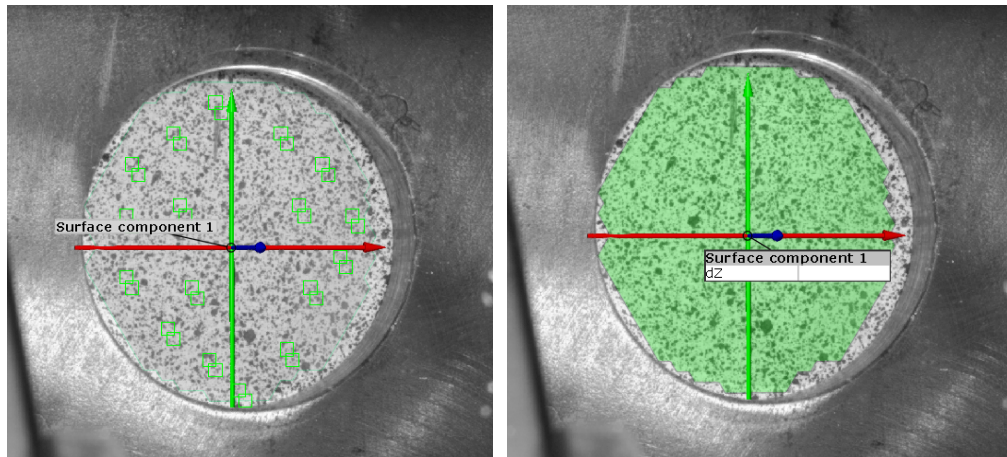


Figure 22. Left: examples of how facets are displayed on the surface of the test specimen. Right: the surface component (green) is illustrated.

#### 4.1.4 Striker Force-Displacement

The striker force-displacement curves from the simulation and the five experiments are analyzed using MATLAB. This is done in two ways. First, by plotting the force-displacement curves from the five tests. The purpose of this is to ensure that the results are statistically correct.

Second, the five curves from the physical experiment are averaged and compared to the curve from the simulation. Since the simulation does not account for fracture the points of breakage cannot be compared. However, the shapes and the values are compared. It is also of interest to note whether the difference between the two curves varies throughout the course of the test or if it remains the same. The difference between the curve obtained through simulation and the averaged experimental curve is calculated at five different stages, the same stages used for the field analysis.

#### 4.1.5 Field Analysis

In order to compare local behaviors in the two test specimens, a field analysis is performed using MATLAB. The analysis is done by comparing the bottom surface of the test specimen in the simulation with the one in the experiment. Comparison is done at five different stages, defined by the displacement of the striker. These are 2, 4,

6, 8, and 10 mm, where zero is defined as when the tip of the striker tangents the top of the test specimen. Three parameters are examined in the comparison:

1. Out-of-plane displacements
2. True in-plane major strains
3. True in-plane minor strains

As mentioned in Section 4.1.3 Data Extraction, data containing information about each node on the bottom of the test specimen is extracted from the simulation results. Since the simulation is done on a quarter of the geometry, the data is mirrored to represent the full geometry. This data is then compared to the surface data captured by the DIC cameras, containing information about each facet.

The aim is to compare data points with corresponding positions on the test specimen in the simulation and the experiment. However, as seen in Figure 23, there are two problems. First, the two coordinate systems are oriented differently. These need to be aligned in order for the comparison to be made. Second, the raw data from the simulation and the experiment contain a significantly different number of data points. Thus, the data needs to be interpolated before it can be compared.

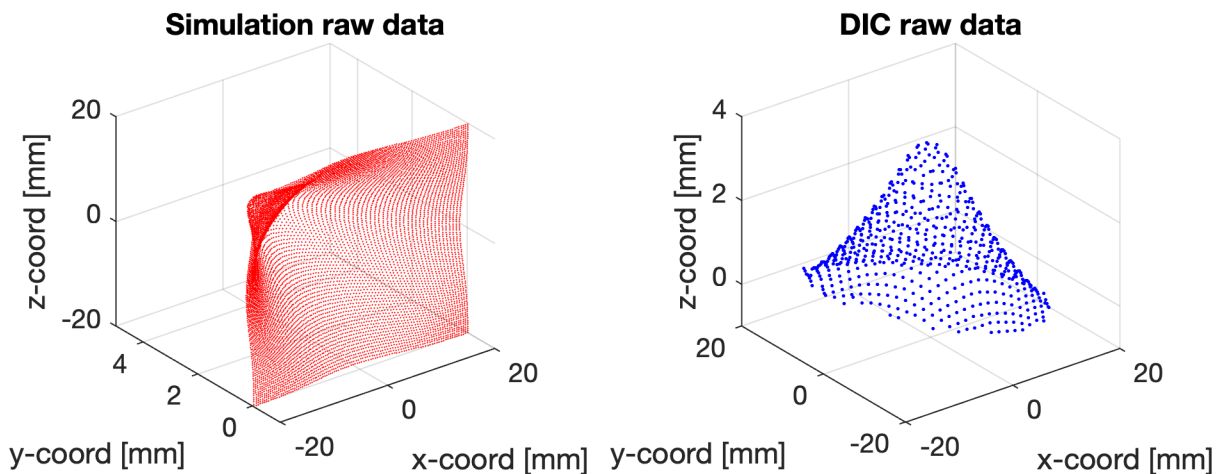


Figure 23: The unprocessed data from the simulation (to the left) and the experiment (to the right)

### Aligning the Coordinate Systems

The approach for aligning the two coordinate systems is to place the origins so that they both are located where the tip of the striker hits the test specimen. In the simulation, this is exactly at the center of the specimen. In the experiment, this should be at the center of the hole, however, in reality, it can never be guaranteed that the

striker is fully centered. Therefore, a mathematical approach is selected for the alignment, instead of performing it based on the coordinates of the center of the hole.

