

Department of Construction Sciences
Solid Mechanics

ISRN LUTFD2/TFHF-26/5273-SE(1-78)

Characterising pull-out of thermoplastic expander dowels from particleboard through 4D X-ray microtomography

Master's Dissertation by
Isabella McAuley Skriver

Supervisors:
Stephen Hall, Div. of Solid Mechanics
Linus Jönsson, IKEA Components AB

Examiner:
Jonas Engqvist, Div. of Solid Mechanics

Copyright © 2026 by the Division of Solid Mechanics
and Isabella McAuley Skriver

Printed by Media-Tryck AB, Lund, Sweden

For information, address:

Division of Solid Mechanics, Lund University, Box 118, SE-221 00 Lund, Sweden

Webpage: www.solid.lth.se

Abstract

This thesis was conducted in collaboration with IKEA Components AB and aims to assess the potential of X-ray computed microtomography (μ CT) and four-dimensional (4D) μ CT for use in product development. The thesis examines the interaction between particleboard and thermoplastic expander dowels during pull-out testing.

An experimental methodology was developed combining mechanical pull-out testing with μ CT imaging. Specimens were subjected to different testing conditions, including continuous and incremental pull-out, using different machinery, and the influence of these conditions on the results was analysed. In addition, a subset of specimens was prepared to investigate relaxation effects. The interaction between the dowel and the material was captured by μ CT imaging of the specimens both before and after ex-situ loading and, for some specimens, multiple times during in-situ loading. The internal deformation was analysed using digital volume correlation (DVC) applied to the three-dimensional μ CT image volumes. This enables the mapping of the three-dimensional displacement and strain tensor fields.

The results show that the pull-out behaviour is strongly influenced by the heterogeneous structure of the particleboard. The mechanical tests for different samples showed similar global responses, but with variations arising from differences between specimens and testing setups. The in-situ tests, and associated μ CT and DVC, provided insight into the internal deformation. The results from the three-dimensional analysis showed that the material did not deform uniformly. Instead, most of the movement and damage were concentrated in a cone-shaped region surrounding the dowel. The analysis also showed that the dowel teeth play a key role in resisting pull-out and transferring load to the surrounding material. In addition, most of the material returned to its original shape after the dowel was removed, while small areas around the dowel teeth remained permanently damaged. The thesis demonstrates that μ CT and DVC can be used to relate global pull-out behaviour to internal structure and deformation mechanisms, making them useful tools for understanding product performance and supporting future development.

Keywords: x-ray computed microtomography, ex-situ pull-out, in-situ pull-out, digital volume correlation, particleboard, thermoplastic expander dowel

Acknowledgments

This Master's thesis was carried out during the spring of 2026 at the Division of Solid Mechanics at Lund University, in collaboration with IKEA Components AB. The project aimed to investigate how X-ray computed microtomography can be used for future product development at IKEA. First and foremost, I would like to thank my supervisor at LTH, Stephen Hall, and my examiner, Jonas Engqvist, for your continuous support throughout this thesis. Thank you for answering my many questions and for always discussing different solutions to the problem at hand. I would also like to express my sincere gratitude to my supervisor at IKEA, Linus Jönsson, for allowing me to develop this thesis freely. I am especially thankful for your positivity and keenness throughout the process. I would also like to thank Björn Stoltz at IKEA for your invaluable input. Your experience and perspective have been greatly appreciated.

A wise man once said, "Det finns ingen vetenskap bakom detta."

This thesis is an attempt to rectify this.

Bella
Lund, June 2026

Contents

Abstract	I
Acknowledgments	III
Contents	VI
1 Introduction	1
1.1 IKEA	1
1.2 Background	1
1.3 Objective and aim	2
1.4 Structure	3
2 Theory	5
2.1 X-ray computed microtomography	5
2.1.1 X-ray generation, attenuation, and contrast	6
2.1.2 Acquisition and reconstruction	7
2.1.3 Voxels, magnification, and spatial resolution	8
2.1.4 Artefacts	9
2.2 Digital volume correlation	9
2.2.1 Continuum mechanics	10
2.2.2 Digital image correlation	13
3 Methodology	17
3.1 Materials and specimens	17
3.1.1 Particleboard	17
3.1.2 Thermoplastic dowels	18
3.1.3 Specimen and fixture geometry	18
3.2 Experimental programme	19
3.2.1 Mechanical testing systems	19
3.2.2 Experimental setup	20
3.2.3 Experimental parameter study	22
3.2.4 Testing	22
3.3 Post-processing	23
3.3.1 Global response	24
3.3.2 Volume preparation	24
3.3.3 Fraction calculation	24
3.3.4 Digital volume correlation	25
3.3.5 Rigid-body removal	26
3.3.6 Coordinate change	26

4	Results	29
4.1	Material	29
4.1.1	Solid fraction over thickness	29
4.1.2	Average solid fraction	30
4.2	Global mechanical response	31
4.2.1	Instron machine	31
4.2.2	MTS machine	32
4.2.3	Pull-out rig	33
4.2.4	In-situ mechanical tests	35
4.2.5	Comparison of testing setups	36
4.2.6	Half-term relaxation	39
4.2.7	Full-term relaxation	39
4.2.8	Relaxation comparison	41
4.3	Tomography and DVC	42
4.3.1	Data	43
4.3.2	Tomography and DVC results for selected specimens	46
4.3.3	Displacement profiles	53
5	Discussion and conclusions	55
5.1	Interpreting the results	55
5.1.1	Material structure and local tooth engagement	55
5.1.2	Global mechanical response	56
5.1.3	Local deformation mechanisms	58
5.1.4	General interpretation	62
5.2	Variability	62
5.3	Future work	64
5.4	Implications for IKEA	65
5.5	Conclusions	67
	References	69

1 Introduction

Furniture performance depends not only on the overall design of a product but also on the behaviour of its connection components. In flatpack particleboard furniture, these components must provide stability, durability, and ease of assembly while remaining simple and cost-efficient. Their performance is governed by the interaction between the component and the surrounding board, particularly during insertion, relaxation, and pull-out. Understanding these local interactions is, therefore, important for improving product development and evaluating new experimental methods.

This chapter introduces the industrial context, the study's background, and the main research aim. It also outlines the structure of the thesis.

1.1 IKEA

IKEA is a furniture retailer founded in 1943 by Ingvar Kamprad in Älmhult, Sweden. Since then, it has developed into one of the world's largest retailers of furniture and interior products. The company aims to improve everyday life for as many people as possible by offering well-designed, functional, and affordable products.

One of IKEA's central principles in product development is Democratic Design. This concept is based on five factors: form, function, quality, sustainability, and affordability. IKEA seeks to develop products in which these factors are balanced, meaning that each element of Democratic Design influences material selection, structural design, production methods, and component development.

IKEA also helped pioneer the concept of flat-pack furniture in Sweden. With this packaging method, products are packed compactly so that they can be stored, transported, and assembled efficiently by the consumer. This approach reduces the costs associated with transportation, logistics, and material use. At the same time, it places high demands on the design of reliable, simple, and cost-efficient mechanical connections.
[1]

1.2 Background

The performance of a piece of furniture is significantly influenced by its components. The behaviour of the connection is governed by the interaction between the dowel and the surrounding particleboard, including deformation, compression, and load transfer. This highlights the importance of understanding such local interactions for improving product development.

Typically, product development relies on physical prototyping, mechanical testing, and numerical simulations to assess a structure's overall performance. Physical prototyping is often used in combination with numerical simulations. However, it may also be used on its own when simulations are not available due to time constraints or insufficient input data for reliable results. Mechanical testing provides global measures of structural performance.

However, in addition to these global measurements, understanding the heterogeneity of many composite materials, such as particleboard, requires information about the internal phenomena that control the measured response. Internal phenomena, such as compression within the test specimen, material damage, or dowel movement, can occur unevenly throughout the test specimen and are typically very difficult to quantify using standard measurement techniques.

This thesis combines mechanical testing with X-ray computed microtomography (μ CT) and digital volume correlation (DVC) to study the pull-out behaviour of thermoplastic expander dowels in particleboard. μ CT enables non-destructive three-dimensional imaging of the specimen at different loading stages, while DVC is used to evaluate internal displacement and strain fields from consecutive μ CT volumes. This makes it possible to relate the measured global response to deformation and damage development in the board around the dowel during insertion, expansion, relaxation, and pull-out.

1.3 Objective and aim

This thesis is an exploratory study aimed at evaluating whether μ CT can be used as a tool for product development at IKEA Components AB. This is addressed by developing an experimental method that combines mechanical testing with μ CT imaging, allowing external mechanical behaviour to be related to internal structural changes. By acquiring a sequence of three-dimensional scans at different stages of loading, structural changes can be tracked over time, a method referred to as four-dimensional (4D) CT. The method is applied to thermoplastic expander dowels and focuses on the interactions that occur during insertion, relaxation, and pull-out. Factors of importance include deformation mechanisms, strain development, contact interaction, and damage progression. In addition, different test methods are assessed to determine the extent to which experimental conditions affect the measured response. The study provides insight into the possible benefits, limitations, and sources of uncertainty associated with using μ CT and DVC.

The thesis has three main objectives:

- How can μ CT be used for product development at IKEA Components AB?
- What methodology should be used to combine μ CT and mechanical testing?
- How do thermoplastic expander dowels interact with particleboard?

The study is limited to one type of thermoplastic expander dowel, inserted into one type of particleboard with a fixed geometry. At the request of IKEA Components

AB, the results are normalised. This limits the direct interpretation of absolute force and displacement values but enables comparison of the relative responses between specimens and test configurations.

1.4 Structure

This thesis is organised as follows. Chapter 1 introduces the background, aims, and structure of the thesis. Chapter 2 presents the theoretical framework, including X-ray computed microtomography and digital volume correlation. Chapter 3 describes the materials and specimens, experimental programme, and post-processing steps. Chapter 4 presents the results, including material structure, global mechanical responses, and μ CT and DVC data. Chapter 5 discusses the interpretation of the results, variability, future work, and implications for IKEA, before presenting the conclusions.

2 Theory

This chapter presents the theoretical background needed to understand the experimental and analytical methods used in the thesis. First, the principles of X-ray μ CT are introduced. These principles are relevant because the quality of the reconstructed image volumes directly affects both visual interpretation and subsequent image analysis.

The second part of the chapter presents DVC. Since DVC provides displacement and strain fields from three-dimensional image data, the continuum-mechanics quantities used to describe motion, deformation, and strain are introduced before the image-correlation procedure itself. This provides the basis for interpreting the DVC results in terms of the physical deformation of the particleboard around the dowel.

2.1 X-ray computed microtomography

μ CT is a non-destructive imaging method used to produce three-dimensional images of the internal structures of materials. A sample is mounted on a rotating stage positioned between an X-ray source and a detector, as illustrated in Figure 2.1. A series of two-dimensional radiographs is acquired as the sample rotates. Each radiograph shows how much of the incident X-ray flux is transmitted through the sample at a particular viewing angle. These projection images are then reconstructed to create a volumetric model of the sample. The theory in the following subsections is based on [2]; [3]; [4]; [5]; and [6].

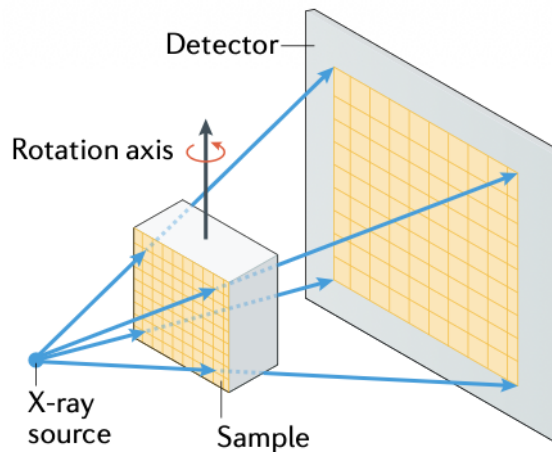


Figure 2.1: Laboratory μ CT cone-beam model [4].

2.1.1 X-ray generation, attenuation, and contrast

In laboratory μ CT systems, X-rays are generated by accelerating electrons through a high voltage and directing them onto a metal target, typically tungsten. The interaction between the accelerated electrons and the target produces polychromatic X-ray radiation.

The tube voltage determines the maximum photon energy and, therefore, the beam's penetration capability through thick materials. Higher photon energies generally reduce material contrast in the resulting image because attenuation differences between materials become less pronounced. The tube current controls the rate at which electrons strike the target and, thus, the photon flux. Increasing the X-ray tube current increases the number of emitted photons without substantially changing the energy spectrum.

The number of detected photons directly affects the signal-to-noise ratio of the resulting images. Increasing the tube current increases the number of photons and, therefore, reduces noise, but it may also increase detector exposure and cause detector saturation if the flux is too high. The contrast-to-noise ratio describes how well features can be distinguished from background noise and depends on both the noise level and the material contrast. When selecting μ CT settings, penetration, contrast, noise, resolution, and acquisition time are all important factors.

The attenuation coefficient, μ , depends on the interactions between X-ray photons and matter. These include Compton scattering, photoelectric absorption, coherent scattering, pair production, and photodisintegration. The latter two require higher energy ranges than those used for μ CT. Compton scattering occurs when a photon interacts with an electron and is scattered with reduced energy. In photoelectric absorption, the photon is absorbed and its energy is transferred to an electron. Coherent scattering changes the direction of a photon with only minor energy loss. The combined dependence of the attenuation coefficient on photoelectric absorption and Compton scattering can be expressed approximately as

$$\mu = \rho \left(a \frac{Z^m}{E^n A} + b \frac{Z}{A} \right), \quad (2.1)$$

where ρ is the mass density, Z is the atomic number, A is the atomic weight, E is the X-ray photon energy, and a , b , m , and n are material- and energy-dependent constants. The first term represents the contribution from photoelectric absorption, while the second term represents the contribution from Compton scattering.

Within the energy range used in X-ray μ CT, attenuation is dominated by photoelectric absorption and Compton scattering, with coherent scattering contributing only slightly. Equation 2.1 shows that the photoelectric contribution has a stronger dependence on both atomic number and photon energy, whereas the Compton contribution is more closely related to electron density and, therefore, to material density.

This attenuation forms the basis of X-ray μ CT. For a homogeneous material irradiated by a monochromatic X-ray beam, the Beer-Lambert law describes the transmitted intensity as

$$I(x) = I_0 e^{-\mu x}, \quad (2.2)$$

where I_0 is the incident X-ray intensity, $I(x)$ is the transmitted intensity after travelling a distance x through the material, and μ is the linear attenuation coefficient. Equation (2.2) assumes that the attenuation coefficient is constant along the beam path. In a heterogeneous material, the attenuation coefficient varies spatially. The transmitted intensity after travelling along a path L is then written as

$$I(L) = I_0 e^{-\int_0^L \mu(x) dx}. \quad (2.3)$$

The projection value measured along a ray path can, therefore, be expressed as

$$p(L) = \ln\left(\frac{I_0}{I}\right) = \int_0^L \mu(s) ds, \quad (2.4)$$

where $p(L)$ is the projection value associated with a ray path of length L . In the monochromatic case (i.e. a single X-ray energy), each projection measurement corresponds to a line integral of the attenuation coefficient along the X-ray path through the specimen. Laboratory μ CT systems use polychromatic X-ray beams rather than monochromatic radiation, due to the nature of the X-ray production. The transmitted intensity is, therefore, described by integrating over the energy spectrum,

$$I(L) = \int_0^{E_{\max}} I_0(E) e^{-\int_0^L \mu(E,x) dx} dE, \quad (2.5)$$

where E is the photon energy, $I_0(E)$ is the incident intensity at energy E , and $\mu(E, x)$ is the energy- and position-dependent attenuation coefficient. This energy dependence means that the attenuation behaviour differs from the monochromatic case and is one of the causes of beam-hardening artefacts in μ CT reconstructions.

2.1.2 Acquisition and reconstruction

During μ CT acquisition, the specimen is rotated while projection images are recorded at discrete angular positions. Each detector measurement represents the attenuation of the X-ray beam along a ray path through the specimen, as described above. The accuracy of the reconstruction depends on the angular sampling of the projection data. According to Fourier sampling theory the ideal number of projections, N_{proj} , is given by

$$N_{proj} = \frac{\pi}{2} N_{pixels} \quad (2.6)$$

where N_{pixels} is the detector width in pixels. Too few projections can lead to streak artefacts, loss of detail, and reduced reconstruction accuracy. Increasing the number of projections generally improves reconstruction quality, but it also increases acquisition time and data size. However, the gains in reconstruction quality diminish as the number of projections exceeds the value given by Equation 2.6.

Tomographic reconstruction is the process of determining the attenuation coefficient distribution as a function of position, $\mu(\mathbf{x})$, from the projection data that are measured. The primary approach for reconstruction is based on analytical back-projection with filtering to reduce blurring (i.e., filtered back-projection).

The geometry commonly used in laboratory μ CT involves an X-ray beam that diverges from a source towards a detector making a cone (i.e., cone beam geometry), as illustrated in Figure 2.1. Cone-beam reconstruction uses the Feldkamp-Davis-Kress (FDK) algorithm, which is an approximate analytical reconstruction method for circular cone-beam trajectories. The method consists of geometric weighting, filtering, and back-projection. The filtering step typically uses a ramp filter, which enhances high-frequency components associated with edges, but may also amplify high-frequency noise. Consequently, the reconstruction algorithm and filter choice influence both spatial resolution and image noise. Since circular cone-beam data are incomplete for exact three-dimensional reconstruction, FDK provides an approximate reconstruction, and the accuracy may decrease away from the central scan plane where cone-beam artefacts can become more pronounced.

2.1.3 Voxels, magnification, and spatial resolution

The reconstructed attenuation field, $\mu(\mathbf{x})$, is discretised onto a three-dimensional grid of voxels. Each voxel represents the average attenuation coefficient over its volume, and the full voxel grid forms a grayscale representation of the internal structure of the specimen. When structural features approach the voxel size, partial-volume effects occur, meaning that a single voxel may contain more than one material phase, so the reconstructed attenuation value represents an average rather than a specific material property.

The voxel size depends on the detector pixel pitch and the cone-beam magnification. Two important geometric distances in a cone-beam μ CT system are the source-detector distance, SDD , and the source-object distance, SOD . The source-object distance is the distance from the X-ray source to the centre of the scanned volume, which ideally coincides with the axis of rotation. The geometric magnification is defined as the ratio between these distances,

$$M = \frac{SDD}{SOD}. \quad (2.7)$$

For a detector pixel pitch, p , the voxel size, v , of the reconstructed volume can then be estimated as

$$v = \frac{p}{M}. \quad (2.8)$$

In addition to the detector pixel pitch, the finite focal spot size contributes to geometric unsharpness, or penumbra. This blurring can be estimated as

$$b = \frac{D \cdot d}{L}, \quad (2.9)$$

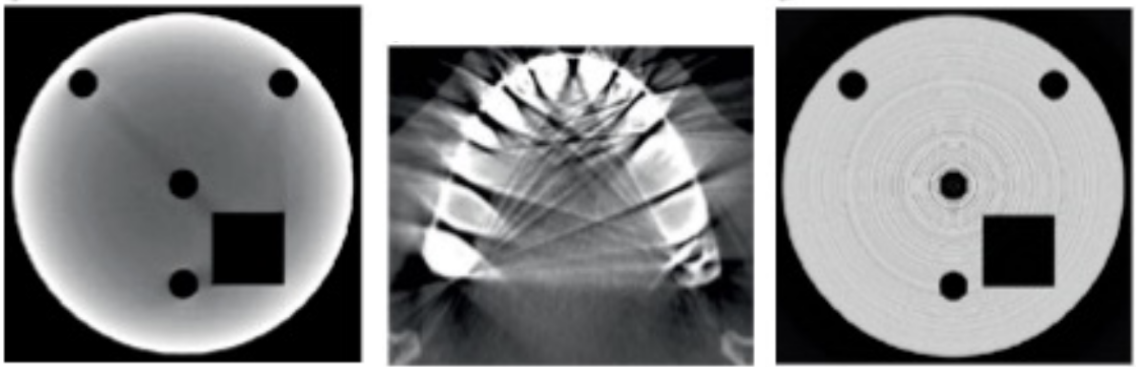
where D is the focal spot size, $d = SDD - SOD$ is the object-detector distance, and L is the source-detector distance. Moving the specimen closer to the X-ray source reduces SOD , which increases the magnification and, therefore, decreases the reconstructed voxel size. However, voxel size is not equivalent to spatial resolution. The true spatial resolution is also affected by focal spot blurring, detector characteristics, beam geometry, mechanical stability, photon statistics, and the reconstruction algorithm. Scan design, therefore, requires a compromise between voxel size, spatial resolution, field of view, image noise, and acquisition time.

2.1.4 Artefacts

Beam hardening is an artefact that can occur in laboratory μ CT systems using polychromatic X-ray radiation. Low-energy photons are absorbed more strongly than high-energy photons as the beam passes through the specimen. As a result, the transmitted spectrum contains a larger proportion of high-energy photons, and the mean photon energy increases with penetration depth. This causes the attenuation behaviour to deviate from the monochromatic Beer-Lambert model in Equation (2.2), and follow the energy-integrated form in Equation (2.5), causing non-linear artefacts in the reconstructed volume.

Beam hardening can cause cupping artefacts, where the centre of an object appears artificially less attenuating than its edges because rays passing through the centre travel through a longer material path and are, therefore, more strongly affected by beam hardening. Beam hardening can also produce streak artefacts, particularly between highly attenuating regions. Examples of cupping and streak artefacts are illustrated in Figures 2.2a and 2.2b. The use of hardware filters can reduce the effects of beam hardening by removing low-energy X-rays before they interact with the specimen, thereby increasing the mean photon energy of the incident beam.