First, the simulation data is rotated so the z-axis corresponds to the direction of deformation and then translated so the center point of the deformation matches the origin. The orientation of the coordinate system is now placed in such a way that x and y describe the position on the test specimen in mm and the z-axis describes the value of the parameter being evaluated.

Next, a rigid transformation of the DIC data is done using the ICP algorithm (point-to-point), to align it with the simulation data. This alignment not only fulfills the purpose of placing the origin at the striker tip but also eliminates several sources of errors that are introduced during the experiment. These errors include, but are not limited to, that the DIC cameras might not be placed perpendicular to the mirror, that the angle of the mirror might not be exactly  $45^\circ$ , that the test specimen might be slightly tilted, and that it never can be guaranteed that the striker hits exactly at the center of the hole.

Since the transformation is rigid, it only translates and rotates the data set, it does not change the interrelationships between the data points. In Figure 24 below, the effect of the ICP algorithm on the DIC data is illustrated. The blue points correspond to the data before the algorithm is used and the green after. If this is not done, it can result in inaccurate comparisons with inaccurately large differences to the simulation.

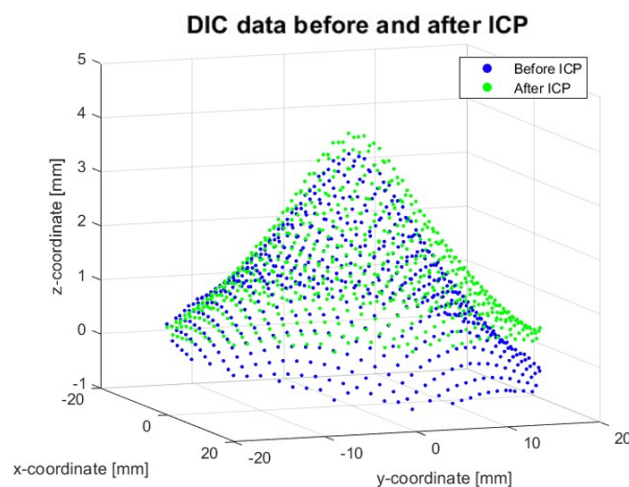


Figure 24. The DIC data before and after transforming it using the ICP algorithm.

## Linear Interpolation of Data

As shown in Figure 25 below, the raw data from the simulation and the DIC collect data at different points. To enable a comparison of the selected parameters, interpolation is necessary. The interpolation is done by creating interpolants of the two data sets and evaluating these at locations specified by a manually created mesh grid. Figure 26 displays the data before and after the interpolation.

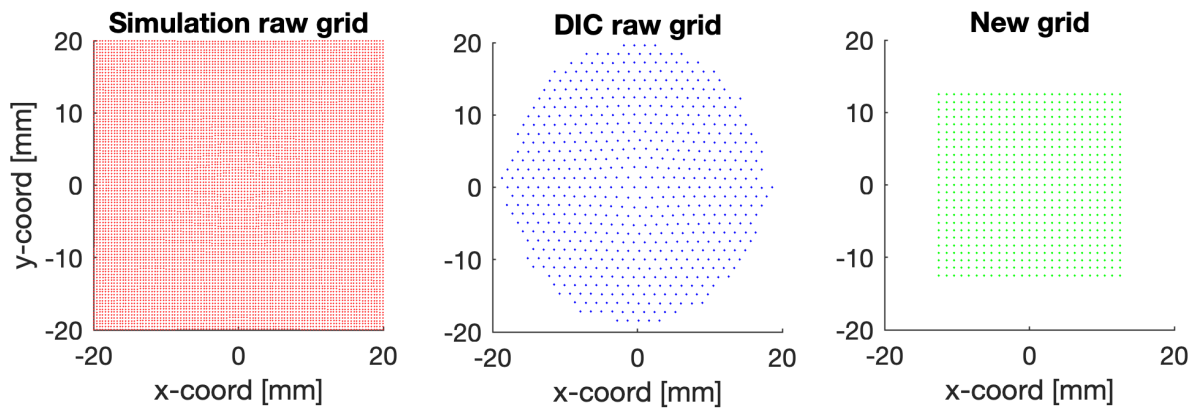


Figure 25. The left graph shows the x- and y-coordinates of raw data from the simulation, the middle graph of raw data from the DIC, and the right graph the manually created mesh grid.