Artefact creation can be influenced by geometry, where cylindrical specimens with no sharp edges tend to produce fewer artefacts than other shapes in μ CT. This is due to reduced variations in the length of the attenuated path and simplified reconstructions. In addition to beam-hardening artefacts, common artefacts in μ CT include ring artefacts and motion artefacts. Ring artefacts form as rings around the rotational axis and may result from detector miscalibration or defective detector elements, as illustrated in Figure 2.2c. Motion artefacts occur if the specimen moves during acquisition, which can blur or distort the reconstructed volume.



(a) Cupping artefact.

(b) Streak artefact.

(c) Ring artefact.

Figure 2.2: Examples of μ CT artefacts [4].

2.2 Digital volume correlation

The μ CT acquisitions provide three-dimensional greyscale volumes of the specimen at different loading stages. DVC is used to compare these volumes and estimate how the

internal structure moves between a reference state and a deformed state. This enables internal displacement fields to be obtained, from which strain measures are derived to describe deformation in the particleboard around the dowel.

To interpret the DVC results, it is necessary to distinguish between displacement, deformation, rigid-body motion, and strain. A displacement field describes the motion of material points, whereas strain describes their relative motion and is therefore related to deformation rather than rigid-body movement. This distinction is important in the present work because the measured motion may include both deformation of the particleboard and rigid-body movement between scans. The continuum-mechanics framework is therefore introduced first to define the quantities later obtained from the DVC analysis.

The image-correlation procedure is then introduced to describe how local greyscale patterns in a reference volume and a deformed volume are matched to estimate the transformation between them. The section also outlines the practical DVC workflow, including global registration, pixel search, local correlation, subset size, and grid spacing. In this way, the mathematical description of motion and strain is connected to the practical procedure used to evaluate internal deformation around the dowel. The theory in the following subsections is based on [7].

2.2.1 Continuum mechanics

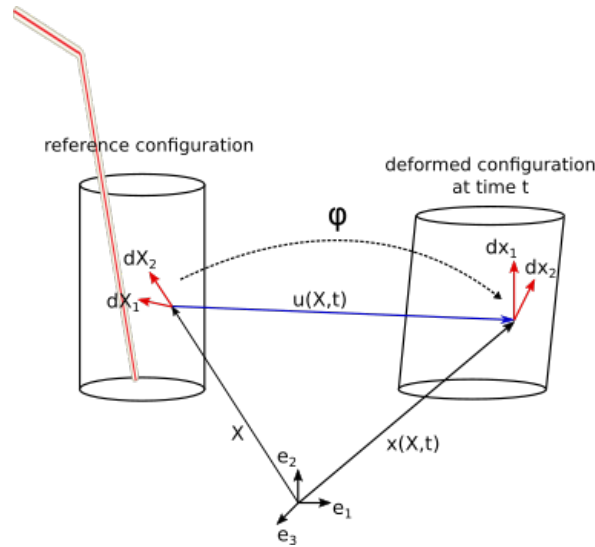


Figure 2.3: Reference and deformed configurations [7].

A material point is described by its position, $\mathbf{X}$, in the reference configuration and by its position, $\mathbf{x}$, in the deformed configuration, as shown in Figure 2.3. The motion of the body is defined by the mapping

$$\mathbf{x} = \phi(\mathbf{X}, t), \quad (2.10)$$

where ϕ describes the position of each material point at time t . The displacement

field is the difference between the deformed and reference positions,

$$\mathbf{u}(\mathbf{X}, t) = \mathbf{x} - \mathbf{X}. \quad (2.11)$$

In the present work, this displacement field corresponds to the primary output from DVC, which estimates the movement of material points between two μ CT volumes. The position after motion can also be written as

$$\mathbf{x} = \mathbf{X} + \mathbf{u}(\mathbf{X}, t). \quad (2.12)$$

While the displacement field describes the movement of individual material points, deformation is determined by the relative movement of neighbouring points. Let $d\mathbf{X}$ be an infinitesimal vector connecting two points in the reference configuration, i.e., a material vector. After deformation, the corresponding vector in the deformed configuration is

$$d\mathbf{x} = \mathbf{x}(\mathbf{X} + d\mathbf{X}, t) - \mathbf{x}(\mathbf{X}, t) = \frac{\partial \mathbf{x}}{\partial \mathbf{X}} d\mathbf{X} + \mathcal{O}. \quad (2.13)$$

Disregarding the higher-order terms, $\mathcal{O}$, gives

$$d\mathbf{x} = \mathbf{F} d\mathbf{X}, \quad (2.14)$$

where

$$\mathbf{F} = \frac{\partial \mathbf{x}}{\partial \mathbf{X}} \quad (2.15)$$

is the deformation gradient tensor. It describes the local change of an infinitesimal material neighbourhood, including stretch, compression, shear, and rotation. Using $\mathbf{x} = \mathbf{X} + \mathbf{u}$, the deformation gradient can be written as

$$\mathbf{F} = \frac{\partial(\mathbf{X} + \mathbf{u})}{\partial \mathbf{X}} = \mathbf{I} + \frac{\partial \mathbf{u}}{\partial \mathbf{X}}. \quad (2.16)$$

Here, $\mathbf{I}$ represents the undeformed state and $\partial \mathbf{u} / \partial \mathbf{X}$ is the displacement gradient. If all material points translate by the same amount, the displacement gradient is zero, and no strain is produced. Therefore, strain arises from spatial variations in the displacement field. This is directly relevant for DVC, where the displacement field is estimated from the transformation between the reference and deformed image volumes, and strain is subsequently obtained from spatial variations in that displacement field.

A finite-strain description is used to account for large deformation. The deformation gradient contains both deformation and rigid-body rotation. Since strain should describe changes in length and angle, rather than rigid-body motion, the rotation must be excluded from the strain measure. This can be done using the polar decomposition theorem,

$$\mathbf{F} = \mathbf{R}\mathbf{U}, \quad (2.17)$$

where $\mathbf{R}$ is a rotation tensor and $\mathbf{U}$ is the right stretch tensor. The tensor $\mathbf{U}$ is symmetric, $\mathbf{U} = \mathbf{U}^T$, and describes pure stretching. The rotation tensor $\mathbf{R}$ is orthogonal,

with $\mathbf{R}^T \mathbf{R} = \mathbf{I}$ and $\det(\mathbf{R}) = 1$, meaning that it preserves lengths and angles. Changes in lengths and angles are governed by the right Cauchy-Green deformation tensor,

$$\mathbf{C} = \mathbf{F}^T \mathbf{F}. \quad (2.18)$$

Substituting the polar decomposition gives

$$\mathbf{C} = \mathbf{F}^T \mathbf{F} = \mathbf{U}^T \mathbf{R}^T \mathbf{R} \mathbf{U} = \mathbf{U}^2. \quad (2.19)$$

The rotation tensor is, therefore, eliminated, leaving a measure that depends only on stretch. For a pure rigid-body motion,

$$\mathbf{F} = \mathbf{R} \quad \text{and} \quad \mathbf{U} = \mathbf{I}. \quad (2.20)$$

A strain measure, ε_U , can, therefore, be based on the stretch relative to the undeformed state,

$$\varepsilon_U = \mathbf{U} - \mathbf{I}. \quad (2.21)$$

To separate volume change from shape change, $\mathbf{U}$ is decomposed into volumetric and deviatoric parts,

$$\mathbf{U} = \mathbf{U}_{\text{vol}} \mathbf{U}_{\text{dev}}. \quad (2.22)$$

The volumetric part represents uniform volume change, defined as

$$\mathbf{U}_{\text{vol}} = J^{1/3} \mathbf{I}, \quad (2.23)$$

while the deviatoric part represents the remaining shape-changing deformation,

$$\mathbf{U}_{\text{dev}} = \frac{1}{J^{1/3}} \mathbf{U}. \quad (2.24)$$

Here $J = \det(\mathbf{F})$ is the local volume ratio, defined as the ratio between the deformed and reference volume elements. The volumetric strain, ε_{vol} , is defined as

$$\varepsilon_{\text{vol}} = J - 1, \quad (2.25)$$

and it describes local volume change. The deviatoric strain, ε_{dev} , is defined as the Frobenius norm of the deviatoric part of the stretch tensor,

$$\varepsilon_{\text{dev}} = \|\mathbf{U}_{\text{dev}} - \mathbf{I}\|, \quad (2.26)$$

and describes the intensity of shape-changing deformation independently of volume change. These strain measures are used in this work as scalars that enable the location and relative intensity of deformation to be identified.

2.2.2 Digital image correlation

Digital image correlation (DIC) is a process to determine the displacement field that maps one image onto another. DVC is the extension of DIC to volumetric images and is based on the comparison of two three-dimensional grayscale images, here referred to as im1 and im2. The first image represents the reference configuration, while the second image represents the deformed configuration. The aim is to determine the transformation, Φ , that maps material points in the reference image to their corresponding positions in the deformed image. The local transformation is written using homogeneous coordinates, i.e. $\mathbf{x} = (z, y, x, w)^T$, with $w = 1$. The coordinate ordering (z, y, x) follows the notation used in SPAM and differs from the conventional Cartesian ordering (x, y, z) . Thus, the transformation matrix, Φ , contains both the deformation gradient tensor, $\mathbf{F}$, and the translation vector, $\mathbf{t} = [t_z, t_y, t_x]^T$, describing the local displacement of the correlation window,

$$\Phi = \begin{bmatrix} F_{zz} & F_{zy} & F_{zx} & t_z \\ F_{yz} & F_{yy} & F_{yx} & t_y \\ F_{xz} & F_{xy} & F_{xx} & t_x \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (2.27)$$

The transformation of a point from the reference, im1, to the deformed state, im2, is, therefore, expressed as

$$\Phi \cdot \mathbf{X} = \mathbf{x}. \quad (2.28)$$

If the correct transformation has been found, the grayscale value of a material point in the reference image should correspond to the grayscale value at the mapped position in the deformed image,

$$\text{im1}(\mathbf{X}) = \text{im2}(\Phi \cdot \mathbf{X}). \quad (2.29)$$

This equality cannot be fulfilled exactly because of image noise, reconstruction artefacts, interpolation errors, changes in grayscale intensity, and limitations in the assumed transformation model. The transformation is, therefore, given by the Φ that minimises the grayscale difference between the two images within a selected region. The error function can be written as a sum of squared differences,

$$\mathcal{T}(\Phi) = \frac{1}{2} \sum_{\mathbf{x} \in ROI} [\text{im1}(\mathbf{x}) - \text{im2}(\Phi \cdot \mathbf{x})]^2. \quad (2.30)$$

The objective of the image correlation is to find the transformation that minimises this error function. Since Φ contains twelve unknown transformation parameters, the minimisation is solved iteratively. Assuming that im2 is differentiable, the minimum of $\mathcal{T}(\Phi)$ is found when its gradient with respect to the transformation parameters is zero, i.e., DIC can be summarised as

$$\text{Find } \Phi \text{ such that } \nabla \mathcal{T}(\Phi) = 0. \quad (2.31)$$

This can, for example, be solved using an incremental Newton optimisation method. At iteration n , the current estimate of the transformation is Φ^n and an incremental

correction $\delta\Phi^{n+1}$ is calculated. The Newton update is written as

$$\nabla\mathcal{T}(\Phi^n) + \nabla^2\mathcal{T}(\Phi^n) : \delta\Phi^{n+1} = 0. \quad (2.32)$$

Here, $\nabla\mathcal{T}(\Phi^n)$ is the gradient of the objective function evaluated at the current estimate, while $\nabla^2\mathcal{T}(\Phi^n)$ is the corresponding Hessian. The double contraction with $\delta\Phi^{n+1}$ gives the linearised Newton correction required to move the solution towards a stationary point of the objective function.

The transformation is then updated according to

$$\Phi^{n+1} = \Phi^n + \delta\Phi^{n+1}. \quad (2.33)$$

This can be written in matrix-vector form as

$$\mathbf{M}^n \delta\Phi^{n+1} = \mathbf{A}^n. \quad (2.34)$$

where $\mathbf{M}^n$ represents the Hessian matrix and $\mathbf{A}^n$ represents the residual vector at iteration n . If $\mathbf{M}^n$ is invertible, the increment can be written as

$$\delta\Phi^{n+1} = (\mathbf{M}^n)^{-1} \mathbf{A}^n. \quad (2.35)$$

The quality of the initial guess is important, since the iterative procedure may fail to converge if the starting transformation is too far from the correct solution. A single global transformation is generally insufficient for a heterogeneous material, where different regions may deform in different ways. For each correlation point, a region around that point is compared between the reference and deformed images, and a local transformation Φ is estimated. Repeating this procedure over a regular grid of correlation points gives a spatially distributed transformation field,

$$\Phi = \Phi(\mathbf{x}). \quad (2.36)$$

The translational part of this transformation field gives the local displacement,

$$\mathbf{u}(\mathbf{x}) = \mathbf{t}(\mathbf{x}). \quad (2.37)$$

In the DVC procedure, this displacement field is obtained from spatial variations in the estimated transformation field. The result is sensitive to image noise, correlation errors, filtering choices, and regions where damage or large deformation reduces correlation quality.

In practice, the DVC procedure is carried out in several steps. First, a global registration is used to obtain an initial estimate of the transformation between the reference and deformed volumes. This initial estimate is important because the iterative local correlation procedure requires a starting point sufficiently close to the correct solution. A pixel search is then used to improve the initial local displacement estimates by searching, within a specified search range, for the integer-voxel displacement that gives

the best match between local image regions. This provides a discrete displacement estimate that is sufficiently close for the subsequent local DVC refinement. Finally, local DVC is performed on a regular grid of correlation points to refine the displacement field by correlating local greyscale patterns between the reference and deformed volumes. At each grid point, a correlation window is extracted from the reference image and compared with the corresponding region in the deformed image. The subset radius defines the half-size of this correlation window, while the grid spacing defines the distance between neighbouring correlation points.

3 Methodology

This chapter describes the experimental and post-processing methods used to investigate the pull-out behaviour of thermoplastic expander dowels in particleboard. The methodology was designed to combine global mechanical measurements with internal structural information obtained from X-ray μ CT. This enabled the external force-displacement response to be related to local deformation, compaction, and damage development within the specimen.

The chapter first presents the materials, specimen geometry, and test fixtures. The experimental programme is then described, including the mechanical testing systems, tomography setup, parameter study, and test groups. Finally, the post-processing workflow is presented, including global response processing, volume preparation, solid fraction calculation, digital volume correlation, rigid-body correction, and coordinate transformation.

3.1 Materials and specimens

The study concerns the interaction between particleboard and thermoplastic expander dowels during pull-out. This section describes the particleboard, dowel components, specimen geometry, and fixtures used in the experimental programme.

3.1.1 Particleboard

Particleboard is a wood-based composite material consisting of wood particles bonded with a polymeric adhesive under heat and pressure. The two outer layers contain smaller particles packed more densely, creating stiffer face layers around a less dense core. This gives the board mechanical properties similar to an I-beam, where the dense outer layers act as flanges and the core acts as the web, as seen in Figure 3.1. This arrangement increases bending stiffness by concentrating material in the outer regions, where bending stresses are highest. The material in each layer is heterogeneous due to local differences in density, porosity, orientation of particles, particle size and how adhesives are distributed. In addition, the material is sensitive to moisture, potentially affecting its overall behaviour under applied forces. These characteristics affect the local deformation and compaction, as well as the damage development during pull-out. Due to these differences, two specimens that have nominally the same form and composition can exhibit different behaviours when subjected to loading. [8]

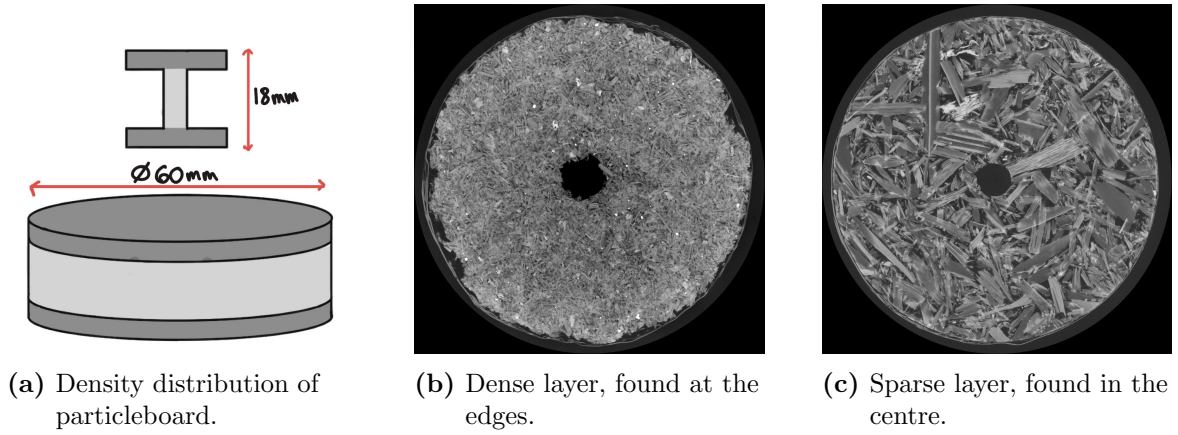


Figure 3.1: Density distribution and example slices of the cross-sectional view extracted from an X-ray tomography image of the specimen.

3.1.2 Thermoplastic dowels

The thermoplastic expander dowels of this study consist of two parts illustrated in Figure 3.2, which are manufactured from polyoxymethylene (POM) and polyamide 6 (PA6). Both materials are suitable for injection moulding of small components with complex geometry, making them ideal for dowel production. POM, used for the pin, is characterised by relatively high stiffness, good dimensional stability, low friction, and good wear resistance. PA6, used for the dowel, is generally more ductile and more moisture-sensitive than POM, meaning that its mechanical properties may be affected by humidity and conditioning. These differences are relevant because they may influence dowel expansion, contact pressure, relaxation behaviour, and load transfer to the surrounding particleboard. [9] [10]

3.1.3 Specimen and fixture geometry

The specimens were cut using a hole saw from a larger sheet of particleboard, resulting in cylindrical specimens with a diameter of 60 mm and a central hole through the entire thickness of 18 mm, as shown in Figure 3.2a and Figure 3.3a. This geometry differs from the final furniture application, where the depth of the hole is a few millimetres greater than the length of the dowel. Nevertheless, it was assumed to provide a representative local pull-out configuration. The approximately cylindrical geometry is advantageous for μ CT imaging because it reduces variations in X-ray path length during rotation. This helped to limit reconstruction artefacts and provided a more stable imaging environment. The particleboard specimens and dowels, shown in Figures 3.2b, 3.2c, 3.2d, 3.3b, and 3.3c, were stored in sealed plastic bags in a dark cupboard to minimise exposure to sunlight and limit moisture exchange with the surrounding environment. No complete drying procedure or humidity-controlled conditioning was performed before testing. Consequently, changes in moisture content may have occurred during storage and testing, which could have influenced the mechanical behaviour of the humidity-sensitive particleboard and polymer components.

The pull-out fixtures, shown in Figure 3.2e and Figure 3.3d, were used to connect the dowel to the loading systems in a repeatable and uniform way. They were manufac-

tured from aluminium to limit X-ray attenuation and reduce artefacts during imaging. The circular fixtures were created to fit several mechanical testing machines by securing a screw through the holes in the top half. The bottom was designed so that a dowel could fit through it and be assembled into the particleboard, similarly to its practical application. The pin, shown in Figure 3.2c, expands the dowel after insertion, producing the assembled dowel shown in Figure 3.2d.

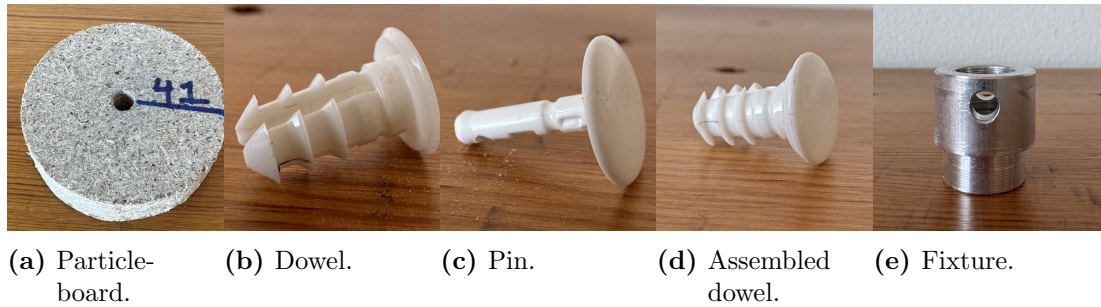


Figure 3.2: Images of particleboard, thermoplastic expander dowel components, and fixture used in the experimental setup.

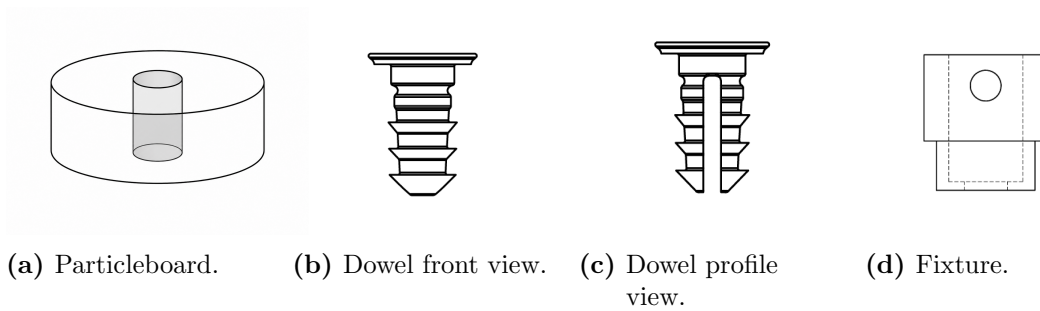


Figure 3.3: Models of particleboard, thermoplastic expander dowel, and fixture used in the experimental setup.

3.2 Experimental programme

The experimental programme was designed to evaluate both the global mechanical response and the internal deformation mechanisms that develop during loading. Different testing systems and loading procedures were, therefore, used to compare conventional pull-out testing with in-situ μ CT. This made it possible to assess how the measured response was influenced by the experimental setup while also providing image data for analysing the internal behaviour of selected specimens. The following sections describe the mechanical testing systems, tomography setup, parameter study, and final testing procedure.

3.2.1 Mechanical testing systems

The experimental work was performed using a laboratory X-ray microtomography system, RX Solutions EasyTom150, together with three mechanical testing systems:

an Instron 3369 testing machine, an MTS 810 testing machine, and a custom-built pull-out rig developed at the Division of Solid Mechanics. The custom-built rig was designed to fit inside the tomograph, allowing pull-out testing to be performed without moving or remounting the specimen and still allowing rotation despite the electrical leads required for power, measurement and control. It is designed to be able to pull straight down as seen in Figure 3.4d. The different testing systems are illustrated in Figures 3.4a, 3.4b, 3.4c, and Table 3.1 were used to compare the mechanical response for different loading conditions.

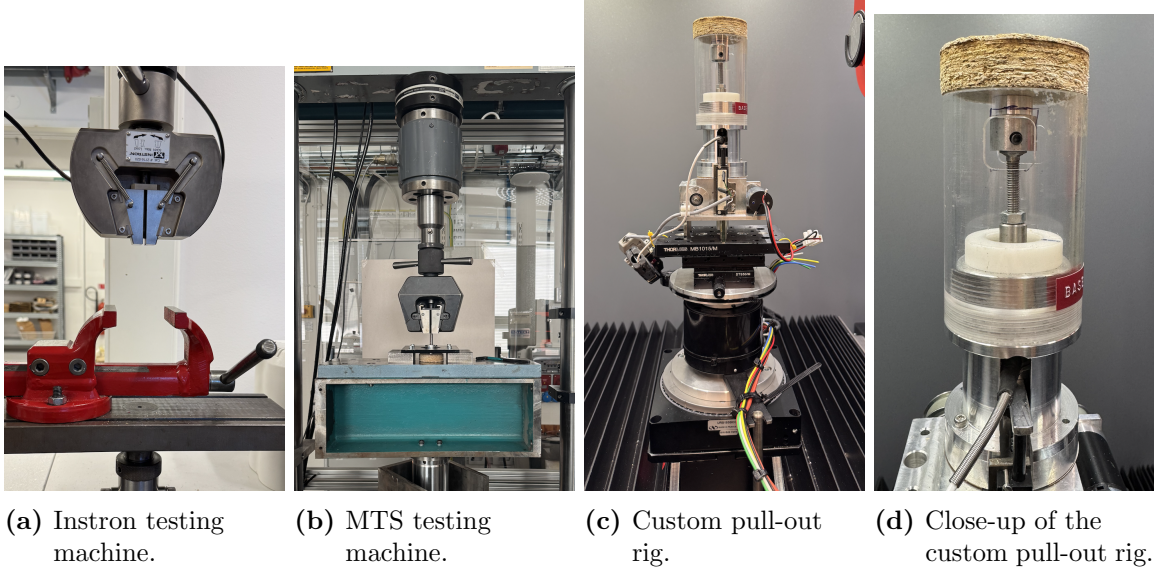


Figure 3.4: Images of the mechanical testing systems.

Table 3.1: Parameters of each mechanical testing system.

Testing system	Loading rate	Load-cell capacity	Used sampling rate
Instron	10 mm/min	50 kN	10 Hz
MTS	5 mm/min	250 kN	100 Hz
Pull-out rig	1 mm/min	4000 N	10 Hz

3.2.2 Experimental setup

The imaging parameters were selected to balance resolution, attenuation contrast, noise, and scan duration. The setup is illustrated in Figure 3.5 and the pCT parameters are summarised in Table 3.2.

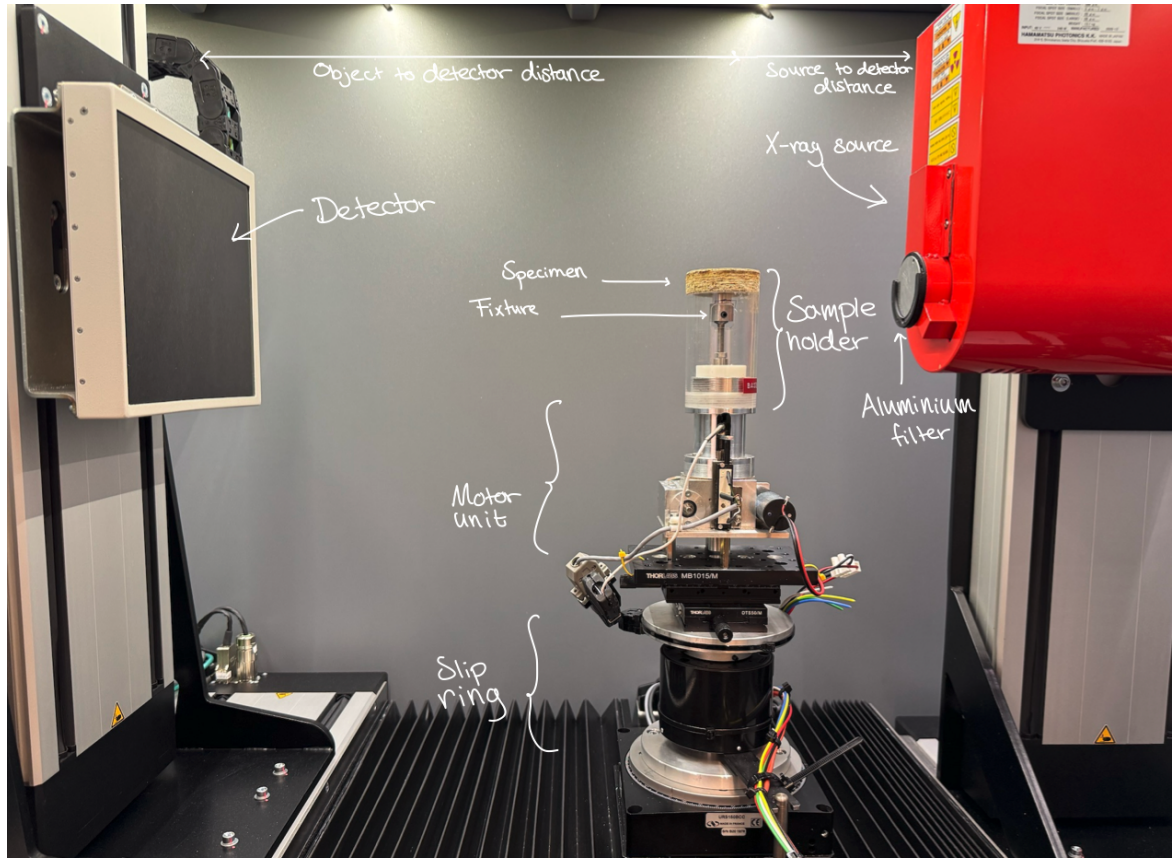


Figure 3.5: Experimental setup with marked components.

Table 3.2: Acquisition and reconstruction parameters used for the tomographic imaging.

Parameter	Value	Unit
Tube voltage	60	kV
Tube current	500	μA
X-ray spot size	medium, 20	μm
Number of projections	2944	–
Field of view (width $\times$ height)	1840 $\times$ 801	pixels
Source-object distance	174.86	mm
Source-detector distance	616.97	mm
Rotation range	360	degrees
Reconstructed voxel size	36 $\times$ 36 $\times$ 36	μm^3
Filter material	Aluminium	–
Filter thickness	1.2	mm
Reconstruction algorithm	FDK (XAct software, RX solutions)	–
Ring filter radius	5	pixels
Calibrations	black, gain	–

3.2.3 Experimental parameter study

A parameter study was performed to determine a suitable imaging configuration for the X-ray μ CT. The aim was to identify a combination of specimen geometry, X-ray tube voltage, and beam filtration that provided sufficient image quality with acceptable scan time.

40 mm and 60 mm diameter circular specimens were compared. The smaller specimens allowed for greater geometric magnification and, thus, higher spatial resolution. Although the smaller specimens would have provided higher spatial resolution, minimising potential mechanical boundary condition effects was prioritised. Therefore, the 60 mm specimen geometry was selected.

As discussed in Section 2.1.1, the X-ray voltage influences the penetration and contrast. Therefore, the influence of tube voltage on the image quality was also evaluated. A tube voltage of 100 kV improved penetration through the specimen, but reduced contrast. Using 60 kV provided stronger attenuation contrast and more distinct grayscale gradients, which were beneficial for both visual interpretation and DVC. Although lower tube voltages can increase sensitivity to noise in thicker specimens, preliminary scans indicated that the selected specimen geometry could be imaged satisfactorily at 60 kV. This voltage was therefore adopted for the subsequent experiments.

The effect of beam filtration was investigated by comparing different filter materials. A 0.2 mm thick iron filter reduced beam-hardening artefacts more strongly than aluminium, but it also reduced the overall grayscale contrast and weakened the image texture required for DVC. 1.2 mm of aluminium provided a more suitable compromise between artefact reduction and preserved grayscale variation; this filter was, therefore, selected for the final μ CT scans.

3.2.4 Testing

The experimental method was designed to compare the global mechanical response with the internal microstructural evolution observed using μ CT. Following each loading step, a 10 minute waiting period was applied to allow immediate relaxation and specimen movement to subside before image acquisition. As each scan required approximately 40 minutes, continuous μ CT imaging during pull-out was not feasible because specimen movement during scanning would have caused motion artefacts. The specimens were therefore either scanned before and after pull-out or subjected to an incremental pull-out procedure, in which each specimen was loaded in a series of displacement increments and scanned at selected loading stages.

A total of 33 specimens were prepared for the main experimental programme and divided into four groups based on test type. The test programme is summarised in Table 3.3. Group 1 was prepared to investigate time-dependent effects after dowel installation. Five specimens were evaluated after one month, referred to as half-term relaxation, while the remaining five were evaluated after two months, referred to as full-term relaxation. These specimens were scanned in the empty state, after dowel insertion, after pin insertion, after the relaxation period, and after pull-out. Groups

2 and 3 were used to obtain global response data from different mechanical testing configurations. These specimens were scanned before and after pull-out. Group 0 consisted of additional Instron tests performed at IKEA, which were not imaged using μ CT. Group 4 was used for in-situ tomography, where specimens were repeatedly imaged during incremental loading.

Table 3.3: Overview of the experimental test programme.

Group	Specimens	Test type	Testing system	Imaging
0	-	Pull-out	Instron	No μ CT imaging
1	01–10	Relaxation	Pull-out rig	Empty, Dowel, Pin, Before, After
2	11–20	Pull-out	MTS	Before, After
3	21–30	Pull-out	Pull-out rig	Before, After
4	31–33	In-situ	Pull-out rig	Before, 5 loading steps, After

All mechanical tests were displacement-controlled, where the global response was recorded continuously during loading. The continuous pull-out tests were loaded without interruption until the selected displacement limit was reached, after which the specimen was unloaded.

For the in-situ μ CT tests, loading was applied incrementally. At predefined force or displacement levels, the displacement was held constant while the specimen was scanned. The selected loading stages were based on previously obtained global responses and were chosen to capture characteristic parts of the mechanical response, including the initial response, the transition into non-linearity, and the later pull-out stage. At each stage, the specimen was held for approximately 5 minutes before scanning to reduce the influence of immediate relaxation and movement during image acquisition. Since μ CT imaging was only performed at selected loading stages, rapid events such as crack initiation, force drops, or local failure could not be captured directly, representing a limitation of the experimental methodology.

3.3 Post-processing

The post-processing workflow was designed to prepare the mechanical data and reconstructed μ CT volumes for quantitative comparison between global response and internal deformation. The measured force-displacement data were first filtered and reduced to enable consistent comparison between test configurations. The reconstructed image volumes were then adjusted, cropped, and resampled to obtain comparable image stacks for solid fraction analysis and DVC.

DVC was performed using the SPAM software to estimate displacement and strain fields between selected loading stages [7]. Additional processing steps, including rigid-body correction and transformation of the displacement components into cylindrical coordinates, were applied to relate the results to the circular specimen geometry and the local response around the dowel.

3.3.1 Global response

The measured force-displacement data were post-processed before plotting and comparison. For the MTS data, a fourth-order low-pass filter with a cut-off frequency of 0.5 Hz was applied to reduce high-frequency noise while preserving the global response. For the pull-out rig data, including the pull-out and relaxation tests, a rolling mean with a window size of 25 data points was applied to smooth local fluctuations while retaining the general shape of the curves. The number of data points in the global force-displacement curves from the in-situ tests was reduced using the function `reducem` in MATLAB with a tolerance of 0.01.

3.3.2 Volume preparation

The reconstructed μ CT volumes were prepared to obtain comparable image stacks. The greyscale range was adjusted using the dynamic ranges listed in Table 3.4, and the volumes were converted to 8-bit format for image handling. This reduced the data size and made the workflow more manageable, but it also meant that some greyscale information was compressed compared with the original reconstructed volumes. Slices outside the region of interest were removed so that the analysed stacks contained the specimen region relevant to the pull-out process.

Two image resolutions were prepared. The full-resolution data, referred to as the fine data, contained 491 slices with an in-plane size of 1660×1660 pixels. A downsampled version, referred to as the coarse data, was generated using bicubic interpolation with a scaling factor of 0.5, resulting in 246 slices with an in-plane size of 830×830 pixels, corresponding to half the original size in each direction. The coarse data were used to estimate larger-scale alignment between scans and solid fraction, while the fine data were used for the local DVC evaluation.

Table 3.4: Dynamic ranges used for tomography, displacement, and strain visualisation.

Image type	Colour map	Minimum	Maximum
Tomography	Greyscale	0	255
Displacement field	Phase	-1	0.7
Deviatoric strain field	Fire	0	0.05
Volumetric strain field	Orange-Hot	-0.05	0.05

3.3.3 Fraction calculation

In addition to analysing the images by DVC, the solid fractions were calculated from the reconstructed greyscale μ CT volumes using an intensity threshold. Before thresholding, each volume was normalised, following

$$I_{\text{norm}} = \frac{I - I_{\text{min}}}{I_{\text{max}} - I_{\text{min}}}, \quad (3.1)$$

where I is the original greyscale value and I_{norm} is the normalised intensity between 0-1. Circular masks were used to include the specimen region while excluding the

central hole. A threshold value of $I_{\text{norm}} = 0.15$ was used to separate pores from solid material,

$$\text{Material} = \begin{cases} \text{pore,} & I_{\text{norm}} \leq 0.15, \\ \text{solid,} & I_{\text{norm}} > 0.15. \end{cases} \quad (3.2)$$

The solid fraction was calculated as

$$f_{\text{solid}} = \frac{N_{\text{solid}}}{N_{\text{total}}}, \quad (3.3)$$

where N_{solid} is the number of voxels classified as solid material and N_{total} is the total number of voxels inside the calculation mask. The procedure was applied for each slice to obtain the fraction profiles over the specimen thickness.

3.3.4 Digital volume correlation

The μCT volumes were registered spatially before local DVC in order to reduce the influence of rigid-body movement between scans. A multi-scale procedure was used. First, the coarse image volumes were used to estimate the relative transformation between the reference and deformed scans. This transformation was then used as an initial estimate for the finer-resolution analysis, reducing the computational cost and improving the robustness of the correlation.

After registration, a pixel search was performed to improve the initial estimate of the local displacement field. The refined estimate from the pixel search was then used as the starting point for local DVC. In the local DVC calculation, the integer-pixel displacement estimates from the pixel search were refined on a regular grid of material points by correlating local greyscale patterns between the reference and deformed volumes.

The resulting displacement field from the DVC was filtered using a median filter before strain calculation to reduce outliers and local noise. This approach was adopted because strain is derived from spatial gradients in the displacement field and is therefore more susceptible to measurement noise than the displacement field itself. Volumetric and deviatoric strain components were then calculated using the Geers strain formulation [11]. The DVC parameters used in the analysis are summarised in Table 3.5.

Since the DVC results were evaluated using a grid spacing of 10 voxels, the resulting displacement and strain fields had a reduced spatial resolution compared with the original μCT volumes. The final DVC output fields consisted of 49 slices with an in-plane size of 165×165 grid points. The displacement fields and strain fields were visualised using dynamic ranges and colour maps according to Table 3.4.

Table 3.5: DVC parameters.

Parameter	Value	Unit
DVC software	SPAM in Python	registerMultiscale, pixelSearch, ldic, filterPhiField, regularStrain
Correlation mode	Incremental	-
Voxel size	$36 \times 36 \times 36$	μm^3
Subset radius	5	voxels
Grid spacing	10	voxels
Search radius	15	voxels
Margin	4	voxels
Median filter radius	1	voxels
Strain method	Geers strain	-
Strain components	volumetric, deviatoric	-

3.3.5 Rigid-body removal

A rigid-body correction was performed to reduce the influence of small translations and rotations between scans. The displaced coordinates were defined as

$$\mathbf{x} = \mathbf{X} + \mathbf{u}. \quad (3.4)$$

The rigid-body motion was approximated by a rotation matrix, $\mathbf{R}$, and a translation vector, $\mathbf{t}$,

$$\mathbf{x} \approx \mathbf{R}\mathbf{X} + \mathbf{t}. \quad (3.5)$$

Here, $\mathbf{R}$ is a 3×3 orthogonal rotation matrix satisfying $\mathbf{R}^T \mathbf{R} = \mathbf{I}$ and $\det(\mathbf{R}) = 1$. The rigid transformation was estimated using a least-squares fit. The corresponding rigid-body displacement field was calculated as

$$\mathbf{u}_{\text{rigid}} = \mathbf{R}\mathbf{X} + \mathbf{t} - \mathbf{X}. \quad (3.6)$$

The corrected displacement field was then obtained by subtracting this rigid-body contribution from the measured displacement field,

$$\mathbf{u}_{\text{corr}} = \mathbf{u} - \mathbf{u}_{\text{rigid}}. \quad (3.7)$$

This correction isolates the deformation associated with the local specimen response by removing the translational and rotational motion of the specimen. [12]

3.3.6 Coordinate change

The displacement field obtained from DVC was expressed in Cartesian coordinates, as the displacement components u_x , u_y , and u_z . To evaluate the deformation relative to the circular specimen geometry, the displacement components were transformed into

cylindrical components. For each material point, the position relative to the specimen centre was defined as

$$r_x = x - c_x \quad r_y = y - c_y, \quad (3.8)$$

where c_x and c_y are the centre coordinates of the image. The angular position was calculated as

$$\theta = \tan^{-1} \left(\frac{r_y}{r_x} \right). \quad (3.9)$$

The radial and transverse displacement components were then calculated as

$$u_r = u_x \cos \theta + u_y \sin \theta \quad (3.10)$$

and

$$u_\theta = -u_x \sin \theta + u_y \cos \theta, \quad (3.11)$$

where u_r describes displacement towards or away from the specimen centre, while u_θ describes the circumferential displacement. [13]

4 Results

This chapter presents the experimental results from the material characterisation, mechanical pull-out testing, tomography, and DVC analysis. The results are organised to progress from the material structure to the global mechanical response and finally to the local internal deformation. First, the solid fraction distribution is used to describe the internal structure of the particleboard. The normalised force-displacement curves are then used to evaluate the global pull-out response across the different test configurations. Finally, the tomography and DVC results are used to visualise the internal response of selected specimens and relate the measured mechanical behaviour to local deformation mechanisms.

4.1 Material

The particleboard was analysed using μ CT data to evaluate how the solid fraction varied through the specimen thickness. The analysis was performed on the coarse image data because the purpose was to describe the larger-scale material structure rather than individual particles or pores. The solid fraction was calculated for each slice across the entire specimen thickness to capture variations in porosity, which is expected to influence dowel engagement, local compaction, and the resulting pull-out response.

4.1.1 Solid fraction over thickness

The solid fraction profiles through the specimen thickness are shown in Figure 4.1, together with the average profile. The profiles show a clear variation, with higher solid fractions near the outer surfaces and lower values towards the centre of the board. A slight increase in solid fraction is observed within the core region. Although all specimens follow the same general trend, differences are observed between individual specimens. This is consistent with the expected structure of particleboard, where denser face layers surround a less dense core.

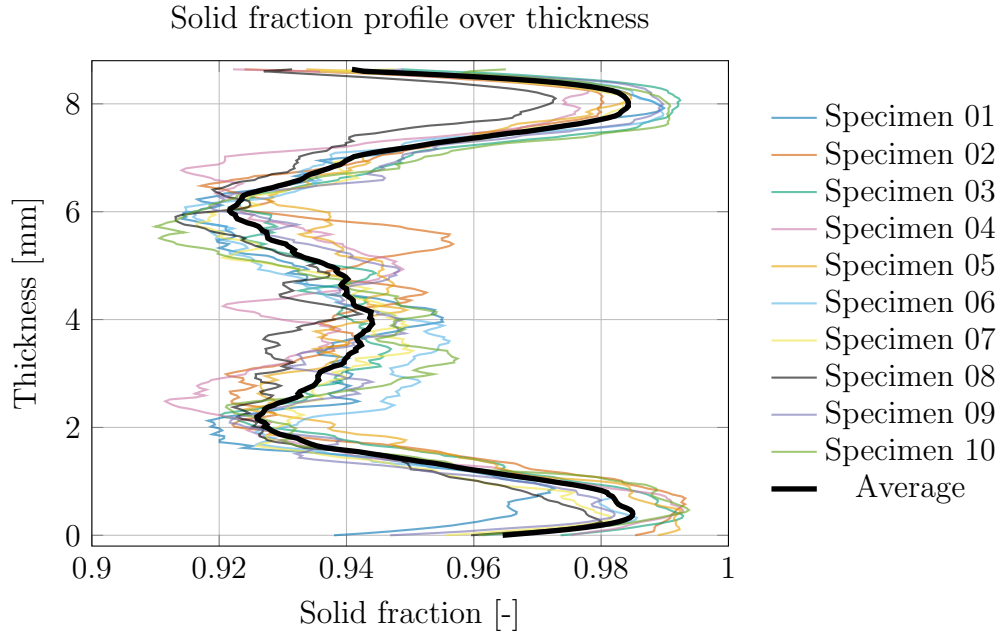


Figure 4.1: Solid fraction over the specimen thickness for specimens 01-10, together with the average profile.