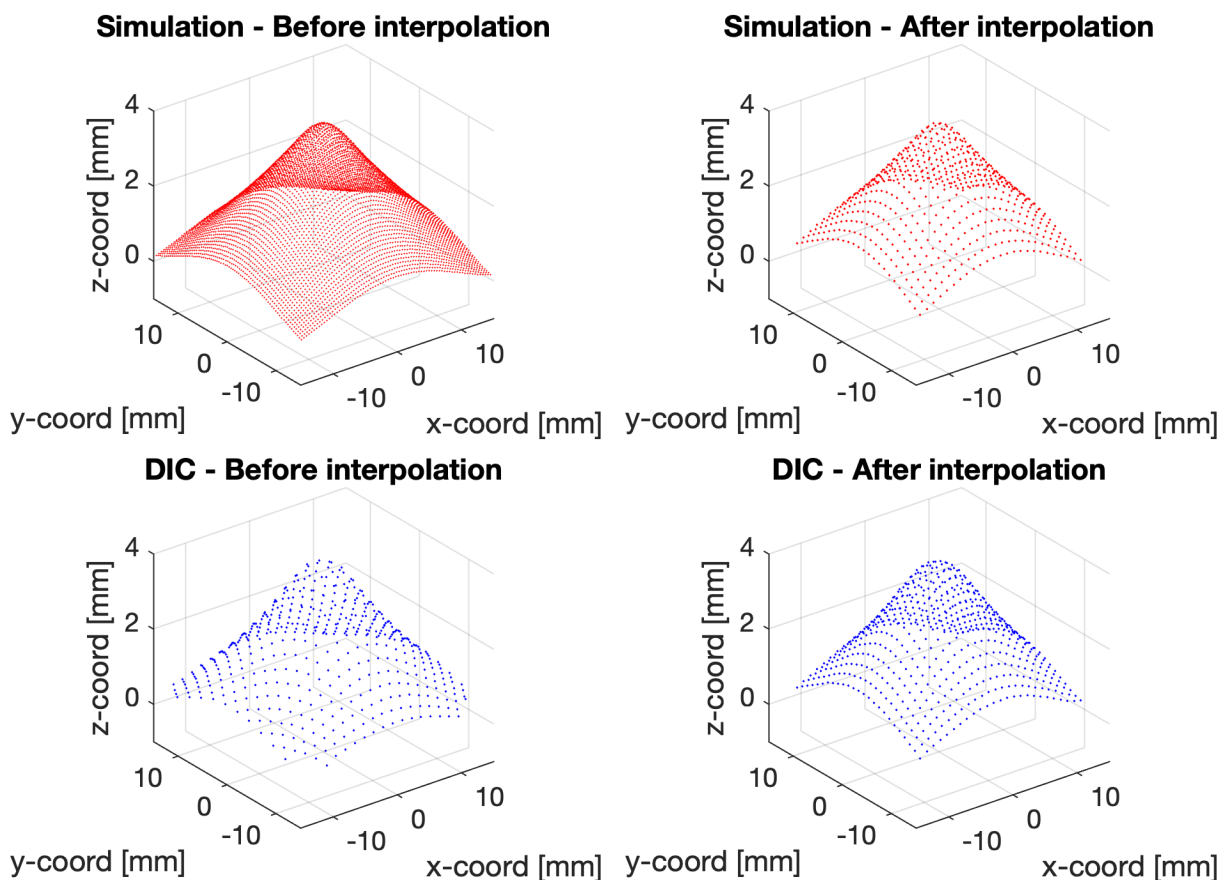


Figure 26. The two left graphs illustrate the data before interpolation and the two right graphs after interpolation, for the simulation and experiment respectively.



The mesh grid is centered around the origin and has a side of 25 mm with 100 points in each dimension, resulting in 10 000 data points in total. The hole through which the specimen is visible has a diameter of 40 mm. The largest square that can fit inside the circle has a side of 28 mm. Choosing a side of 25 mm allows for some margin since the DIC cannot detect the deformations of the specimen all the way to the edge of the hole.

Interpolants of the data sets are created linearly. Each interpolant is then evaluated for the data points in the mesh grid, resulting in three pairs of data sets that are comparable, one pair for each parameter being evaluated.

### **Comparison**

As mentioned previously, three comparisons are made for each striker displacement stage. One for the out-of-plane displacements, one for the major strains, and one for the minor strains. The comparisons are done by calculating the absolute value of the difference between the results from the simulation and the experiment. This is then done for the five stages.

#### **4.1.6 Major vs. Minor In-Plane Strains**

Finally, the major strains are plotted against the minor strains for each data point. Both are in-plane strains since the DIC cameras cannot measure the thinning of the specimen.

This comparison also acts as a validation of the punch test. Since the purpose of the test is to validate material models enduring biaxial loads, it is important that the material actually deforms biaxially. Whether it is biaxial or not is revealed by the first quadrant of the strain diagram. If there are data points in the first quadrant, where both the major and the minor strains are positive, it means that the specimen is stretched in two directions, hence displaying biaxial behavior.

## 4.2 Results

The validation method results in five comparisons of the following parameters:

1. Striker force-displacement curves
2. Local out-of-plane displacements
3. Local in-plane major strains
4. Local in-plane minor strains
5. Major vs. minor in-plane strains

The results listed in this section are obtained through the evaluation of the chosen material model for POM. As mentioned, the objective of this project is not to evaluate any specific model, but to construct a method to evaluate the performance of material models in general. However, this section illustrates which results are obtained from the process and enables evaluation of the methodology.

### 4.2.1 Striker Force-Displacement

In Figure 27, the force-displacement curves obtained from the five samples are displayed in the left graph. The right graph contains the curve obtained from the simulation and a curve obtained by averaging the five experimental curves. A comparison of the two illustrates how the error evolves along with the displacement. In Table 4, the size of the error is reported for five different stages of the experiment, showing both the actual error and the error in relation to the striker displacement.

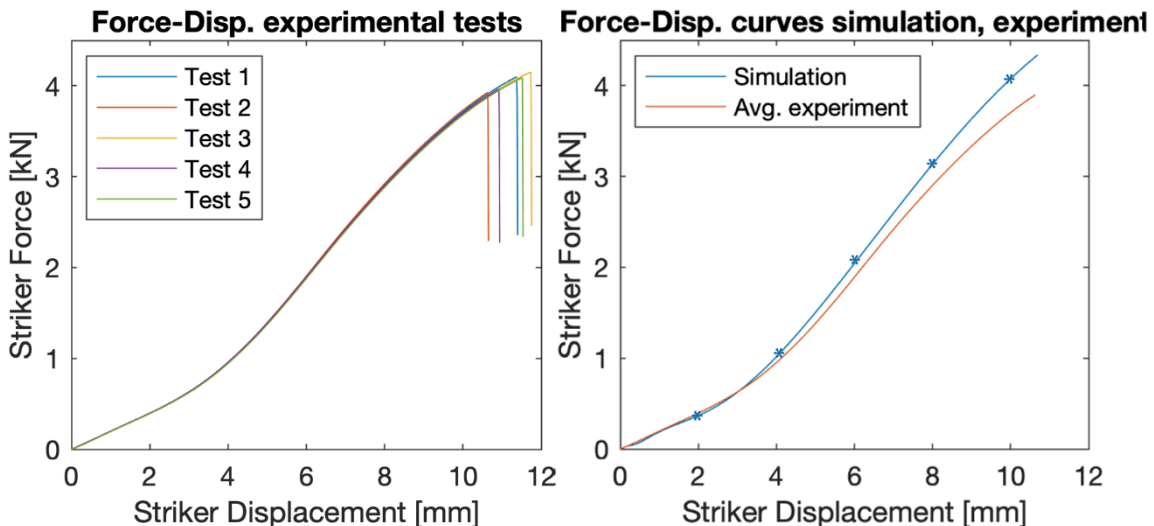


Figure 27. Left: Force-displacement curves for the five experiments. Right: Force-displacement curves for the average experiment compared to the simulation. Also, blue stars mark the five stages at which the later field analysis is made.

Table 4. The size of the difference between the simulated curve and the experimental curve at five different stages of the experiment.

Striker Disp.	2 mm	4 mm	6 mm	8 mm	10 mm
Error (N)	-27	63	150	230	370
Error (%)	-6.8	6.6	8.0	8.0	10.0

#### 4.2.2 Field Analysis

The results from the field analysis consist of three comparisons between the simulation and the experiment. One for out-of-plane displacements, one for major in-plane strains, and one for minor in-plane strains. The comparison is done at five different stages which are illustrated to the right in Figure 27 above.

##### Out-of-Plane Displacements

The results for the out-of-plane displacements are displayed in Figure 28 for each striker displacement. The left column shows the out-of-plane displacements for the simulation and the experiment. The z-axis represents the displacements and the x- and y-axis the position on the test specimen. The right column shows the absolute value of the difference between the simulation and the experiment. The color reports the size of the error and the x- and y-axis the position on the test specimen.

##### Major In-Plane Strains

The results for the in-plane major strains are displayed in Figure 29 for each striker displacement. The left column shows the major in-plane strains for the simulation and the experiment, displaying different strain levels over the specimen surface. The right column shows the absolute value of the difference between the simulation and the experiment, where the color represents different strain levels. The figures display a 15 × 15 mm surface over the center part of the specimen.

##### Minor In-Plane Strains

The results for the in-plane minor strains are displayed in Figure 30 for each striker displacement. The left column shows the minor in-plane strains for the simulation and the experiment, displaying different strain levels over the specimen surface. The right column shows the absolute value of the difference between the simulation and the experiment, where the color represents different strain levels. The figures display a 15 × 15 mm surface over the center part of the specimen.