4.1.2 Average solid fraction

The average solid fraction for each specimen is shown in Figure 4.2. The average of the specimen averages is also shown, together with the standard deviation. The average values are similar, but the profiles show that the average values still correspond to different distributions. The average solid fraction, therefore, gives a useful overall measure of the material, while the profiles provide more information about where dense and sparse regions are located through the board thickness.

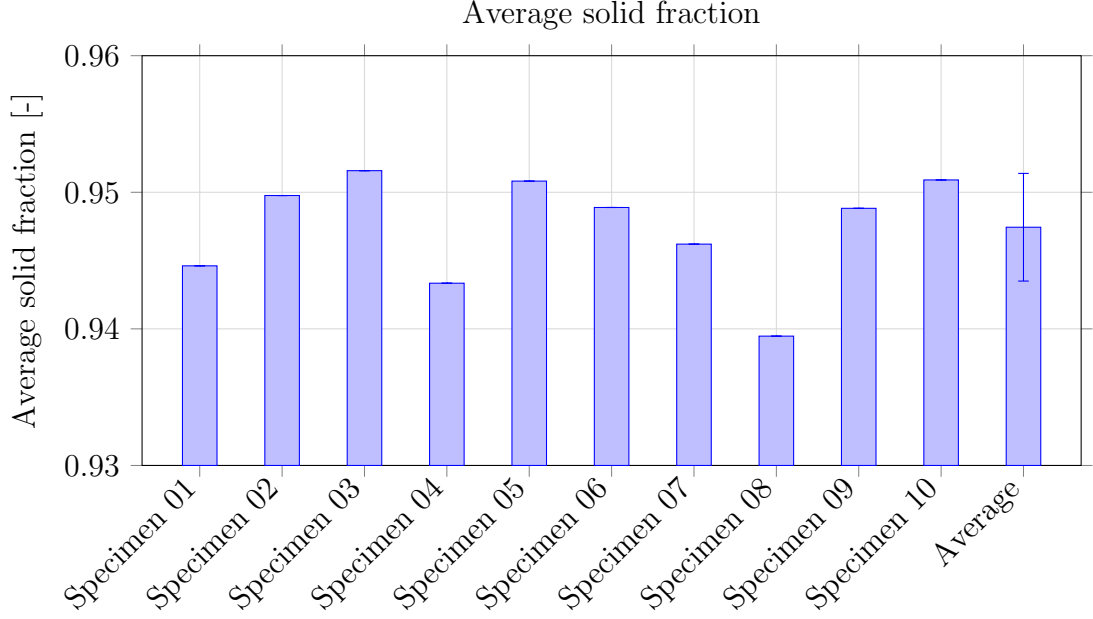


Figure 4.2: Average solid fraction for specimens 01-10, together with the average of the specimen averages and its standard deviation.

4.2 Global mechanical response

The global mechanical response was evaluated from the force-displacement curves recorded during pull-out. The responses were normalised, allowing comparison of curve shape, maximum force, and displacement development between test groups. The responses are presented by test type, with subgroupings based on similarities in response. To facilitate interpretation, curves with visually similar characteristics, such as comparable initial stiffness and post-peak behaviour, have been grouped together. The grouping is based solely on qualitative visual inspection and does not represent a formal classification based on quantitative measures. Average curves and maximum force summaries are used to compare the different testing configurations.

The global mechanical responses were normalised using the maximum force from Instron test 09 and the displacement corresponding to this maximum force, as this test produced the highest recorded force among all responses. The normalisation was performed using the force, F , and displacement, u , according to

$$F_{\text{normalised}} = \frac{F_{\text{specimen}}}{F_{\text{max}}} \quad u_{\text{normalised}} = \frac{u_{\text{specimen}}}{u(F_{\text{max}})}. \quad (4.1)$$

4.2.1 Instron machine

Figure 4.3 shows the normalised force-displacement curves obtained using the Instron testing machine with a loading rate of 10 mm/min. Since these samples were tested at IKEA and not imaged using μ CT, their numbering differs from the specimens tested at LTH, which are denoted Specimen 01-XX. Test 02 was removed because it was

performed using a different loading rate than the remaining samples. The curves show a relatively steep initial linear increase in force, followed by a non-linear region. After the maximum force, the force responses generally decrease, although the post-peak behaviour differs between specimens. Some curves show a more gradual reduction in force, while others contain local drops and secondary peaks.

The grouped plots in Figure 4.3 show that several specimens have similar curve shapes, e.g. similar initial stiffness, similar post-peak behaviour, even though the maximum force and displacement development are not identical. This indicates that response groups can be identified within the Instron curves, while still showing clear variation. Some curves show indications of double-peaking, but the feature is not distinct enough to categorise the responses as a separate group.

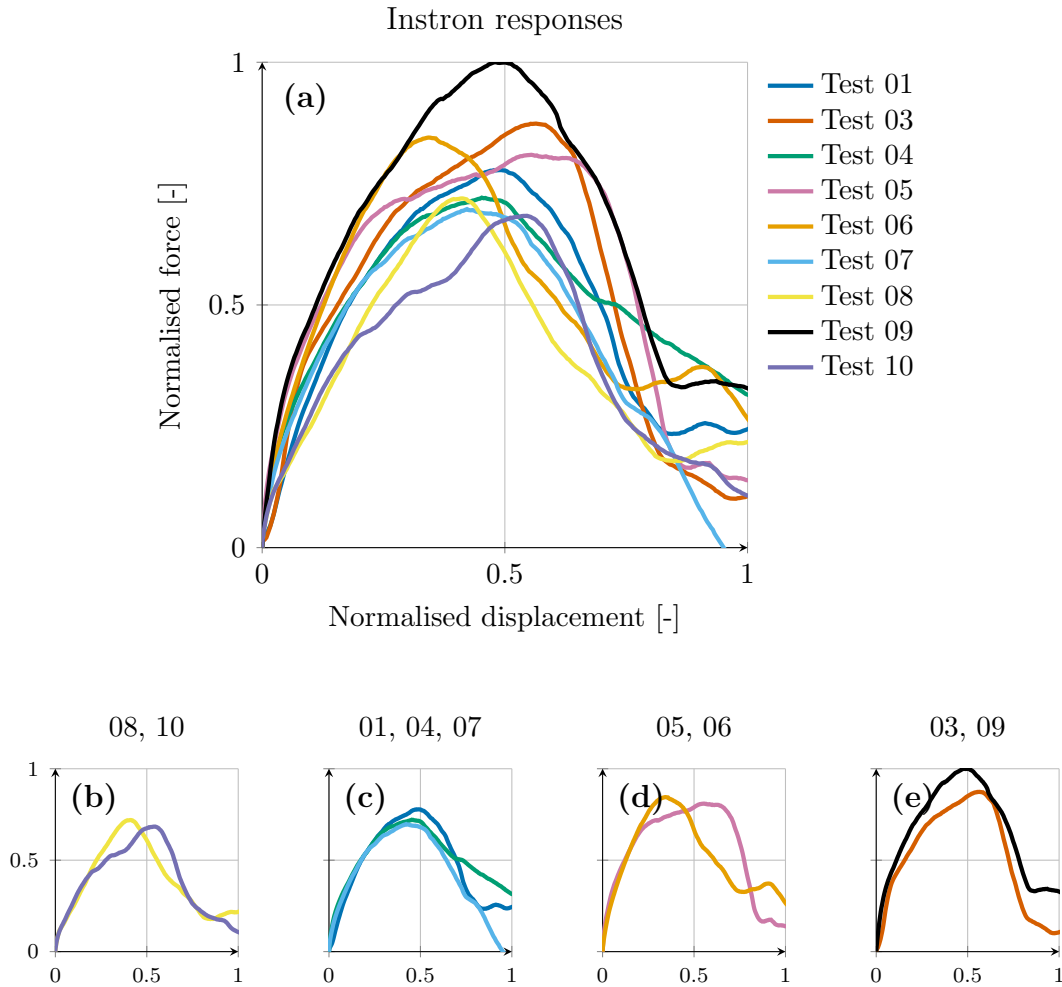


Figure 4.3: Normalised force-displacement curves for the Instron tests. The complete set of curves is shown in the upper plot, while visually identified response groups are shown below.

4.2.2 MTS machine

Figure 4.4 shows the normalised force-displacement curves obtained using the MTS machine with a loading rate of 5 mm/min. The curves show variation in both the initial

slope and the shape of the response around the maximum force. Some specimens reach a peak followed by a reduction in force, while others show a more irregular response.

Compared with the Instron results, the MTS curves show the same general behaviour, with an initial linear force increase followed by non-linear pull-out. The variation between individual specimens remains large, and some curves show indications of double-peaking more prominently than for the Instron, and are therefore grouped together.

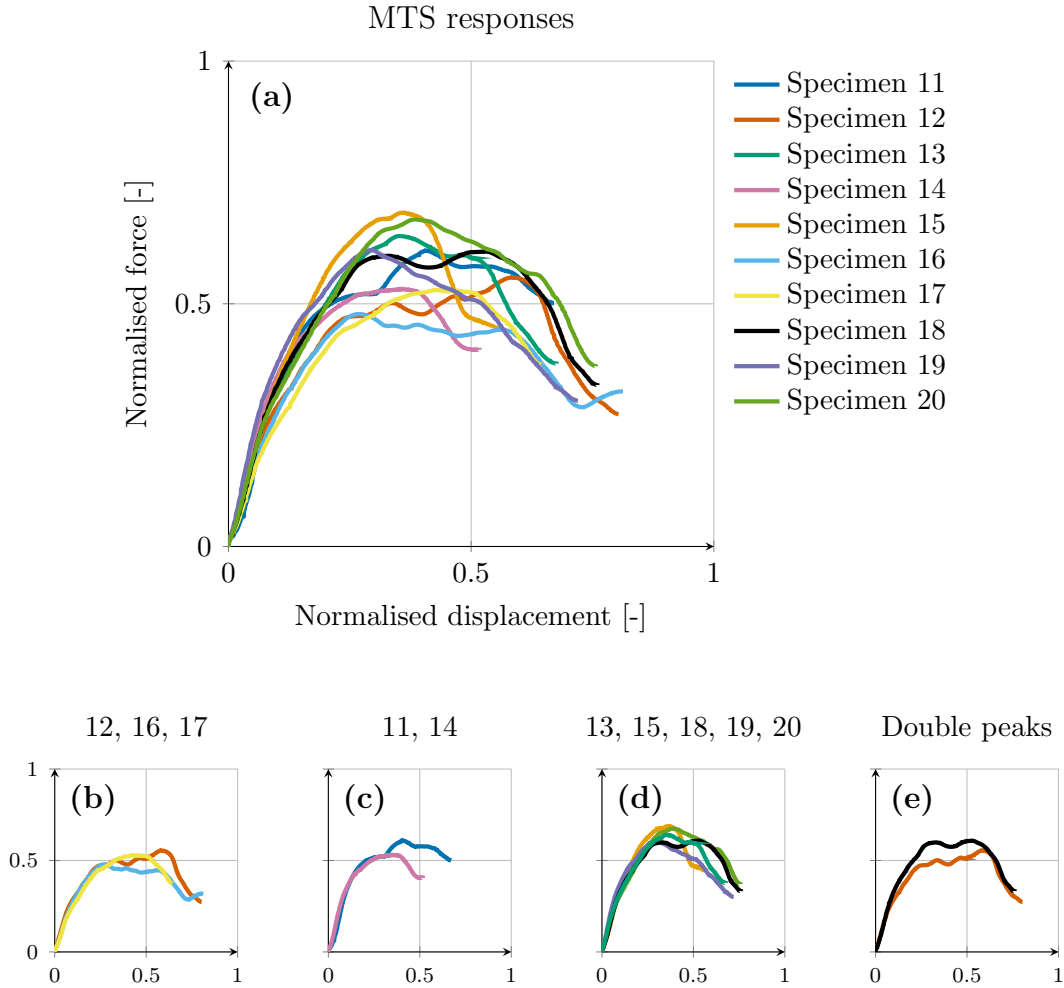


Figure 4.4: Normalised force-displacement curves for the MTS tests. The complete set of curves is shown in the upper plot, while visually identified response groups are shown below.

4.2.3 Pull-out rig

Figure 4.5 shows the normalised force-displacement curves obtained using the pull-out rig with a loading rate of 1 mm/min. The responses show clear variation in both curve shape and maximum force, where several curves show multiple local peaks. For this test group, some curves are categorised as double-peaked because they show two local maxima, suggesting that the pull-out resistance can develop in more than one stage.

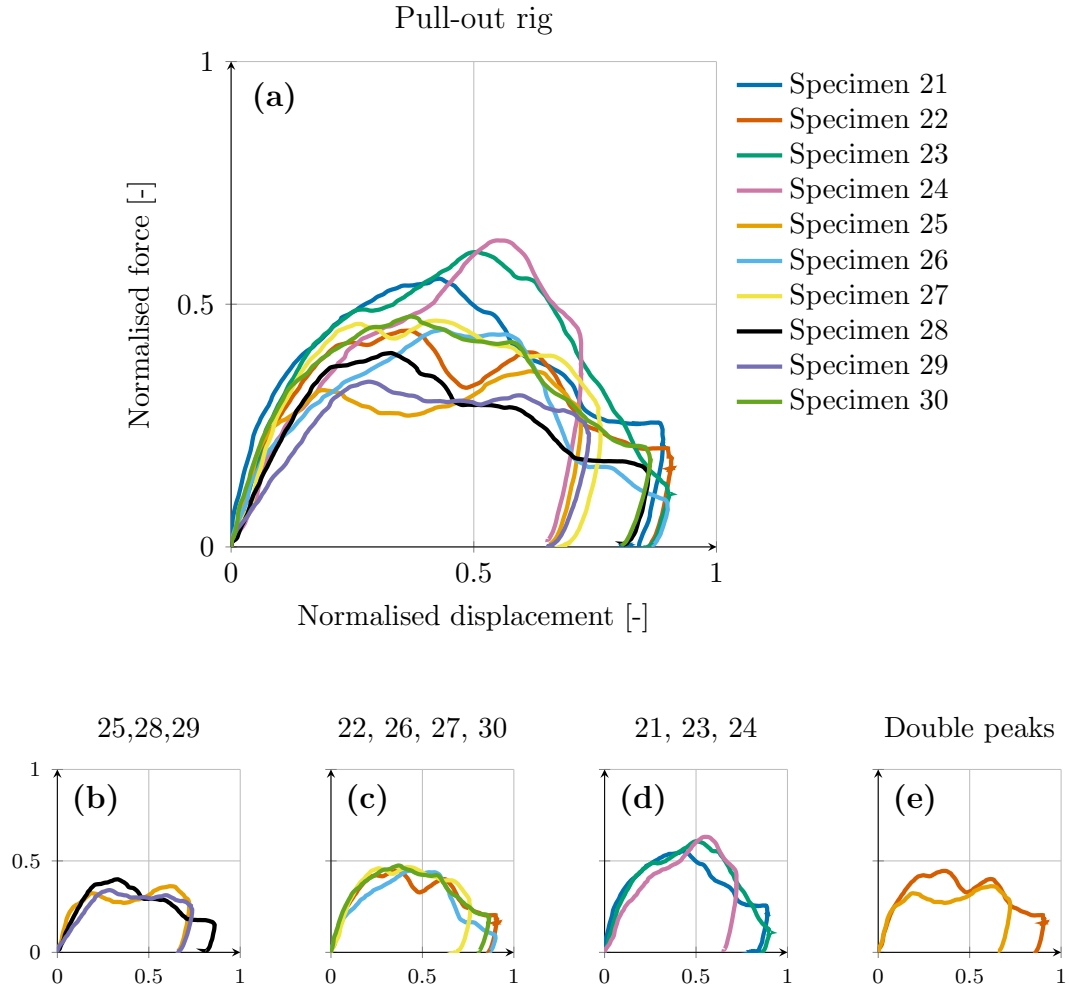


Figure 4.5: Normalised force-displacement curves for the pull-out rig tests. The complete set of curves is shown in the upper plot, while visually identified response groups are shown below.

4.2.4 In-situ mechanical tests

The normalised in-situ pull-out responses are shown in Figure 4.6. These specimens were loaded incrementally, with interruptions at selected stages to allow μ CT imaging. During each interruption, the displacement was held constant while the specimen was scanned. The measured response, therefore, includes the pull-out behaviour, the influence of incremental loading, and relaxation seen each time that the loading was paused for the μ CT. Specimen 31 has been removed because it was primarily used to determine the intervals at which loading should be performed. As a result, it does not follow the same procedure as specimens 32 and 33 and is therefore not comparable.

The two in-situ specimens show the same general response as the continuous pull-out rig tests, but the incremental loading procedure appears to affect the curve shape by reducing the peak force. The comparison of incremental and continuous loading is illustrated in Figure 4.7.

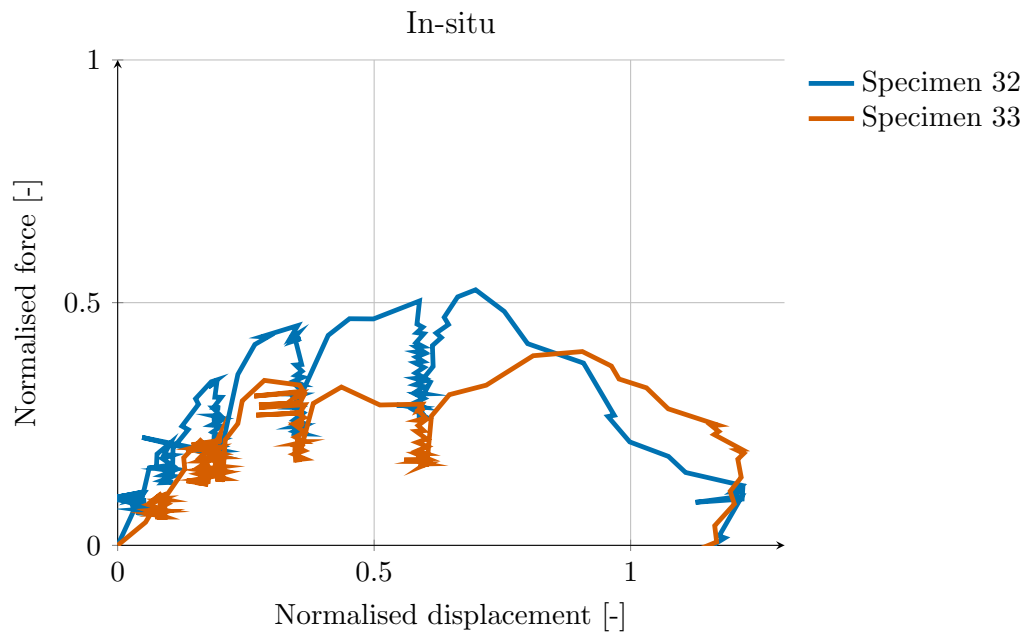


Figure 4.6: Normalised force-displacement responses for the in-situ pull-out tests.

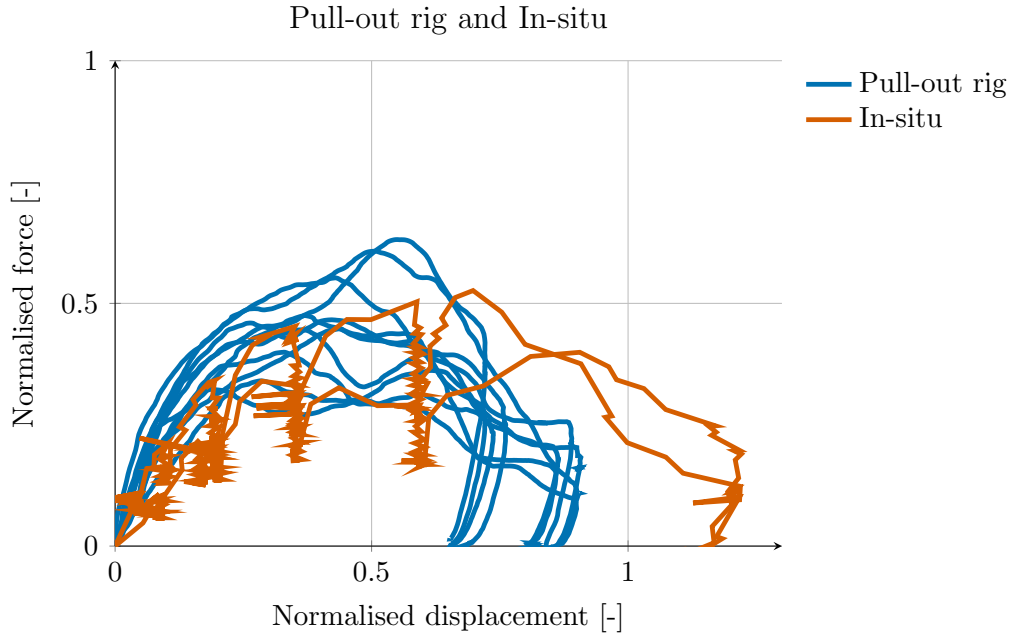


Figure 4.7: Comparison of the normalised force-displacement responses for the continuous pull-out rig tests and the in-situ tests.

4.2.5 Comparison of testing setups

The average force-displacement curves for the Instron, MTS, and pull-out rig tests are compared in Figure 4.8. The individual curves are shown in grey for each test type to indicate the spread within each group. As previously mentioned, all test configurations show the same general response with an initial linear increase in force, followed by a non-linear region, a maximum force, and a subsequent reduction in resistance. However, the average curve shape and maximum force differ between the testing systems. Since the tests were performed at different displacement rates, part of this difference may be associated with rate-dependent behaviour in addition to differences in the test setups.

The rate dependence of the normalised maximum force is shown in Figure 4.9, where the loading rates correspond to those listed in Table 3.3. The results show that the measured maximum force changes between test groups. However, the loading rate is not the only difference between the tests. The Instron, MTS, and pull-out rig also differ in load-cell capacity, machine stiffness, and configuration.

The mean maximum force and standard deviation for each test type are shown in Figure 4.10. The standard deviations show that there is considerable variation within each test group.

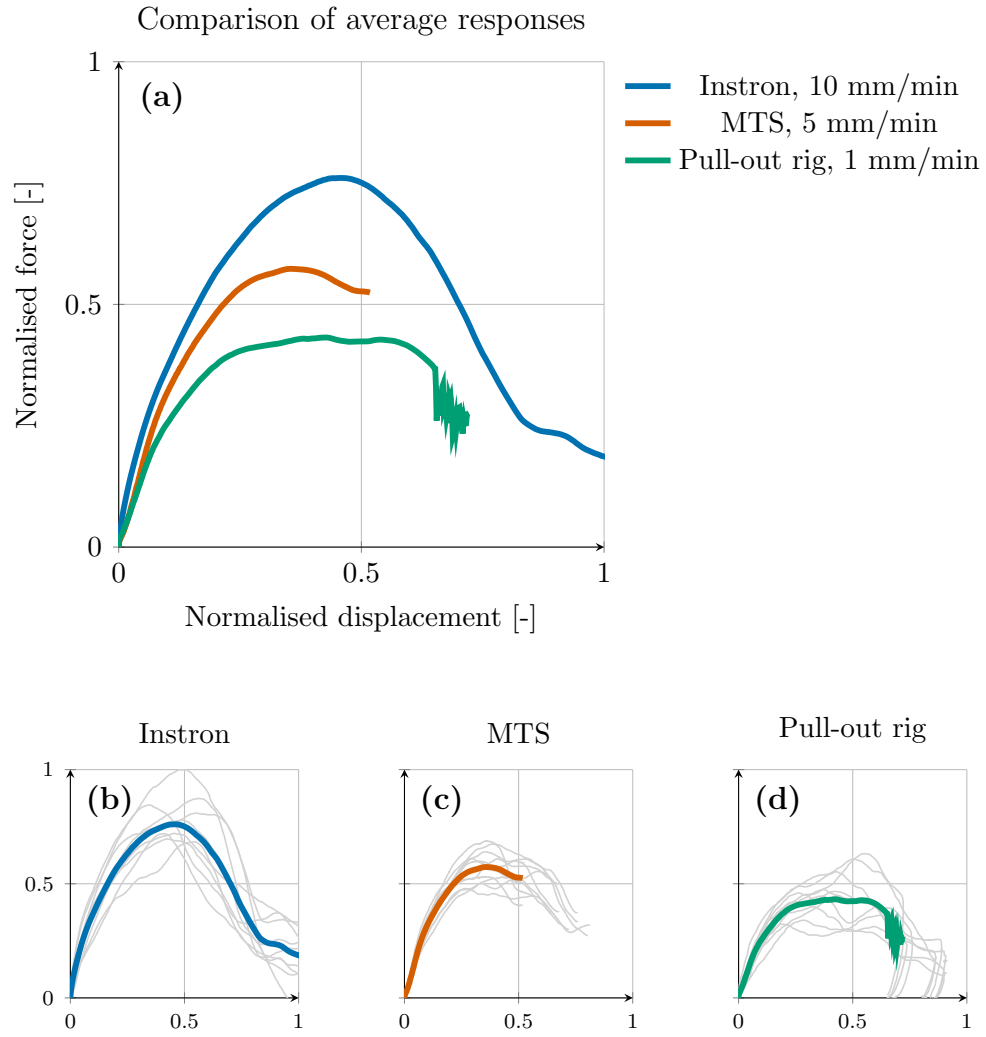


Figure 4.8: Comparison of the normalised average force-displacement curves for the Instron, MTS, and pull-out rig tests. The tests were performed at different displacement rates. The upper plot shows the average curves, while the lower plots show the individual curves in grey together with the corresponding average curve for each test type.

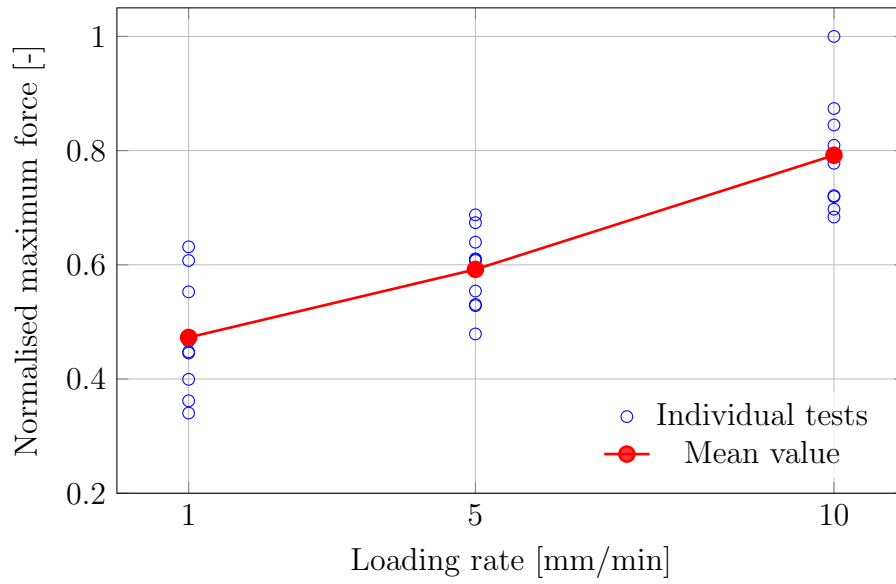


Figure 4.9: Rate dependency of the normalised maximum pull-out force, where 1 mm/min corresponds to the pull-out rig tests, 5 mm/min corresponds to the MTS tests, and 10 mm/min corresponds to the Instron tests.

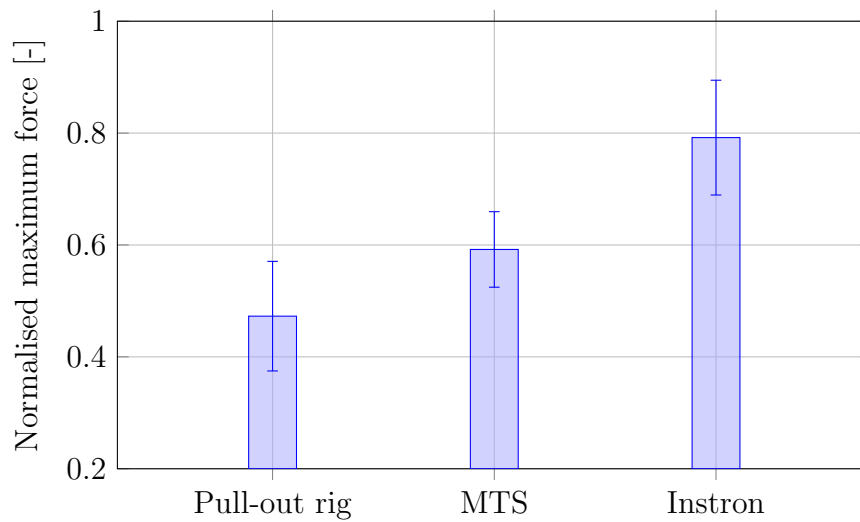


Figure 4.10: Comparison of the normalised maximum pull-out force for the pull-out rig, MTS, and Instron tests. The mean value and standard deviation are shown.

4.2.6 Half-term relaxation

Figure 4.11 shows the normalised force-displacement curves for the half-term relaxation specimens pulled out with the pull-out rig with a rate of 1 mm/min. The curves show that the response varies between specimen, but similar initial response shapes can be identified and grouped. Specimen 04 was excluded from the analysis due to an error in the force measurement. The recorded response contained a large initial offset, resulting in force values that were consistently higher than those measured for the other specimens, while the overall curve shape remained similar.

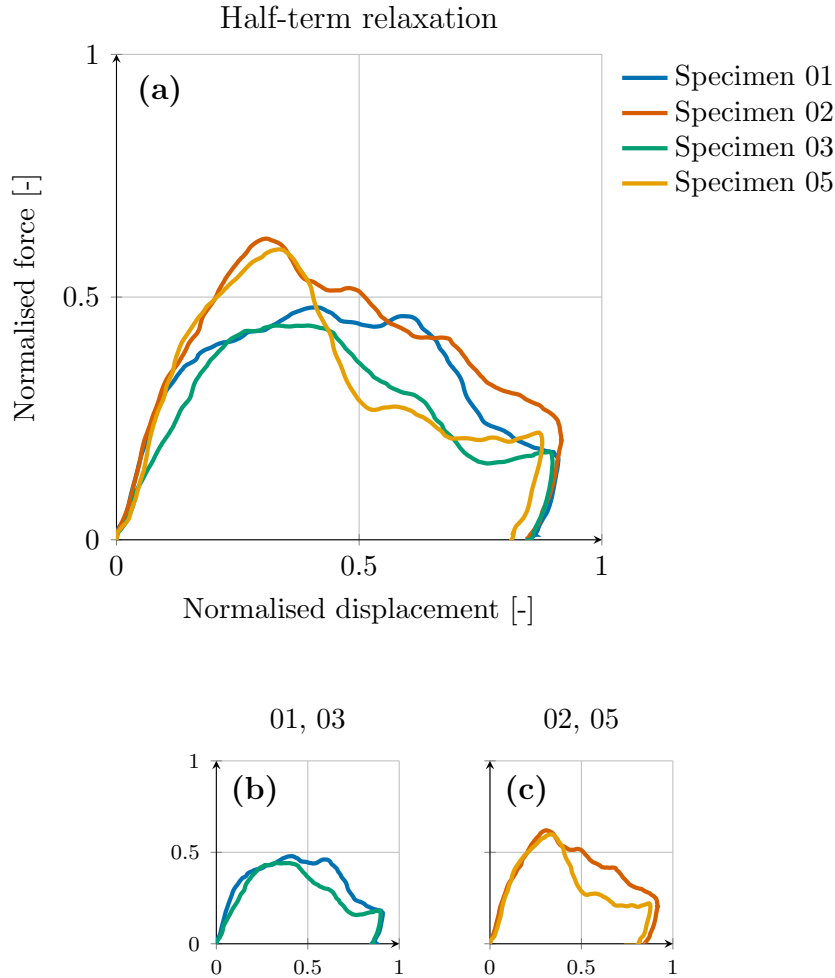


Figure 4.11: Normalised force-displacement curves for the half-term relaxation tests. The complete set of curves is shown in the upper plot, while visually identified response groups are shown below.

4.2.7 Full-term relaxation

Figure 4.12 shows the normalised force-displacement curves for the full-term relaxation specimens pulled out with the pull-out rig with a rate of 1 mm/min. The overall response is similar to the half-term group, with an initial increase in force followed by a maximum and post-peak reduction. The grouped plots indicate that some specimens have similar response shapes.

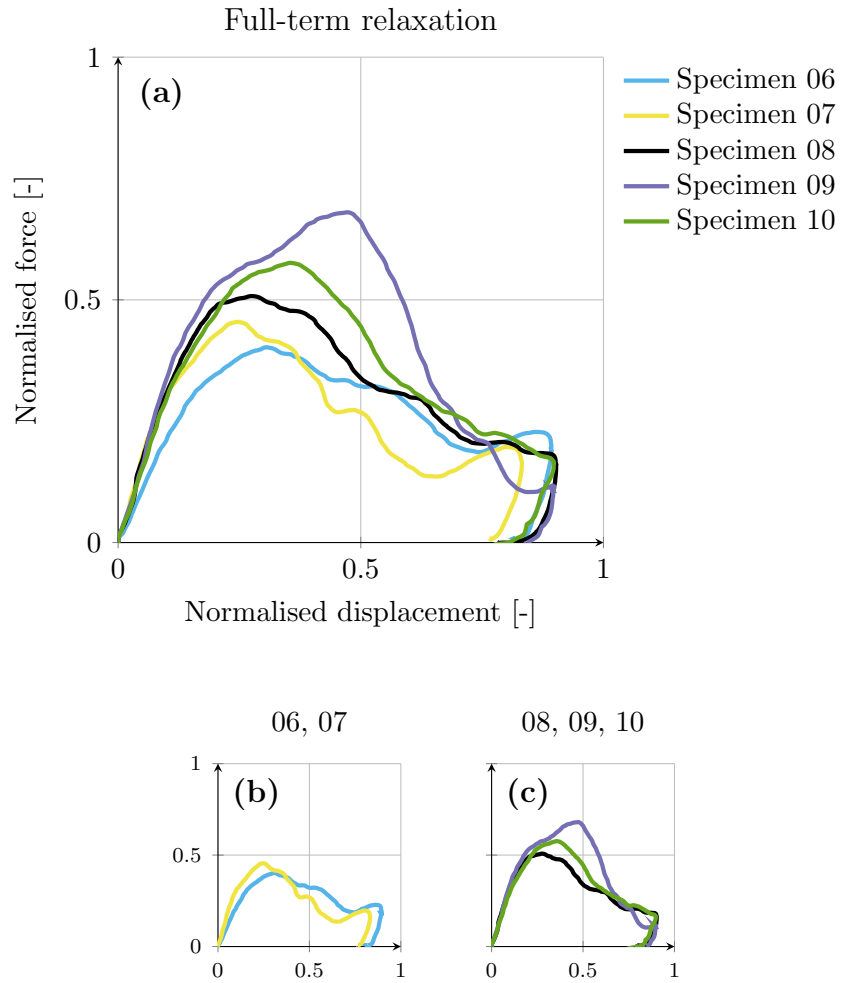


Figure 4.12: Normalised force-displacement curves for the full-term relaxation tests. The complete set of curves is shown in the upper plot, while visually identified response groups are shown below.

4.2.8 Relaxation comparison

The average responses of the half-term, full-term, and non-relaxed pull-out rig specimens are compared in Figure 4.13, which are all pulled out with the same setup and rate of 1 mm/min. The individual curves are also shown in grey to illustrate the spread within each group. The average curves show that the relaxed specimens have a similar general force-displacement behaviour to the pull-out rig specimens, although differences can be seen in maximum force level.

The maximum force comparison in Figure 4.14 shows the mean value and standard deviation for each group. The half-term and full-term relaxation groups are close to each other. This indicates that the difference between the two relaxation periods is small relative to the variation observed in the tests.

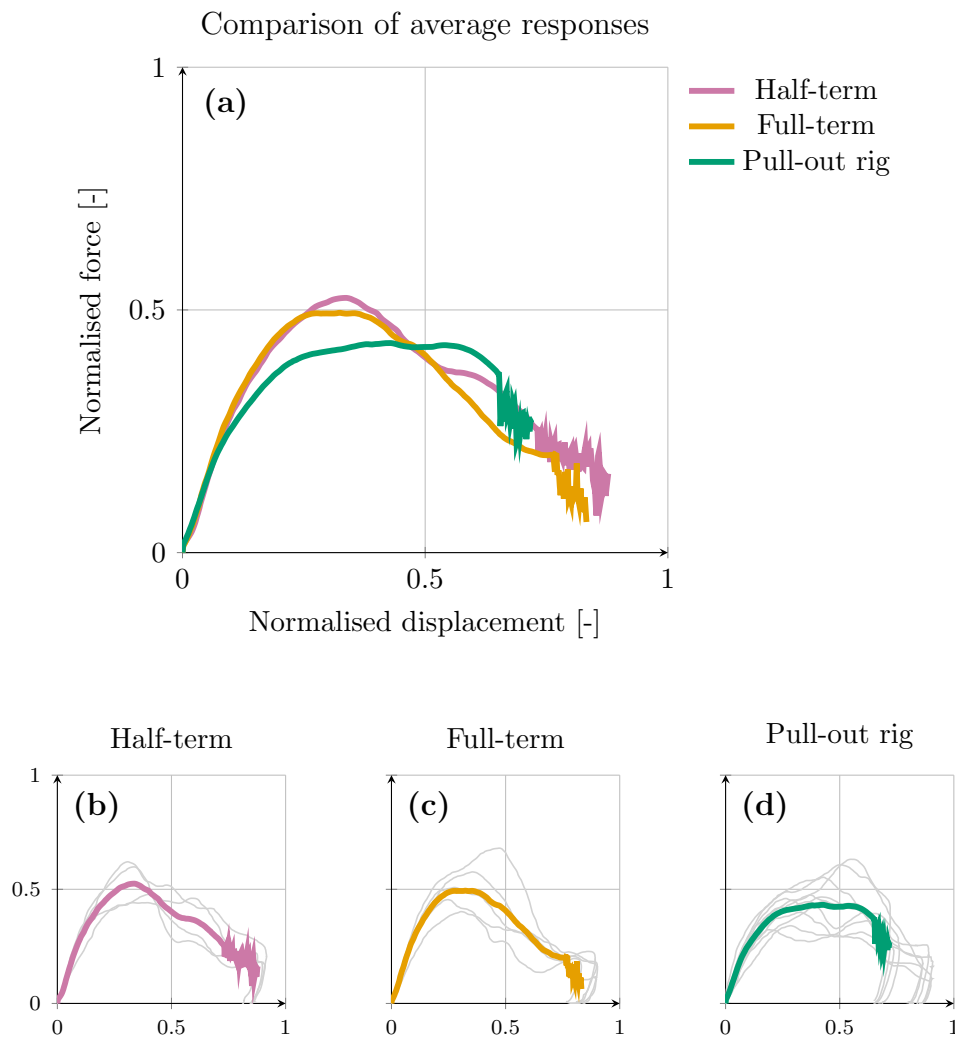


Figure 4.13: Comparison of the normalised average force-displacement curves for the half-term relaxation, full-term relaxation, and pull-out rig tests. The upper plot shows the average curves, while the lower plots show the individual normalised curves in grey together with the corresponding average curve for each test type.

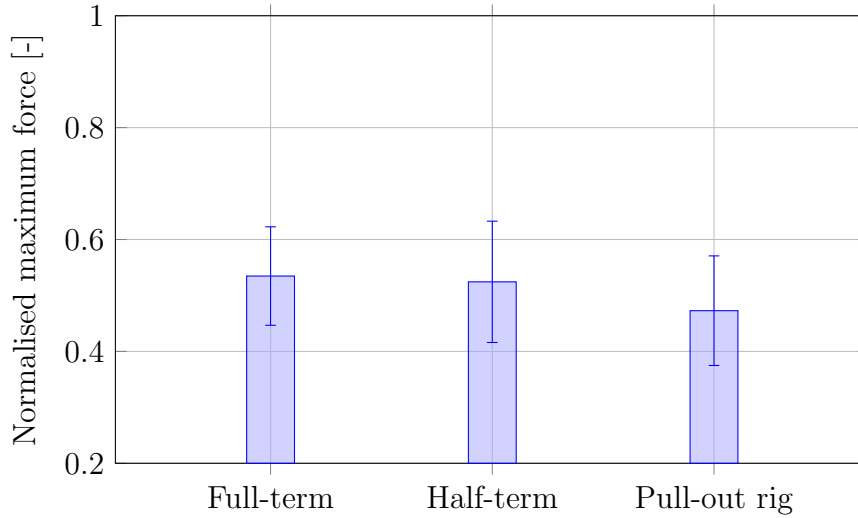


Figure 4.14: Comparison of the normalised maximum pull-out force for the half-term relaxation, full-term relaxation, and pull-out rig tests. The mean value and standard deviation are shown.

4.3 Tomography and DVC

The tomography and DVC results are used to examine the internal response of selected specimens during assembly, relaxation, and pull-out. The DVC results quantify the internal displacement and strain fields, making it possible to identify where deformation is concentrated and how it evolves during loading.

The results in this section include tomographic images, displacements, deviatoric strain, and volumetric strain. These are represented using different colours, indicated by the colour bars beneath the respective data. The colour bars follow the values and colour scales shown in Table 3.4.

For the tomographic images, white represents high attenuation, while black represents low attenuation. For the displacement data, red represents a positive value, corresponding to movement towards the bottom edge of the resliced view and into the page in the original views. Conversely, blue represents movement towards the top edge, which is the same direction in which the dowel is pulled. In the original view, this corresponds to movement out of the page. The deviatoric strain data show high strains as bright colours, while zero strain is represented by darker colours, since deviatoric strain cannot be negative. The volumetric strain can be either positive or negative, with bright colours representing positive values and dark colours representing negative values.

This section first presents the variation in the resulting data and explains the criteria used to select the data considered most relevant to the thesis. The selected data are then presented to illustrate the internal response of the specimens and support the subsequent analysis.

4.3.1 Data

The acquired μ CT data and DVC results were processed, and the images presented were selected to represent the results clearly. Images not shown were excluded based on the following considerations.