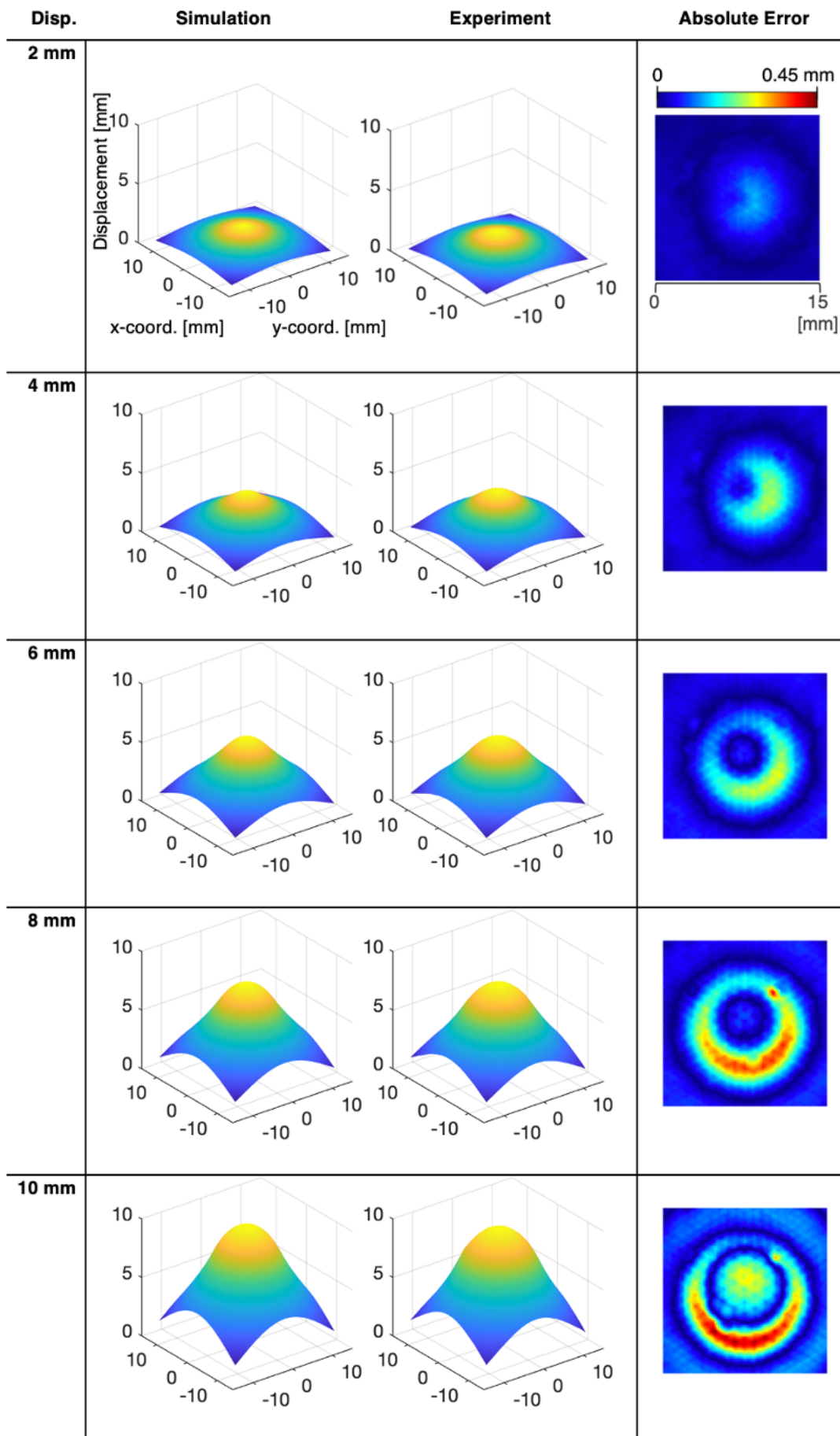


Figure 28. Comparison of the out-of-plane displacements for the simulation and the experiment.

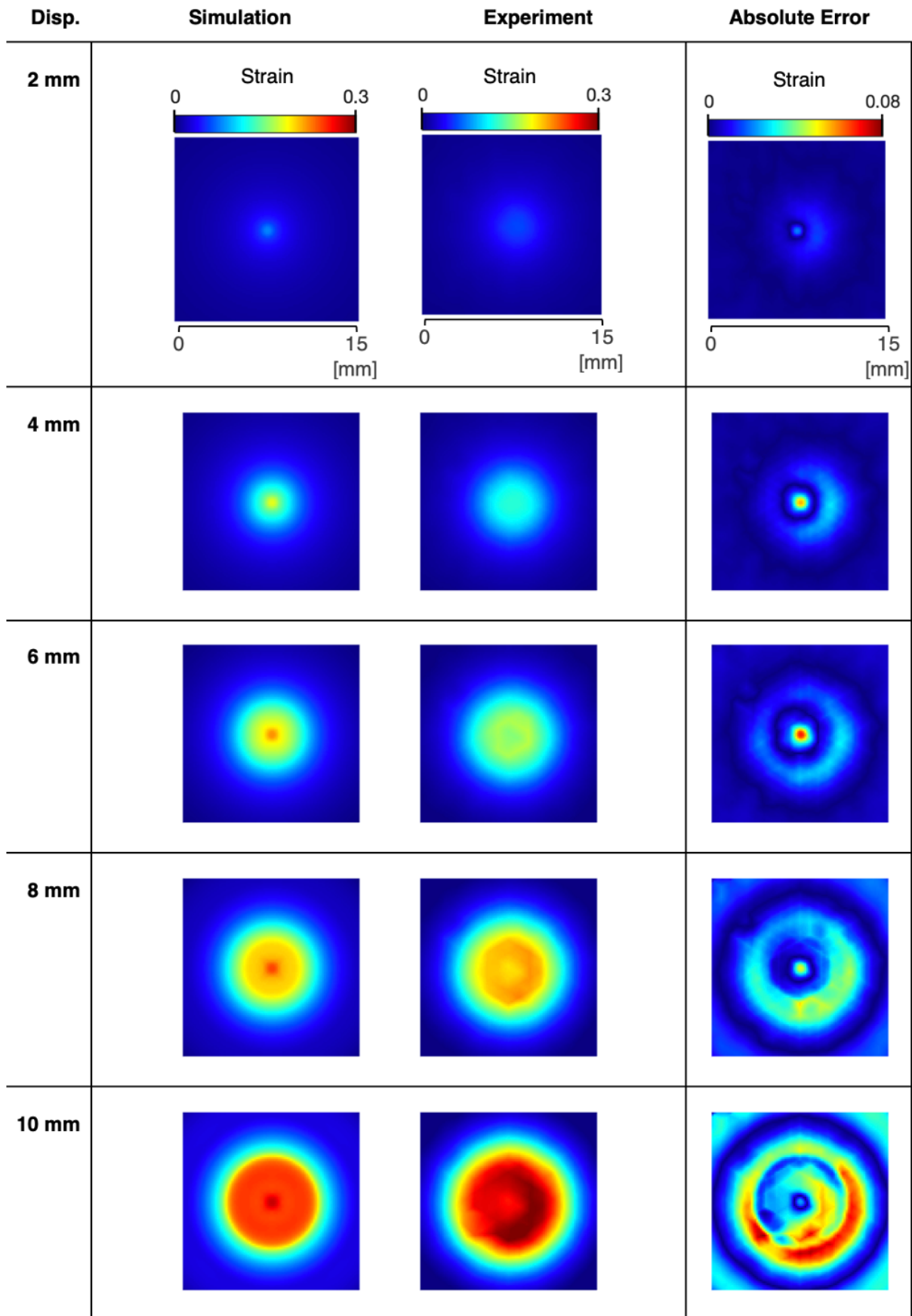


Figure 29. Comparison of the major in-plane strains for the simulation and the experiment.

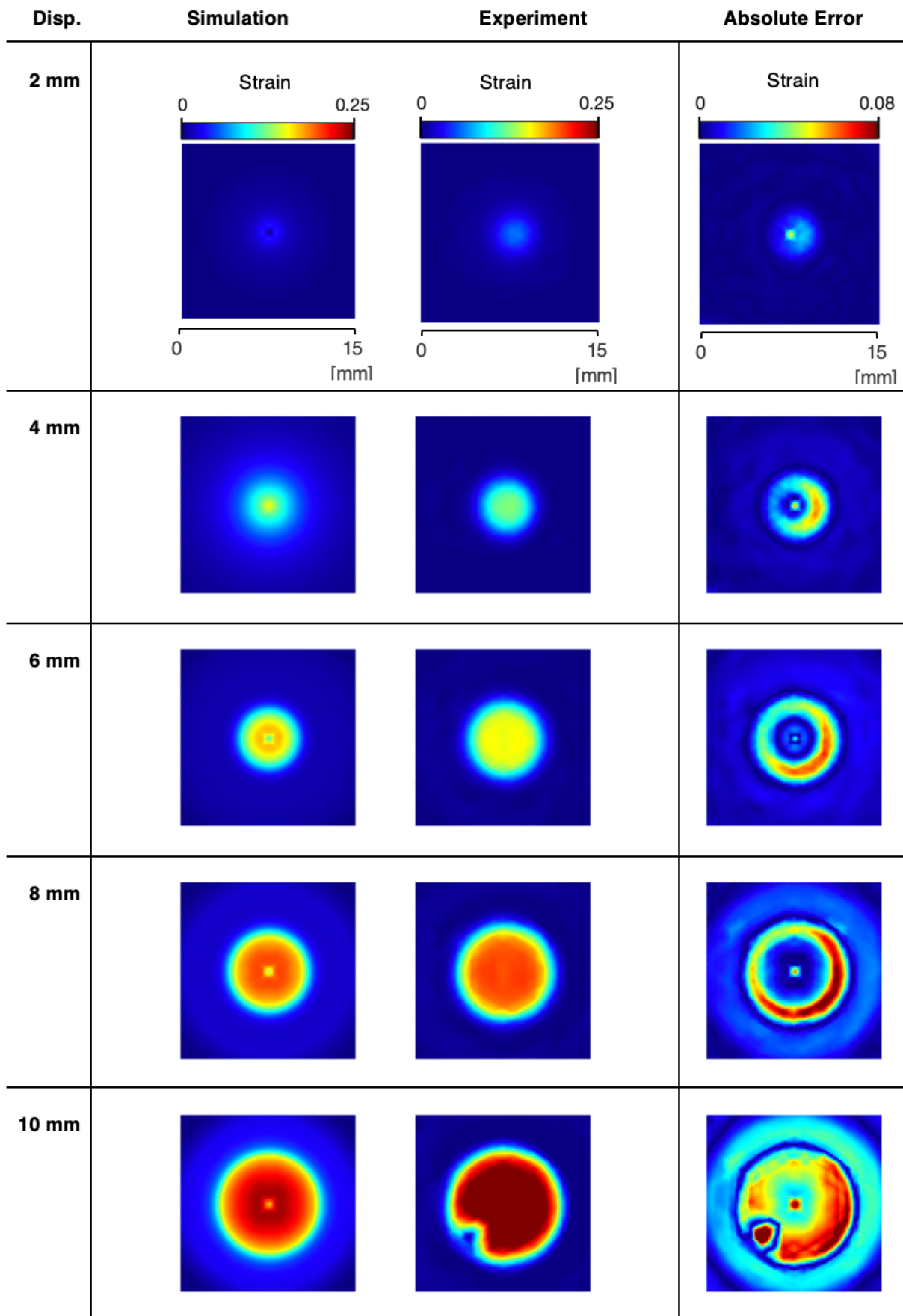


Figure 30. Comparison of the minor in-plane strains for the simulation and the experiment.

### 4.2.3 Major vs. Minor In-Plane Strains

Figure 31 below show the in-plane major strains against in-plane minor strains for the simulation and experiment, obtained by plotting the raw, unprocessed, data. They display both how the simulation and experiment vary along with striker displacement, from 2 mm to 10 mm, and also how large the biaxial behavior is for each step. The more data points in the first quadrant the more biaxial behavior.