Figure 4.15 shows the μ CT data for the empty specimen, the dowel inserted, and the pin inserted for specimen 01. Small differences in the specimen's appearance between scans are due to remounting between image acquisitions, which resulted in slight changes in specimen orientation. In addition, because the specimen was rotated, reslicing had to be performed manually. Therefore, the sections shown do not correspond to the same angle. The images with the inserted dowel, shown in Figure 3.2b, present the position of the dowel before expansion but provide limited additional information when viewed together with Figures 4.15a and 4.15c. They are therefore not included in the subsequent result presentations.



Figure 4.15: μ CT slices of specimen 01 empty, with dowel, with pin.

The DVC results were filtered and corrected for rigid-body motion before further analysis. A comparison of these processing steps is illustrated in Figure 4.16 for specimen 33 and load step 1. The raw displacement field contains unwanted contributions from noise and rigid-body motion. Filtering reduces outliers and makes the displacement pattern more continuous. The high positive values observed around parts of the specimen circumference represent erroneous boundary correlations rather than physical displacement. The rigid-body correction removes the global motion component so that the remaining field more clearly represents deformation of the specimen. The corrected displacement fields were used for the subsequent analysis and are illustrated in Figure 4.16c.

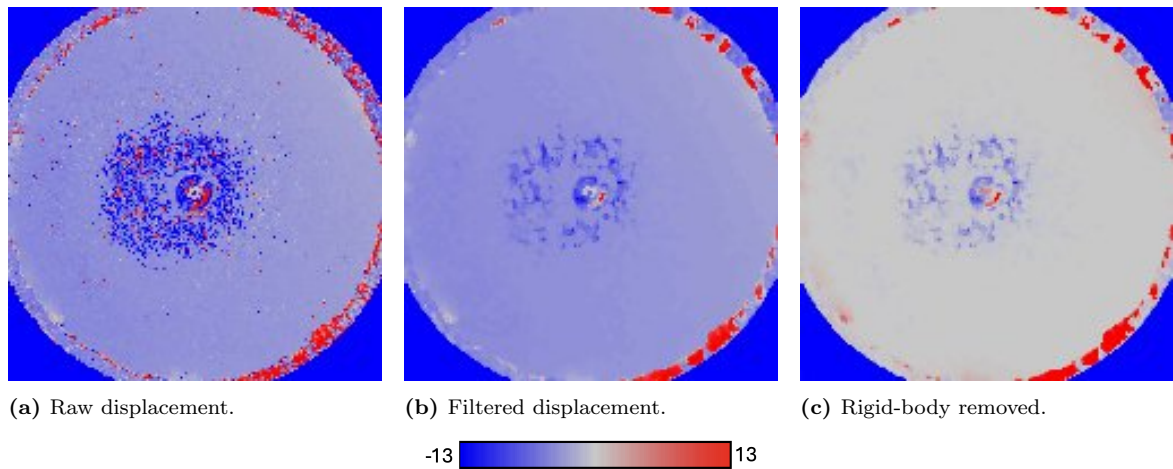


Figure 4.16: Comparison of the vertical displacement field before filtering, after filtering, and after removal of rigid-body motion from specimen 33 and load step 1.

Example displacement fields obtained from the DVC analysis are shown in Figure 4.17 for specimen 33 and load step 1. The radial, transverse, and Cartesian displacement components are presented in both cross-sectional and resliced views. The radial and transverse components were calculated to describe the displacement relative to the circular specimen geometry, while the Cartesian components describe displacement in the original image coordinate system. However, the radial, transverse, u_x , and u_y fields contained substantial noise in relation to displacement magnitude and were therefore not studied. The vertical displacement component, u_z , showed the most meaningful results for further analysis.

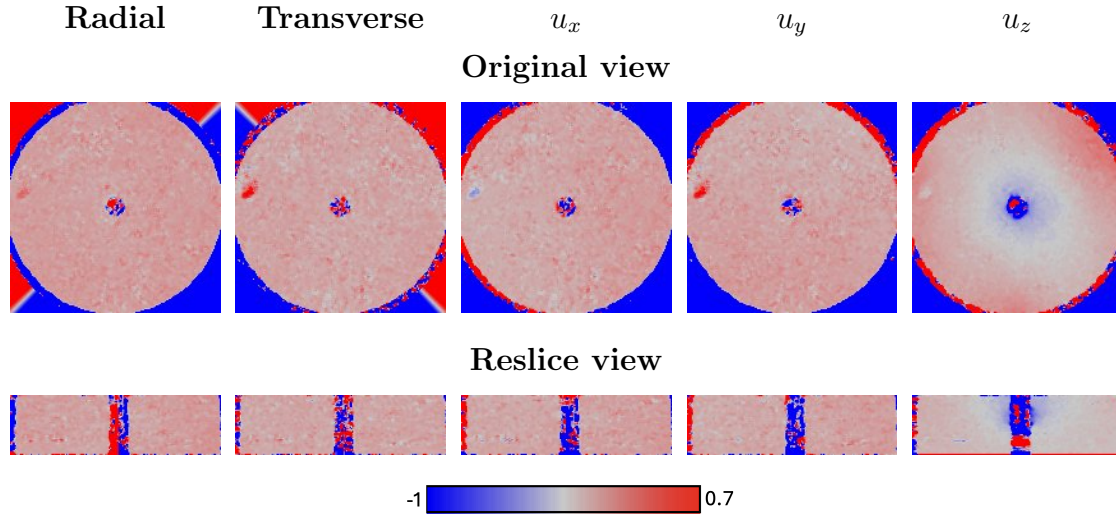


Figure 4.17: Comparison of displacement fields after filtering and rigid-body removal from specimen 33 and load step 1. The upper row shows cross-sectional views, while the lower row shows the corresponding resliced views. Each column represents the same displacement component.

The DVC showed that the deformation can be considered to have two principal directions, parallel to the dowel teeth or orthogonal to the dowel teeth. Slices parallel to the teeth were selected for the main analysis, as illustrated in Figure 4.18 of specimen 33 load step 1. This direction shows the tooth geometry and its interaction with the particleboard more clearly.

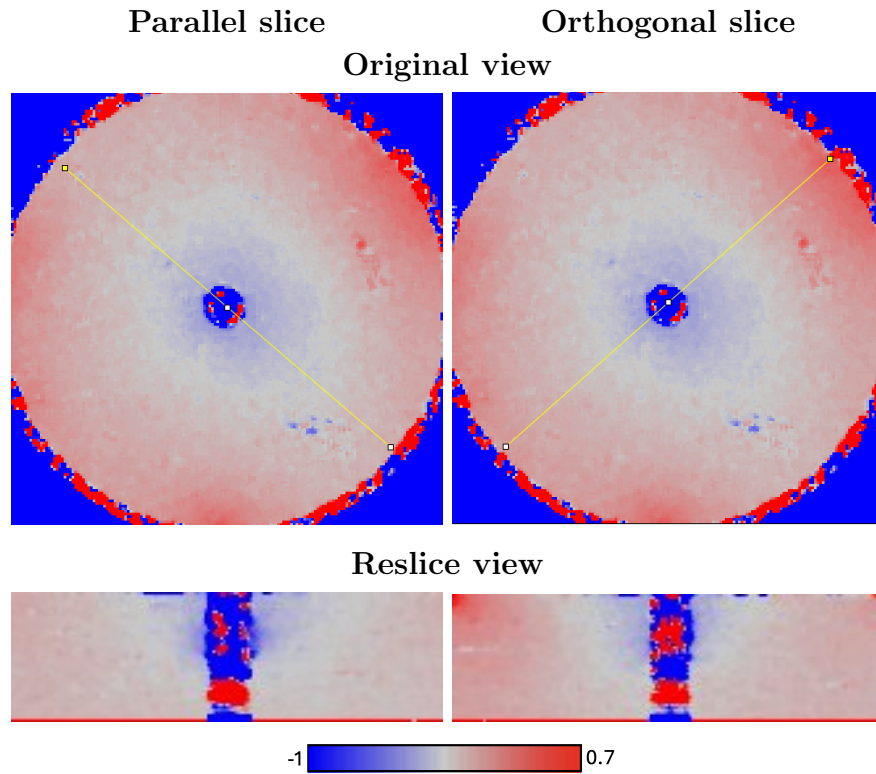


Figure 4.18: Reference images and corresponding original and resliced views used for visual comparison from specimen 33 and load step 1. Each column represents the same image before and after reslicing.

The specimens selected for DVC analysis were chosen based on mechanical response and DVC quality. The aim was to include representative results from different force-displacement response types, while excluding results of poor correlation quality. The quality varied between specimens, particularly for the MTS tests, since these specimens were removed and remounted between scans. Small differences in positioning resulted in issues with registration and correlation. An example of this is shown for specimen 18 in Figure 4.19a. As a result, two MTS subgroups were not represented in the selected results.

For the relaxation specimens, the DVC step between assembly and the scan before pull-out was excluded, due to the movement between these two stages being very small. This caused the resulting displacement field to be dominated by noise rather than deformation. An example of this behaviour is shown for specimen 02 in Figure 4.19b. The following results, therefore, focus on the DVC results where the deformation field could be interpreted properly.

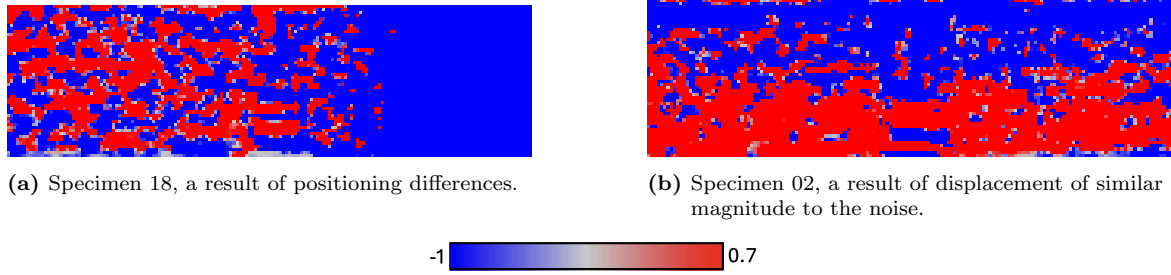


Figure 4.19: Examples of low quality displacement fields caused by positioning differences and by displacements of similar magnitude to the noise.

4.3.2 Tomography and DVC results for selected specimens

The following figures present tomography and DVC results for selected specimens. The selected specimens include two half-term relaxation specimens (02, 03), two full-term relaxation specimens (06, 08), one MTS specimen (11), three pull-out rig specimens (21, 27, 29) and two in-situ specimens (32, 33).

For each specimen, the tomography images show the internal structure, while the displacement and strain fields show the change between scan stages. The results are presented as qualitative visualisations of where deformation occurs and how it develops. The displacement fields indicate the direction and relative magnitude of material movement, while the volumetric and deviatoric strain fields indicate regions of volume change and shape-changing deformation.

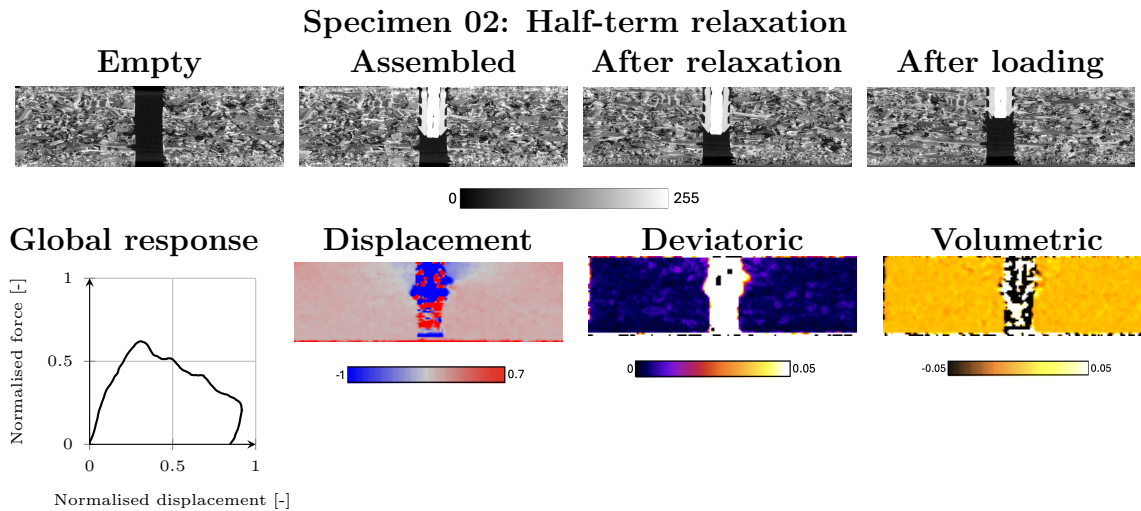


Figure 4.20: Tomographic images, normalised force-displacement response, displacement field, deviatoric strain field, and volumetric strain field for specimen 02. The tomography sequence shows the specimen before assembly, after assembly, after relaxation, and after loading, while the field results correspond to the step during loading.

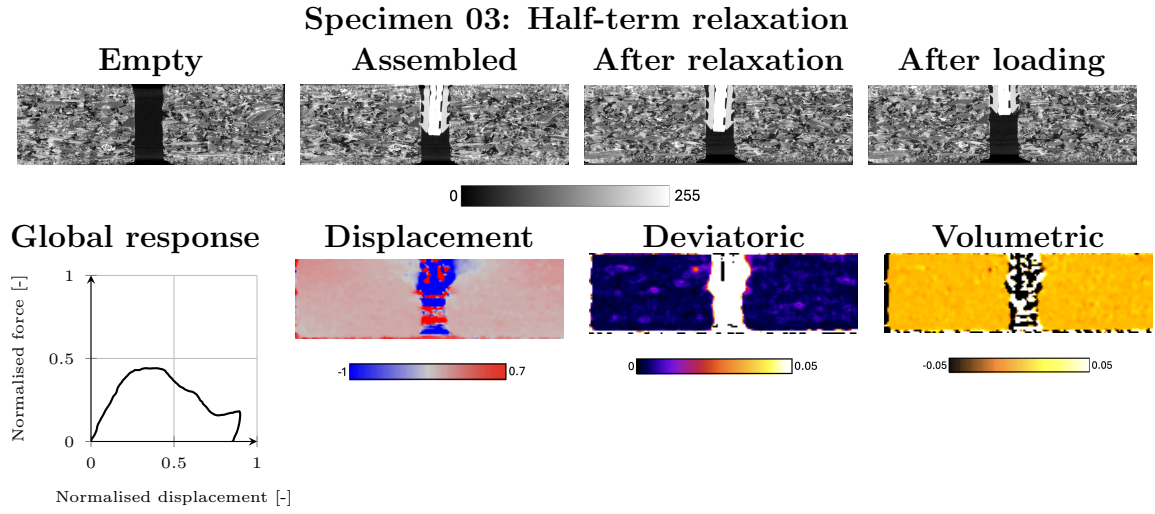


Figure 4.21: Tomographic images, normalised force-displacement response, displacement field, deviatoric strain field, and volumetric strain field for specimen 03. The tomography sequence shows the specimen before assembly, after assembly, after relaxation, and after loading, while the field results correspond to the step during loading.

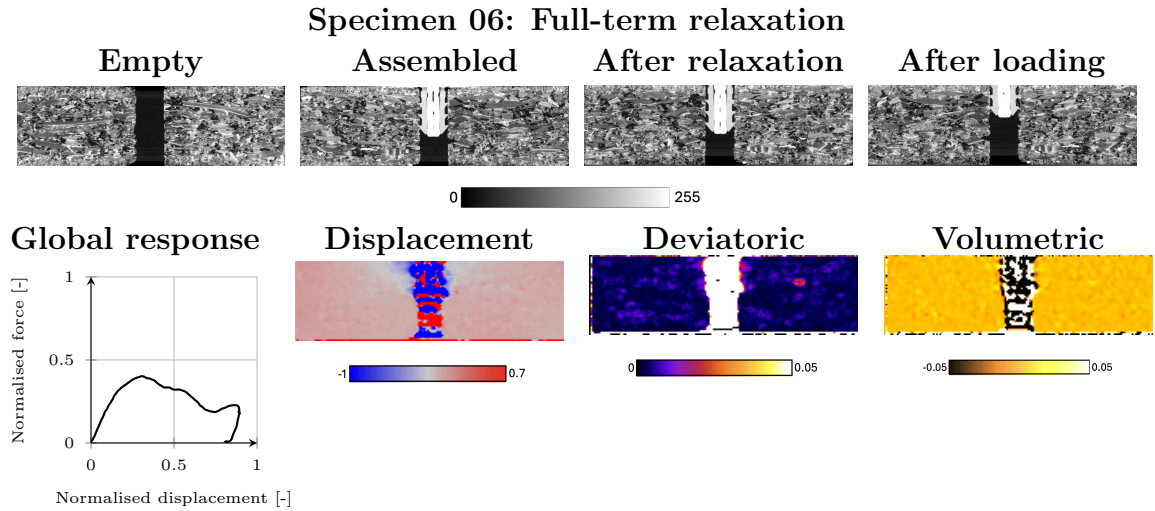


Figure 4.22: Tomographic images, normalised force-displacement response, displacement field, deviatoric strain field, and volumetric strain field for specimen 06. The tomography sequence shows the specimen before assembly, after assembly, after relaxation, and after loading, while the field results correspond to the step during loading.

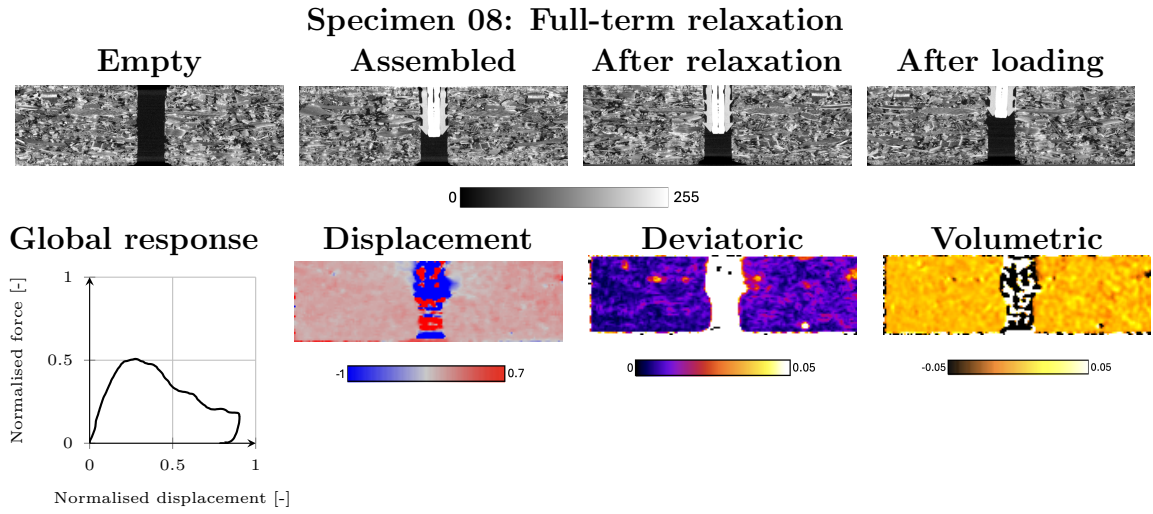


Figure 4.23: Tomographic images, normalised force-displacement response, displacement field, deviatoric strain field, and volumetric strain field for specimen 08. The tomography sequence shows the specimen before assembly, after assembly, after relaxation, and after loading, while the field results correspond to the step during loading.

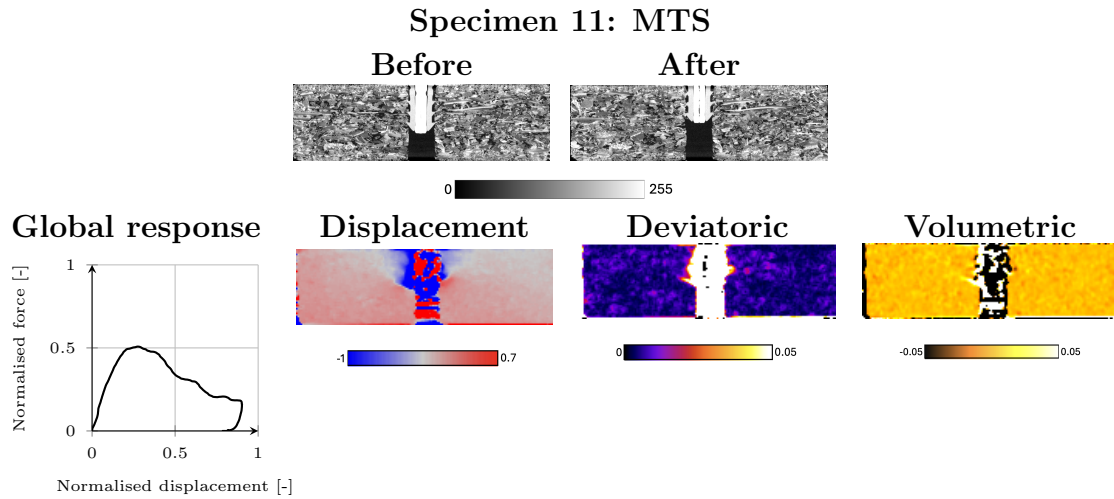


Figure 4.24: Tomographic images, normalised force-displacement response, displacement field, deviatoric strain field, and volumetric strain field for specimen 11. The tomography images show the specimen before and after loading, while the field results correspond to the step during loading.