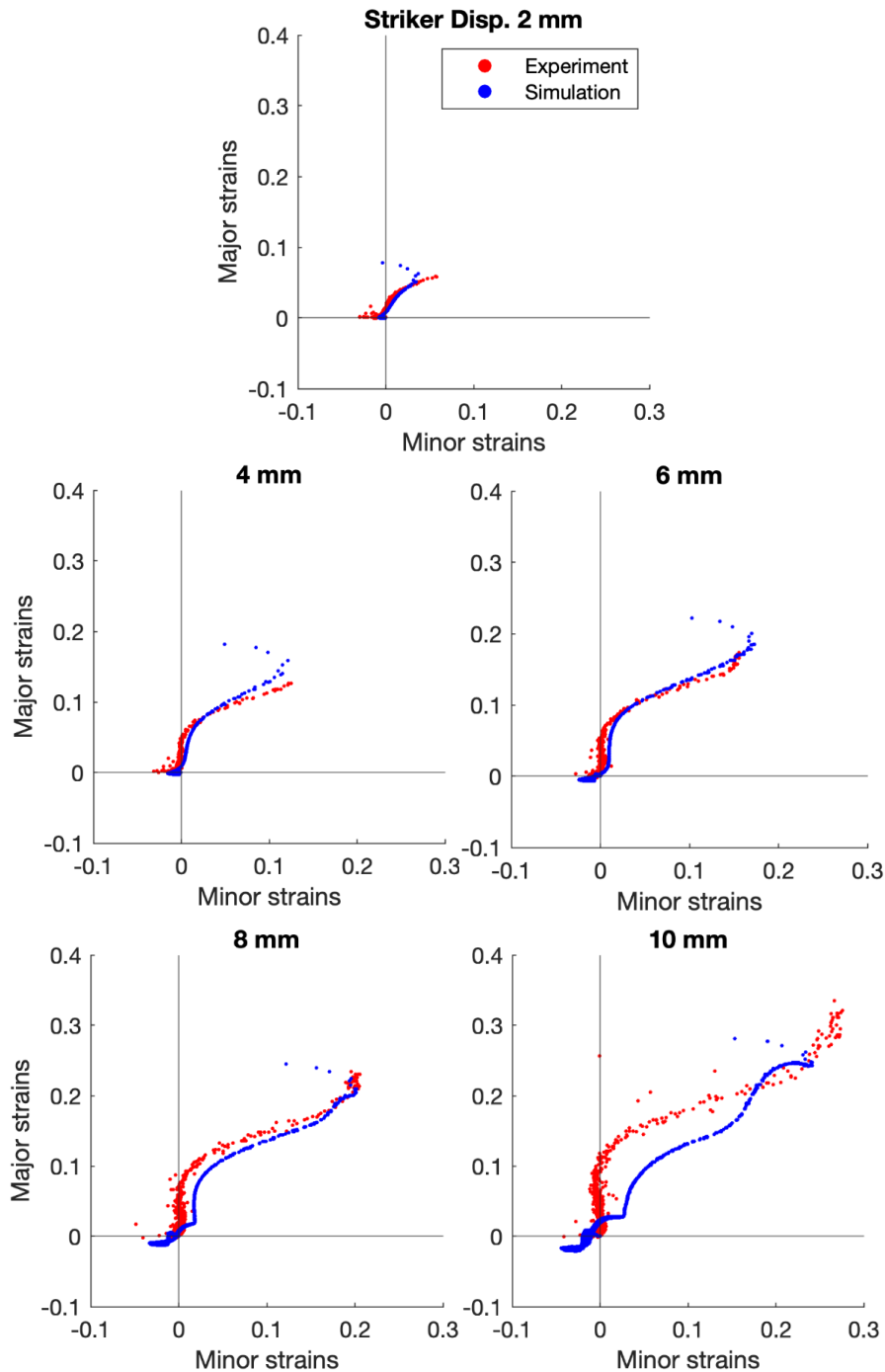


Figure 31. The major vs. minor in-plane strains for five stages during the experiment.

## **5 Discussion**

In this section, the results of the project are discussed. First, reflections on the design of the test setup are made. Second, the method for evaluating material models is discussed. Third, sources of errors and their significance for the results are discussed. Lastly, ideas for future work are presented.

### **5.1 Designing the Test Setup**

In this section, reflections on the designing of the test setup are made. Both the efficiency of the methodology that was employed and the final concept are discussed.

#### **5.1.1 Reflections on the Methodology**

Using Ulrich & Eppinger's concept development process is an effective approach to systematically generate and select a design concept while considering all important parameters. However, skipping some steps that are inapplicable for this purpose was a wise decision, as it is unlikely that a better concept would have been found by doing them. At some points throughout the process, certain steps were unnecessary and time-consuming. However, the preparatory work resulted in the established product requirements which were great to use as a checklist to ensure that no important details were overlooked.

An especially helpful part of the process was the concept generation; both decomposing into subproblems and benchmarking existing punch tests. The benchmarking provided plenty of inspiration and clever ideas that would not have been found otherwise.

#### **5.1.2 Reflections on the Design**

Overall, the result of the design process is considered as successful. Out of the 16 product requirements that were established, 15 were achieved. The only one not fulfilled was the piston stroke of 100 mm. Due to the vertical clamps, it was restricted to around 30 mm. This problem can be solved by switching clamps, manufacturing a new test jig that has the clamps further from the hole, or manufacturing a new striker with increased length. The test can still be executed on POM since puncture is reached when the striker displacement is around 10 to 12 mm. However, more ductile materials may only be tested to limited deformation around 30 mm, not puncture.



Another problem that was not anticipated is that the paint that is used to create the speckle pattern on the specimen, stains the hardened glass that is placed inside the test jig to protect the mirror. These stains are very difficult to remove. To resolve this problem, an efficient cleaning solution can be found, or several pieces of glass can be manufactured and changed when needed.

## **5.2 Evaluating Material Models**

In this section, the evaluation of material models is discussed. First, it is discussed how the results can be interpreted. Second, reflections are made on the overall effectiveness of the methodology that was used.

### **5.1.1 Interpreting the Results**

The results from the evaluation can be used to calibrate and compare different material models. Further, the material's behavior during the test can be analyzed qualitatively, which may reveal details about the material's properties.

The test can be done on different material models and the resulting errors for each of them can be compared. An approach for verifying a single material model is to choose the largest acceptable value that the error can have and see if it is exceeded or not. The size of this value of course depends on the application the material model is to be used for.

An example evaluation of a material model for POM was done in this thesis. Below, the results from this evaluation are interpreted to illustrate how this can be done:

In thm 27, the results from the striker force-displacement curves are illustrated. The difference between the curve for the simulation and the averaged experimental curve increases as the displacement increases, both in terms of value and percentual value. This implies that the model better describes what happens during small deformations rather than larger ones.

In Figures 28, 29, and 30, the results from the field analysis are displayed. The results for all three parameters that were evaluated all display larger errors on the same part of the test specimen: the bottom to the right side of the graphs. The errors also increase along with the displacement of the striker, once again implying that the model better captures the material behavior at small deformations. This strengthens the

methodology's efficiency since the material model that was evaluated is not calibrated against use after damage occurs, which happens at larger deformations. To further investigate the error, it would be interesting to calculate the percentual error.

Lastly, Figure 31 displays the comparison of the major vs. minor strain graphs. These indicate a relatively similar behavior between the experiment and the simulation for all stages except for the last one, where the striker has a displacement of 10 mm. This also indicates a higher accuracy of the material model for lower deformations.

In summary, the material model that was evaluated performs better the smaller the deformations are. It also displays relatively small errors throughout the entire analysis. Whether these errors are small enough to produce sufficient simulation results depends on the application that it is going to be used for.