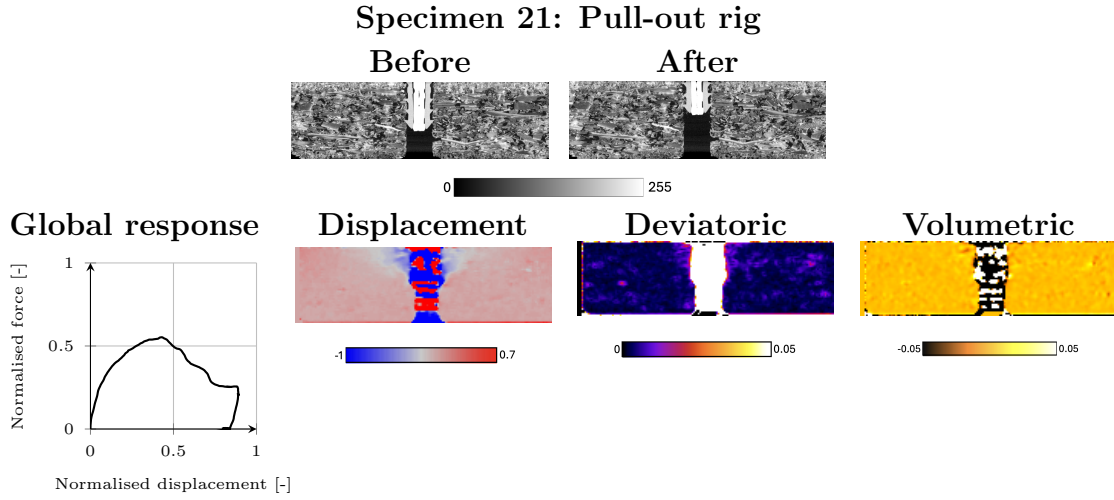


Figure 4.25: Tomographic images, normalised force-displacement response, displacement field, deviatoric strain field, and volumetric strain field for specimen 21. The tomography images show the specimen before and after loading, while the field results correspond to the step during loading.

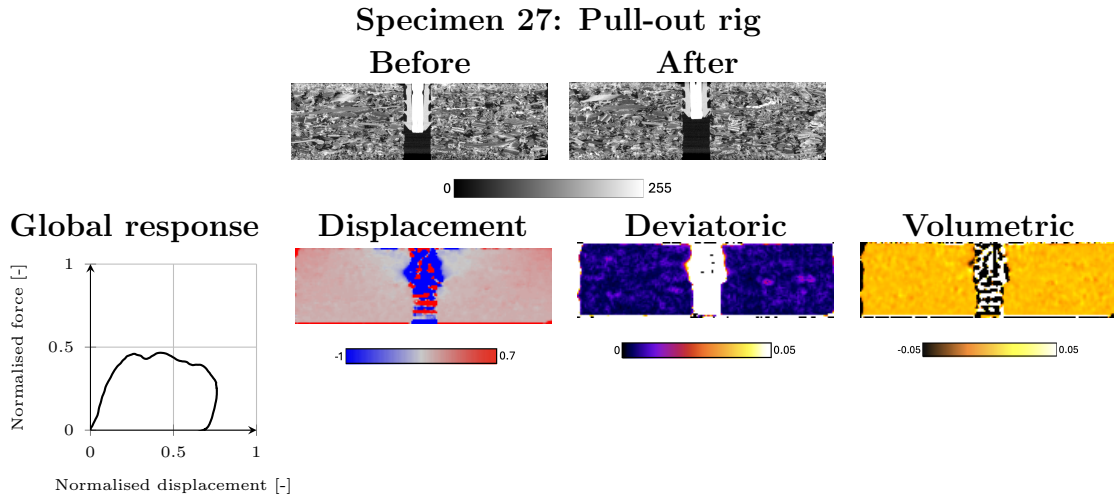


Figure 4.26: Tomographic images, normalised force-displacement response, displacement field, deviatoric strain field, and volumetric strain field for specimen 27. The tomography images show the specimen before and after loading, while the field results correspond to the step during loading.

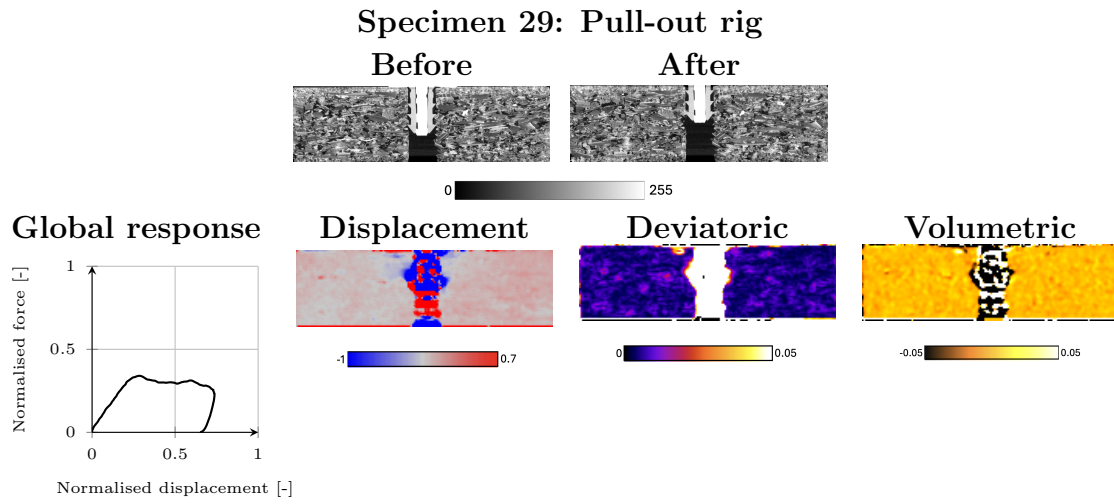


Figure 4.27: Tomographic images, normalised force-displacement response, displacement field, deviatoric strain field, and volumetric strain field for specimen 29. The tomography images show the specimen before and after loading, while the field results correspond to the step during loading.

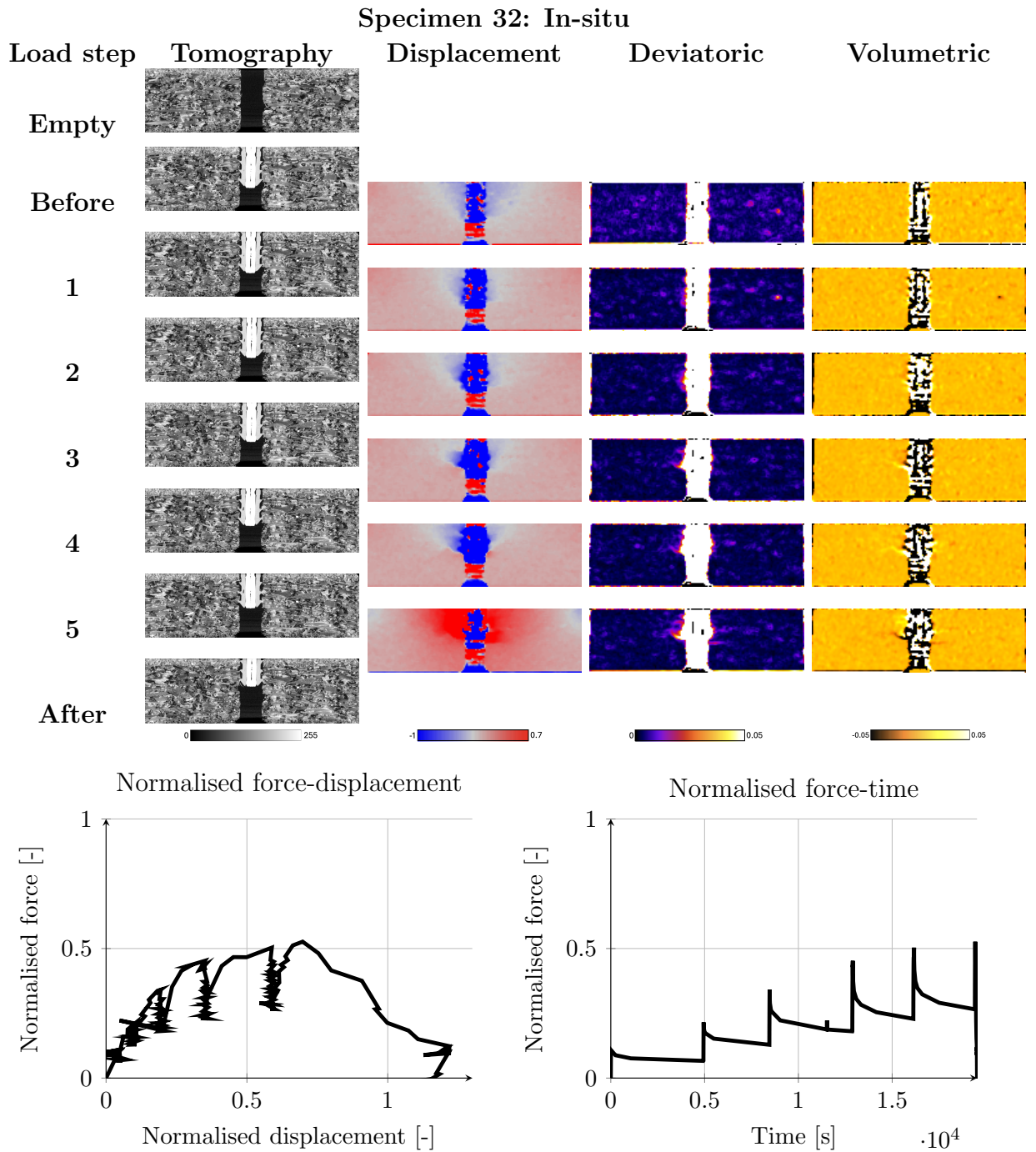


Figure 4.28: Tomographic images, displacement fields, deviatoric strain fields, and volumetric strain fields for each load step of specimen 32. The lower plots show the normalised force-displacement and force-time responses.

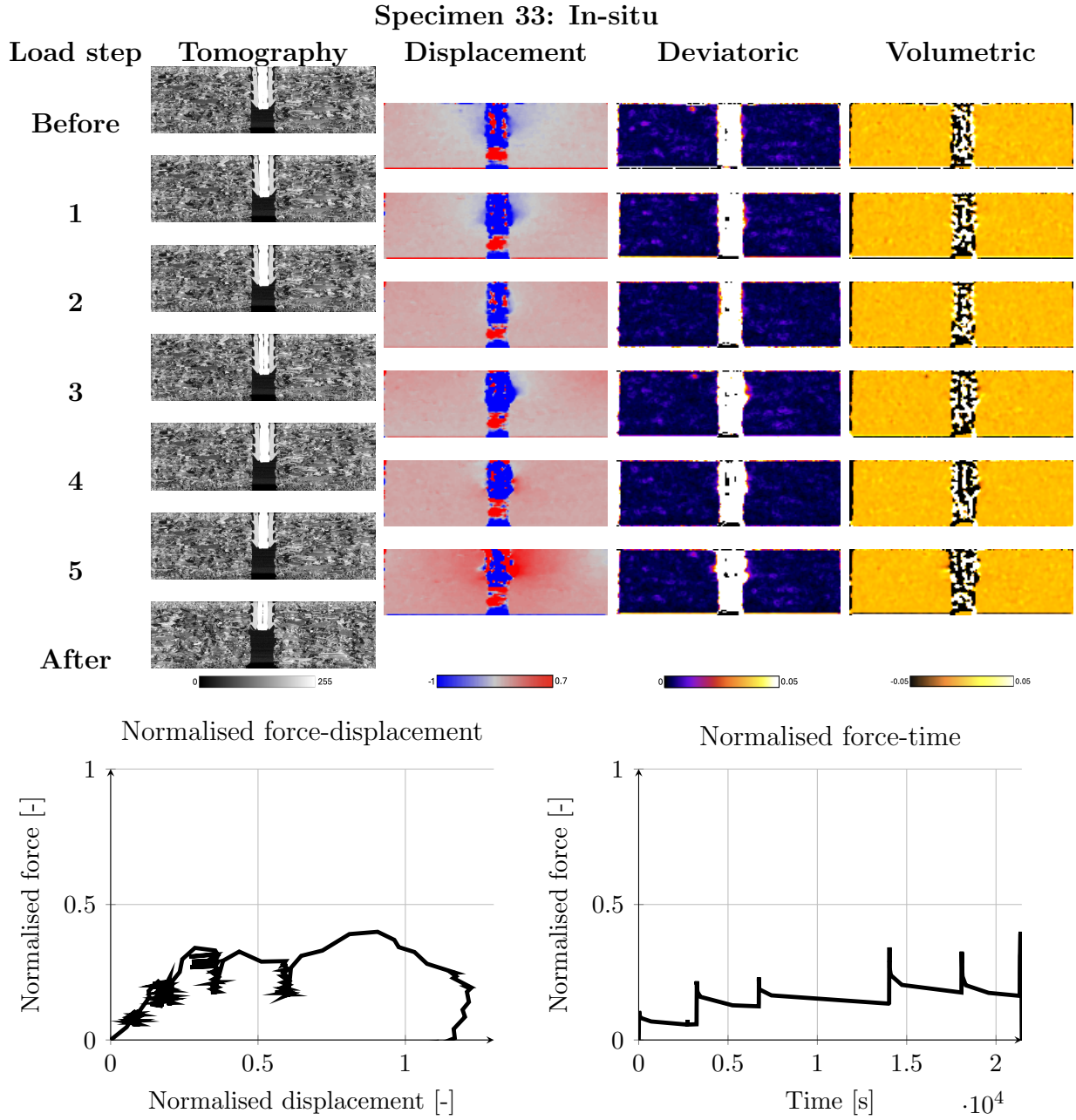


Figure 4.29: Tomographic images, displacement fields, deviatoric strain fields, and volumetric strain fields for each load step of specimen 33. The lower plots show the normalised force-displacement and force-time responses.

4.3.3 Displacement profiles

The profiles of the vertical displacement were extracted from specimen 32 to compare local changes around the dowel during the in-situ loading sequence. Three profile heights were selected, one at each tooth. For each height, the figure shows the profile location and a view of the profile. The colour gradient represents the loading sequence, with lighter curves corresponding to earlier loading steps and darker curves corresponding to later loading steps. A negative value indicates movement towards the top edge of the μ CT image, which corresponds to the direction of pull-out. The final step is missing for the lowest tooth because the data were scaled differently and are therefore not comparable.

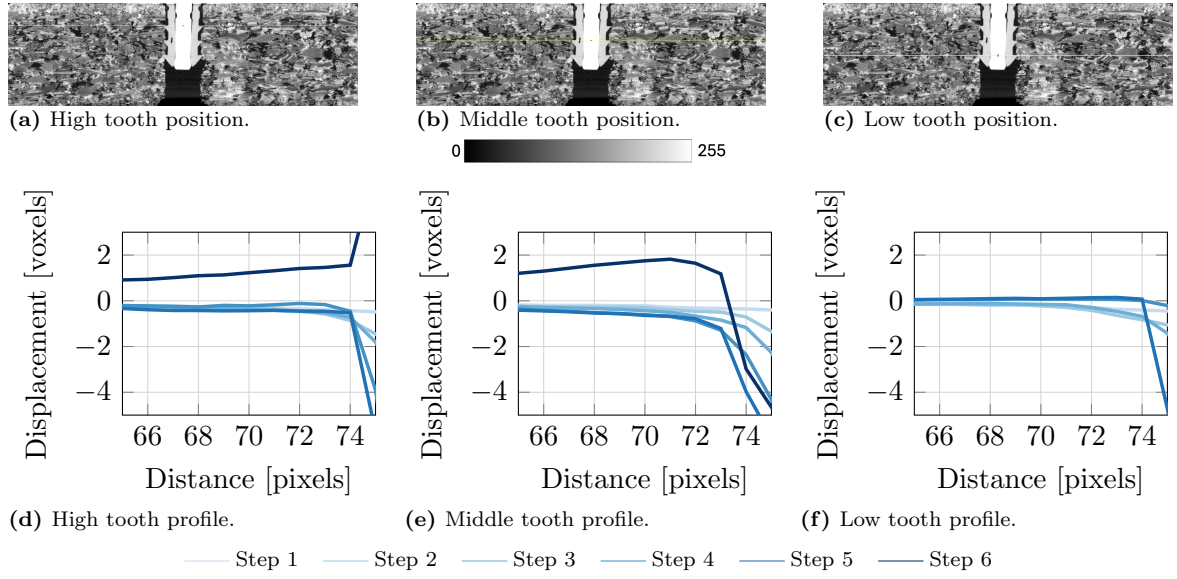


Figure 4.30: The top row shows the profile-line locations, while the bottom row shows the corresponding vertical displacement profiles for the high, middle, and low tooth positions.

5 Discussion and conclusions

This chapter discusses the main findings of the study. The discussion focuses on how the global force-displacement response is governed by local interactions and how material heterogeneity and the test setup influence the measured response. It also examines how μ CT and DVC can be used to interpret deformation mechanisms that are not visible from mechanical testing alone. The implications of these findings for product development, future experimental work, and variability are also discussed. Finally, conclusions are drawn based on the analysis.

5.1 Interpreting the results

The results are interpreted by linking the measured global response to the internal structure and deformation observed in the tomography and DVC data. The force-displacement curves provide information about the overall pull-out resistance, while the μ CT images and DVC fields provide insight into how this resistance develops locally around the dowel. The following sections, therefore, discuss the material structure, global mechanical response, specimen-specific observations, displacement profiles, and general deformation mechanisms as connected parts of the same pull-out process.

5.1.1 Material structure and local tooth engagement

A critical aspect of evaluating the pull-out response of the particleboard is the structural variation within each specimen. The board has dense outer layers and a less dense core, as illustrated in Figure 4.1. In addition to this layered structure, the particle density also varies locally within each layer and between specimens. The ability to transfer load from the dowel to the surrounding board, therefore, depends not only on the dowel geometry but also on the local material structure into which each tooth expands.

If a dowel tooth expands into a dense region, contact with the surrounding board can be established early during loading, allowing the tooth to contribute effectively to pull-out resistance. If the tooth is instead located near a pore local compaction, movement or redistribution may occur before significant resistance develops. The average solid fraction, shown in Figure 4.2, therefore provides useful information about the overall material composition, but it does not describe the local structure governing tooth engagement. Comparing the average solid fractions alone suggests several similarities between specimens, whereas the corresponding solid fraction profiles reveal substantial variation through the thickness and between individual specimens. The average solid fraction can, therefore, be useful for assessing whether a manufactured particleboard meets specified requirements, while the local density profile is more relevant for interpreting the mechanical response of individual dowel teeth.

The local interaction between the dowel and the surrounding material is illustrated in Figure 4.15, where the positions of individual teeth relative to the regions can be observed. Since pull-out resistance depends on the degree of contact and mechanical interlocking between the teeth and the surrounding board, the number of teeth effectively embedded in load-bearing material strongly influences the maximum pull-out force. If one or more teeth are poorly supported by the board structure, the achievable resistance may be reduced. This effect is shown for specimen 29 in Figure 4.27, where the lower teeth appear to be situated near local pores and were, therefore, not properly engaged initially, leading to a lower peak force. All teeth connections affect the peak-force, but if the lower teeth lack interlocking the peak force is substantially lowered. This is consistent with the non-uniform load distribution observed in screw threads, where the first engaged thread carries the largest proportion of the applied load and the following threads carry progressively less [14].

5.1.2 Global mechanical response

The mechanical pull-out tests showed the same general response across the different testing methods. An initially steep increase in force, followed by non-linear behaviour and an eventual loss of pull-out resistance. This common response indicates that the same overall mechanisms were activated in all test setups, namely progressive engagement, sliding, compaction, and local failure around the dowel teeth. However, the force level, initial stiffness, and post-peak behaviour varied between specimens and test groups.

Continuous pull-out tests

The continuous pull-out tests, shown in Figures 4.3, 4.4, and 4.5, demonstrated the same general pull-out behaviour across all testing systems. The Instron tests, performed at 10 mm/min, generally produced the highest peak forces and comparatively consistent post-peak behaviour. The MTS tests, performed at 5 mm/min, showed slightly lower peak forces and a more distinguishable tendency toward double-peaked responses than the Instron tests. The pull-out rig tests, performed at the lowest displacement rate of 1 mm/min, showed the greatest variation in curve shape, with several specimens exhibiting multiple local maxima.

The comparison of average responses in Figure 4.8 and the rate-dependency results in Figure 4.9 suggest that the measured maximum force increased with pull-out rate. The double-peaked response also became more apparent as the pull-out rate decreased. This may indicate that slower loading allowed the dowel teeth to slip, redistribute load, and re-engage with the surrounding particleboard, whereas higher loading rates produced a more continuous pull-out response. The double peaks were, therefore, distinguishable in the lower-rate tests, while indications of similar behaviour in the Instron tests were not distinct or frequent enough to justify separate categorisation.

At the same time, the observed differences cannot be attributed to loading rate alone. The testing systems also differed in machine stiffness, load-cell capacity, fixture compli-

ance, and sampling frequency. The differences among the Instron, MTS, and pull-out rig results should, therefore, be interpreted as setup-dependent effects, with loading rate as one large contributing factor. The spread shown in Figure 4.10 further demonstrates that the specimen variation within each group, illustrated by maximum force and standard deviation, was substantial. This indicates that the measured pull-out response was governed not only by the testing machine but also by local material structure, dowel alignment, and the number of teeth effectively engaged in load-bearing material.

Effect of relaxation

The relaxation tests provided additional information about the time-dependent effects on the dowel and board interaction. The half-term and full-term relaxation curves, shown in Figures 4.11 and 4.12, exhibited similar trends, with specimen variation in initial stiffness, peak force, and post-peak behaviour. Based on these results, there was no clear difference between specimens tested after one and two months of relaxation.

The comparison between relaxed and non-relaxed specimens in Figure 4.13 indicates that relaxation may influence the pull-out response, as the relaxed specimens showed an increase in maximum force, as shown in Figure 4.14. However, this effect cannot be fully separated from specimen variability. The similarities between the one- and two-month relaxation periods suggest that a substantial part of the relaxation process may have occurred before the first measured relaxation state. Possible occurrences during the relaxation period include dowel movement, changes in local contact conditions, and humidity-dependent effects.