### **5.1.2 The Effectiveness of the Methodology**

The major vs. minor strain graphs (Figure 31) confirm that the punch test indeed does induce biaxial loads on the specimen, as was intended. This is revealed by the many data points that are located in the first quadrant, where both the major and the minor strains are positive. It can also be observed that the test has high repeatability by observing the striker force-displacement curves in Figure 27 (left). The five curves that were obtained from the executed tests are very similar. The only difference is that the specimens break at different points. Apart from that, the curves are basically identical.

The methodology fulfills its aim of being a way of verifying material models. It gives an overview of how the material model performs as the deformation progresses, by comparing the force-displacement curves. It also quantifies the error across the whole surface, which allows observation of local phenomena and the distribution of the error throughout the specimen. The methodology can be applied to other types of tests as well, not only punch-to-break but also relaxation, creep, and so on.

There are a few limitations to the methodology. It does not capture the characteristics of damage and fracture of the material. Further, the DIC camera cannot measure the thickness of the specimen. Therefore, the full strain tensor is not available. Also, the analysis is only done at a select number of displacement steps and not continuously. The methodology also has limitations regarding user-friendliness as it requires plenty of manual involvement. Extracting the data from both the simulation and the

experiment is very time-consuming. Further, the analysis is highly adapted to POM. If a material with different properties were to be tested, the code would need to be modified. For instance, POM breaks after a striker displacement of 10 to 12 mm, therefore, the analysis is performed for similar displacements. If a material were to break before or after that, modifications to the code would need to be made.

### **5.3 Sources of Error**

Considering and eliminating sources of error is especially important in this project since it compares a simulation with fully controlled conditions to reality, which you can never control fully. Sources of error that are introduced during the project may result in inaccurate analyses, and in extension, conclusions about material models are incorrect.

Several sources of errors are introduced in the physical test setup. All measurement equipment has limited precision and accuracy. Further, deformations of parts that should not be deformed may occur, i.e., of the test jig and the striker. The test specimen may not be placed exactly in the center and since it is manufactured with a tolerance it may not be of the exact same thickness as the height of the milled-out square. All these errors are estimated to be so small that they are neglectable.

Using a mirror in combination with DIC introduces some errors. Its surface might not be fully flat since it is manufactured with a tolerance. As mentioned in Section 3.5.2 Benchmarking, a similar test was conducted. The errors were found to be small during small deformations, but larger during large deformations. This was not quantified in the study, and therefore it is not known how large errors it can produce. However, it is worth investigating its effect on the results.

In the simulation, a friction coefficient of 0.2 was used. However, this value is only approximate and can therefore result in inaccurate material behaviors in the simulation. Another source of error in the simulation is introduced by the boundary conditions not fully representing reality.

In the post-processing of the data, interpolation is used to enable comparison and the ICP algorithm to minimize errors. These are not guaranteed to produce fully accurate results.

One error in the analysis of the major vs. minor strains was also detected. In the DIC, only data points inside the part of the specimen surface that is visible through the hole are used. However, in the simulation, all nodes on the bottom surface of the specimen are used, including the ones that are concealed by the hole. Thus, the two sets are not entirely comparable. However, since the data points outside of the hole only are deformed very little, these points will most likely be located around the origin.

## **5.4 Future Work**

In order for the methodology to be efficient, the amount of manual involvement that is needed must be reduced. Therefore, the next natural step is to automate the process. The code also needs to be translated from MATLAB to Python, since Python is what is used at IKEA.

To further increase the performance of the method, the analysis could be conducted over a continuous range rather than a finite set of predetermined data points.

## 6 Conclusion

Overall, the results of the project are considered to be successful. The design of the test jig fulfills almost all requirements and is easy to use for test lab personnel. By using a first surface mirror in combination with DIC it is possible to view the bottom surface of the specimen from the side. The experiment induces biaxial loads on the test specimen and produces repeatable results.

The methodology fulfills its purpose, to evaluate the performance of material models during biaxial loads. The results from the evaluation can be used to verify and compare different material models. In addition, the material's behavior during the test can also be analyzed qualitatively, which may reveal important details about the material's properties.

By analyzing the striker force-displacement curves, the three parameters in the field analysis, and the major vs. minor strains, a comprehensive understanding of its success can be obtained. It is also possible to see in which deformation range the model performs best.

## References

- [1] V.D. Vijayanand, M. Mokhtarishirazabad, J. Peng, Y. Wang, M. Gorley, D.M. Knowles, M. Mostafavi, "A novel methodology for estimating tensile properties in a small punch test employing in-situ DIC based deflection mapping," Elsevier, p. 3, 2020.
- [2] S. Arunkumar, "Small Punch Creep Test: An Overview," *Met. Mater. Int.*, 2020.
- [3] J.T. Hammer, T.J. Liutkus, J.D. Seidt, A. Gilat, "Using Digital Image Correlation (DIC) in Dynamic Punch Tests," *Exp Mech* 55, 2015. [Online]. Available: <https://doi.org/10.1007/s11340-014-9924-9>.
- [4] ISO, "Determination of puncture impact behaviour of rigid plastics (ISO 6603-2 : 2000)," 2002.
- [5] S. Hall, "Digital Image Correlation in Experimental Geomechanics," Division of Solid Mechanics, Lund University and European Spallation Source AB, Lund, Sweden, 2012.
- [6] C. Ressler, C. Briese, N. Pfeifer, P. Glira, "A Correspondence Framework for ALS Strip Adjustments based on Variants of the ICP Algorithm," E Schweizerbart Science Publishers, 2015.
- [7] K.T. Ulrich, S.D. Eppinger, *Product Design and Development*, McGraw-Hill Education, 2011.
- [8] Y.J. Mergler, R.P. Schaake, "Material transfer of POM in sliding contact," Elsevier, 2004.