Effect of incremental loading

The in-situ pull-out tests, shown in Figure 4.6, provided a direct link between the global force-displacement response and the internal deformation of the specimen, by using μ CT and DVC. This is the main advantage of the method, since it allows local displacement and strain fields to be related to specific loading stages. However, the incremental loading procedure also changes the mechanical conditions compared with continuous pull-out testing. During each scan, with an acquisition time of approximately 40 minutes and a post-loading pause of 10 minutes, the displacement was held constant, allowing relaxation, local redistribution of contact pressure, and possible damage stabilisation to occur before loading continued.

The force-displacement curves obtained from in-situ testing should be interpreted as the response of incrementally loaded specimens rather than as direct replacements for continuous pull-out tests. This does not reduce the value of the method, but defines its role. Continuous mechanical tests are more suitable for evaluating the global pull-out response under uninterrupted loading, while in-situ μ CT is more suitable for identifying the internal mechanisms responsible for that response.

The comparison between continuous pull-out rig tests and in-situ tests, performed

using the same setup and loading rate, is shown in Figure 4.7. The in-situ tests showed lower peak forces but an overall similar curve shape. This may indicate that the interrupted loading procedure influences the measured pull-out response. However, because of the limited number of in-situ tests and the substantial specimen variation observed throughout the test programme, this effect cannot be confidently separated from ordinary specimen variability.

Interpretation of curve shape

The shape of the force-displacement curve provides insight into how pull-out resistance increases and decreases. The initial response is influenced by position, fixture compliance, loading rate, dowel alignment, and the degree of contact between the teeth and the surrounding particleboard. As loading continues, the response is increasingly governed by tooth engagement, sliding, compaction, and localised damage in the contact regions. A smooth curve with one dominant maximum may indicate that several contact regions contribute to a gradual loss of resistance, whereas curves with several local maxima may indicate that individual teeth engage, slip, or lose contact at different stages.

The number of dowel teeth involved in load transfer, therefore, affects both the peak force and the curve shape. If several teeth contribute, the resistance may decrease gradually as damage develops around multiple contact regions. If one tooth carries a dominant part of the load, slip or failure at that tooth may produce a more distinct local maximum or a more rapid loss of resistance. Double-peaked responses may therefore reflect redistribution of load between teeth during pull-out. The maximum force should consequently be interpreted as the result of several localised resistance mechanisms rather than as a single material parameter.

5.1.3 Local deformation mechanisms

The tomography and DVC results provide the local information needed to interpret the global mechanical response. The selected specimens are used to illustrate how differences in local board structure, assembly condition, tooth engagement, and loading procedure influence the development of displacement, strain, and coning around the dowel. As discussed in relation to Figure 4.19, the aim was to illustrate one curve from each subgroup, e.g. three different MTS responses, however, because of the varying quality of certain results, this was not possible.

Specimen-specific observations

As previously mentioned, the following specimens were selected to illustrate representative differences in local tooth engagement, assembly condition, and deformation pattern. They are not intended to provide a statistical comparison between test groups, but rather to show how variations observed in the global force-displacement curves

can be interpreted using the corresponding μ CT and DVC results. Together, the selected specimens show how similar nominal test conditions can lead to different local deformation mechanisms.

Specimen 02, subjected to half-term relaxation and shown in Figure 4.20, is visibly crooked in both the assembled and post-relaxation states. This likely influenced the global response, which contains three smaller peaks. The response may indicate that the teeth did not engage simultaneously, but instead contributed sequentially as the dowel moved. Such behaviour is a plausible consequence of crooked assembly, because the teeth are subject to different levels of interlocking as a result of the angle. The coning effect is relatively small but is clearly connected to the left lowest tooth. The strain fields indicate that two teeth carry most of the load, one on each side of the dowel and at different heights. This distribution is consistent with the asymmetric assembly condition.

Specimen 03, also subjected to half-term relaxation and shown in Figure 4.21, is more crooked than specimen 02. The coning is concentrated around the right side rather than being evenly distributed. This asymmetry is also visible in the strain fields, where strain localises around two teeth on opposite sides and at different heights. The global response shows one dominant peak followed by a decrease, suggesting that one tooth, most likely the lower right tooth, contributed more to the pull-out resistance. The empty scan shows a small void where a particle appears to have fallen out, which may have contributed to the uneven load transfer.

Specimen 06, subjected to full-term relaxation and shown in Figure 4.22, shows particle loss on the left side in the empty tomography image. This region later coincides with the position of the lower-left tooth. In the displacement field, this is reflected by smaller displacement around this tooth compared with the right side. The reduced support around the lower left tooth appears to have allowed the middle left tooth to play a larger role, as indicated by increased displacement and strain around it. Strain is also localised around the lower right tooth, suggesting that this tooth contributed significantly to load transfer when the lower left tooth was positioned in a more porous region. The global response shows a peak followed by a smooth decrease, indicating that the same group of teeth likely remained engaged throughout much of the pull-out process.

Specimen 08, subjected to full-term relaxation and shown in Figure 4.23, appears slightly shifted to the right, resulting in stronger embedding of the right-side teeth than the left-side teeth. This is visible in the displacement field, where displacement localises around the lower-right tooth. The dowel appears to have been pulled out relatively straight, without strong interlocking with the material, which may explain the limited coning compared to several other specimens. The strain concentration around both teeth at the lowest height indicates that these teeth contributed substantially to load transfer. The global response suggests that the teeth remained engaged throughout the test, with only minor slipping.

Specimen 11, pulled out using the MTS and shown in Figure 4.24, exhibits a larger coning effect than specimens 02, 03, 06, and 08. The peak force is also higher, which may be related to the higher pull-out rate used in the MTS test. At slower rates, the

thermoplastic dowel may have more time to deform and redistribute contact, whereas at higher rates, the response may become stiffer and transfer higher local stresses to the surrounding board. This may lead to larger coning and material displacement. The strain fields show load transfer around two teeth at different heights, which is consistent with the slight asymmetry observed in the displacement field.

Specimen 21, pulled out using the pull-out rig and shown in Figure 4.25, reached the highest peak force among the three selected pull-out rig specimens. The larger force is consistent with the more pronounced coning observed around the dowel, in relation to other pull-out rig tests. The global response is relatively smooth, and the strain fields indicate that the two lower teeth carried most of the load. This supports the interpretation that effective engagement of the lower teeth contributes strongly to the maximum pull-out force.

Specimen 27, also pulled out using the pull-out rig and shown in Figure 4.26, reached a slightly lower peak force than specimen 21. This difference is visible when comparing their displacement fields. The strain fields suggest that the lower right tooth and the middle left tooth carried most of the load. This may explain both the lower peak force and the double-peaked global response. A plausible interpretation is that one tooth was initially engaged and that, after local slip or loss of contact, another tooth became more active in carrying load.

Specimen 29, pulled out using the pull-out rig and shown in Figure 4.27, reached an even lower peak force. This appears to be related to the porous material surrounding the teeth, which resulted in a smaller coning effect. Despite the limited visible coning damage, strain still accumulated around the teeth, indicating that the dowel remained in contact with the surrounding material.

Specimen 32 was pulled out incrementally, as shown in Figure 4.28, allowing the displacement and strain fields to be evaluated at several loading stages. Because of the incremental loading procedure, direct comparison of the global force-displacement curve with those of continuously loaded specimens is less straightforward. However, the deformation fields provide valuable information about the development of local mechanisms. The displacement field shows that loading has a large initial effect, after which the coning changes gradually with each step, where the displacements become more local to each individual tooth. After unloading, the apparent reversal in displacement reflects elastic recovery or bounce-back. The strain fields show a gradual increase in localisation around the teeth, particularly around the lower left tooth in the later stages. A clear increase in coning occurs after load step 3, which corresponds to the transition into the nonlinear part of the global response. This suggests that the nonlinearity is associated with the beginning of movement, redistribution, or slip around the dowel teeth. The force-displacement curve shows that, after each load step, the specimen relaxed before rejoining the expected pull-out response when loading resumed. The force-time curve illustrates this relaxation more clearly. Because the test was displacement-controlled, the displacement was kept constant during each scan. The observed decrease in force during these hold periods therefore reflects relaxation, local redistribution of contact pressure, and possible stabilisation of damage around the dowel teeth.

Specimen 33 was also pulled out incrementally, as shown in Figure 4.29. The specimen exhibits substantial coning during the first two loading steps, followed by a smaller change in the later stages. The global force level is lower than that of specimen 32, which is consistent with the less pronounced deformation response. After the initial coning response, the displacement field shows a more concentrated local response around individual dowel teeth, suggesting that the particleboard was subjected to a smaller damage area. This is also reflected in the strain field, where strain appears highly localised.

Displacement profiles

The vertical displacement profiles in Figure 4.30 were extracted from the displacement fields of specimen 32. The profile lines were placed at three heights corresponding to the high, middle, and low tooth positions, as indicated in the top row of the figure. The plotted values represent the vertical displacement along each line, measured in voxels. Positive values indicate displacement in the positive direction, towards the bottom edge of the images, while negative values indicate displacement in the opposite direction. In this case, the negative values in steps 1-5 indicate that the board material moves towards the top edge of the tomography images, corresponding to the pull-out direction.

At the high tooth position, the profiles remain relatively close to each other during the early loading steps, followed by a larger change in the final step as a result of bounce-back. This indicates that the displacement field at this height changes gradually during most of the loading sequence, with larger local movement occurring towards the end of the test. A similar trend is observed at the middle tooth position, where the profiles show a progressive upward shift and a clear increase in negative displacement near the right side of the profile line during the later loading steps. At the low tooth position, the early loading steps show only small changes along most of the profile. Overall, the profiles show that the vertical displacement field does not evolve uniformly across the three tooth positions. Instead, the local response changes with height and loading step, supporting the interpretation that the pull-out process involves progressive and spatially varying deformation around the dowel teeth.

This local variation can be related to the force-displacement response. During the early loading steps, the relatively small and uniform changes in the profiles across all heights suggest very limited movement, which corresponds to the linear region. As loading progressed, the larger separation between the profiles, particularly near the high and middle tooth positions, indicates that the internal displacement field became more localised. This corresponds to the transition from the initial, more linear part of the global response to the later nonlinear response, where slip, compaction, and redistribution of load between the dowel teeth become more important. The profile analysis, therefore, supports the interpretation that changes in the global force-displacement curve are associated with localised deformation around individual tooth positions.

5.1.4 General interpretation

Analysing the results shows that the dowel geometry defines the potential load-transfer mechanism, but the resulting pull-out behaviour depends on how each tooth interacts with the local board structure. The empty scans reveal the original board structure, while the assembled scans show how the dowel teeth expand into the board. Comparing these states indicates that the same dowel configuration can produce different local interactions depending on the specific local material structure. The pull-out behaviour is governed by local interactions at the individual tooth level. The main mechanisms are tooth engagement, frictional interaction, compaction of the surrounding material, and mechanical interlocking between the dowel and the board. The vertical displacement fields support this interpretation by showing a cone-shaped deformation zone around the dowel.

The coning region and strain localisation are closely related to the position and engagement of the dowel teeth. Teeth embedded in denser regions can develop stronger contact pressure and mechanical interlocking, while teeth located near pores may contribute less to pull-out resistance. In such cases, the load may instead be redistributed to other teeth. This is reflected in the force-displacement response, where a gradual post-peak decline indicates distributed load transfer, while secondary peaks indicate loss of contact at one tooth followed by redistribution to another.

The DVC results provide quantitative displacement and strain fields. The vertical displacement fields were sufficiently large to reveal meaningful deformation patterns, particularly the coning behaviour around the pull-out zone. The horizontal displacement components were generally close to the noise level and could, therefore, not be interpreted reliably. The strain fields are useful for identifying where deformation localises and how the active load-bearing regions develop between loading steps.

For specimens 32 and 33, the movement of strain accumulation between loading steps shows how the active load-bearing regions evolve during pull-out. This demonstrates the value of combining μ CT and DVC with mechanical testing by mapping changes in the global response to the image-based analysis, which helps identify where and how the internal deformation develops.

5.2 Variability

The variability observed in the pull-out response reflects the combined influence of the local particleboard structure, dowel assembly, testing system, loading rate, moisture conditions, and loading procedure. These factors should not primarily be regarded as sources of error, but rather as part of the behaviour being investigated.

One important source of variability is the heterogeneous structure of the particleboard. The board consists of wood particles, pores, and adhesive, which are not uniformly distributed. Although the specimens had approximately the same nominal dimensions, the local structure around each dowel tooth varied. A tooth positioned in a dense region can develop higher contact pressure, stronger mechanical interlocking,

and greater pull-out resistance, while a tooth located near a pore may contribute less to the overall response. These local differences help explain why nominally similar specimens can produce different curve shapes, peak forces, and deformation patterns.

Dowel assembly may also influence the initial contact conditions. If the dowel is not inserted straight, or if the hole preparation results in small differences in diameter or surface quality, the teeth may not engage with the surrounding board in the same way. Crooked assembly, as observed in several specimens, can produce asymmetric load transfer and may cause individual teeth to engage sequentially rather than simultaneously. This can affect both the initial stiffness and the development of local maxima in the force-displacement curve.

The testing system provides another contribution to the measured variability. Differences in machine stiffness, fixture compliance, mounting configuration, and load-cell capacity influence how the imposed displacement is transferred to the specimen and how the force response is recorded. A more compliant setup may absorb part of the displacement compared with a stiffer setup. The Instron, MTS, and pull-out rig results should therefore be interpreted with caution, since the results may be not only material-dependent but also setup-dependent.

Mounting and remounting of specimens, which were necessary for the relaxation and MTS samples, can affect the results. Small changes in specimen positioning may also influence the quality of the DVC, since it depends on matching corresponding images. This variability is clearly illustrated in Figure 4.19.

The pull-out rate also appears to influence the measured response. The tests performed at higher pull-out rates generally produced higher peak forces, while the double-peaked response became more visible at lower rates. This suggests that slower loading may allow more time for local slip, contact redistribution, and re-engagement between the dowel teeth and the board. However, because the loading rate was not varied independently of the testing system, the observed rate dependence should be interpreted together with the setup-dependent effects.

Moisture may also contribute to variability, since both the particleboard and the thermoplastic dowel can be affected by humidity. Changes in moisture content may influence board stiffness, local swelling or shrinkage, dowel dimensions, friction, and the contact pressure between the dowel and the board.

The difference between continuous and in-situ loading is also important. For the in-situ loading during each tomographic scan, the displacement was held constant, allowing stress relaxation, local creep, redistribution of contact pressure, and possible damage stabilisation before loading continued. The in-situ curves should therefore be interpreted as responses under interrupted loading rather than as direct replacements for continuous pull-out curves.

Overall, the observed variability demonstrates that the pull-out response is governed by a combination of local material conditions, assembly quality, and test procedure. The force-displacement curves should therefore be interpreted together with the tomography and DVC results, since the global response alone cannot identify which factor

controls the specific behaviour. Rather than reducing the value of the results, this variability highlights the importance of linking mechanical testing to internal deformation measurements when studying dowel connections in heterogeneous materials.

5.3 Future work

Future work should include larger test series to make it possible to categorise the different pull-out responses more reliably. In the present study, several curve shapes were observed, including double-peaked responses. However, the number of specimens was too limited to define these as separate response categories with statistical confidence. A larger test programme would make it possible to record and compare parameters such as initial stiffness, maximum force, post-peak behaviour, and the occurrence of secondary peaks. This would also allow DVC results to be compared between specimens belonging to the same response category, making it possible to identify whether similar global curve shapes are associated with similar internal deformation mechanisms and which internal mechanisms govern the different responses.

The influence of loading rate and test setup should also be investigated in a more controlled way. The present results indicate that both maximum force and curve shape may depend on the pull-out rate, with double-peaked behaviour becoming more visible at lower rates. A controlled rate-dependent study should therefore be performed using the same equipment, fixture, specimen geometry, and measurement procedure at different loading rates. This would make it possible to separate material rate dependence from machine stiffness, fixture compliance, and mounting configuration.

Future studies could compare different loading schedules, including varying hold times and numbers of loading increments, while maintaining the same total displacement. This would provide insight into whether the observed differences between continuous and in-situ tests are governed primarily by relaxation time, the frequency of interruptions, or ordinary specimen variability.

Moisture effects should be studied using controlled environmental conditioning. Both the particleboard and the thermoplastic dowel can be affected by humidity, which can influence board stiffness, swelling or shrinkage, dowel dimensions, friction, and the contact pressure between the dowel and the board. Future tests should therefore include specimens conditioned at defined relative humidity levels before assembly and testing. This would make it possible to determine whether moisture primarily affects the board structure, the dowel expansion behaviour, or the load-transfer mechanism between them. This would be useful for assessing the suitability of the connection in wet environments, e.g., bathrooms.

The image-based analysis could be further improved by increasing the scan resolution. A smaller voxel size would make it possible to resolve finer details of the particle-board structure, including smaller pores, local cracks, and sharper deformation gradients around the dowel teeth. Higher-resolution images would also improve the sensitivity of the DVC analysis, since the same physical displacement would correspond to a larger fraction of a voxel. This could make it easier to detect smaller local displacements and

to evaluate the deformation field closer to individual teeth.

Future DVC analyses should also investigate the effect of using a denser grid of calculation points. Increasing the number of grid points would provide a more detailed spatial description of the displacement and strain fields, which could help identify localised deformation, slip, and strain accumulation around individual teeth. However, this should be balanced against image quality, subset size, noise level, and computational cost, since a denser grid does not necessarily improve the reliability of the results unless the image texture supports it.

The relationship between CT-based solid fraction and physical density should also be examined further. Future studies could measure the specimen volume and weight before testing and compare the resulting bulk density with the solid fraction profiles obtained from the tomography data. This would provide an additional validation of the image-based material characterisation and help relate local CT measurements to conventional physical material properties.

Shorter relaxation periods should also be examined. The present results showed limited difference between specimens tested after one and two months of relaxation, which suggests that a substantial part of the relaxation process may occur earlier. Future tests should therefore include measurements shortly after assembly, for example after days and weeks, to determine how the contact pressure and interaction develop over time.

Future work should also investigate the combined influence of dowel orientation and particle orientation in the board. Since the dowel teeth are positioned in specific directions rather than continuously around the circumference, rotating the dowel before installation could change which teeth interact with dense regions, pores, or differently oriented particles. Particle orientation may also influence local stiffness, compaction behaviour, tooth engagement, and resistance to pull-out. Controlled tests with defined dowel orientations, combined with μ CT and DVC, would make it possible to relate tooth position, local particle orientation, density, and porosity to the measured force-displacement response and internal deformation fields. This could help determine whether differences in orientation contribute systematically to changes in stiffness, peak force, curve shape, and load sharing between teeth.

5.4 Implications for IKEA

For IKEA, the main value of combining mechanical testing, μ CT, and DVC is that it links product performance to the internal mechanisms underlying that performance. A conventional pull-out test can show how much force a connection withstands, but not why it behaves in a certain way. By adding μ CT and DVC, it becomes possible to see how the dowel expands, how the board deforms, which regions carry load, and where slip, compaction, and damage develop during pull-out. This provides information that can support more mechanism-based design, testing, and simulation of dowel connections.

The additional value of μ CT lies in revealing information that cannot be obtained from CAD, visual inspection, or global mechanical testing alone. CAD describes the dowel geometry, but not the actual assembled state or the local particleboard structure surrounding the dowel teeth. Similarly, the global force-displacement curve describes the overall response, but not whether the resistance comes from one dominant tooth, several teeth acting together, local compaction, or redistribution of load during pull-out. The μ CT images make it possible to inspect the real interaction between the dowel and the board, including tooth position, local pores, density variations, contact regions, and deformation of the surrounding material.

The information described above is particularly relevant for particleboard, where the local material structure strongly affects the interaction. The results show that the effectiveness of a dowel tooth depends on whether it is supported by dense material or located near pores. This means that variation in pull-out behaviour should not be attributed only to average board density. Average density may describe the specimen as a whole, but it does not show the local conditions around each tooth. Assembly also contributes to the response, since a dowel that is not inserted straight may engage the board asymmetrically and cause uneven load sharing between teeth.

The in-situ tests further show why it can be useful to image the specimen during loading rather than only before and after pull-out. Scans before and after testing can identify the initial and final states, but they cannot show when local slip, compaction, contact redistribution, or damage localisation occurred. The in-situ results indicate that the pull-out process develops progressively, with local deformation and load transfer changing between loading steps. This is important because the first slip is not necessarily the only relevant event

The observed behaviour was not limited to one simple failure mode. The results indicate progressive pull-out, local compaction and coning of the surrounding board material, slip or loss of contact at individual teeth, and redistribution of load between teeth. Some specimens showed one dominant maximum, while others showed secondary peaks or several local maxima. This suggests that failure is controlled by the interaction between dowel geometry, local board structure, and assembly conditions, rather than by the dowel or the board alone. For product development, this means that dowel performance should be evaluated not only from maximum force but also from how the load is transferred, redistributed, and localised during pull-out.

The method can support the development of dowel geometries that promote more consistent tooth engagement and improved load distribution. Relevant design parameters include the number of teeth, tooth spacing, tooth height, tooth angle, expansion behaviour, and circumferential tooth distribution. In the current geometry, the teeth are located in two positions rather than continuously around the circumference of the dowel. A different tooth distribution could change how the load is shared between teeth. μ CT and DVC provide a way to evaluate these effects directly, rather than relying only on the final pull-out force.

The results can also support simulation based product development. μ CT data can be used to describe the real geometry of the assembled joint and the local board structure, while DVC provides displacement and strain fields that can be compared with finite

element simulations. A possible workflow is to begin with a numerical model based on the nominal dowel geometry, compare the simulated force-displacement response and deformation pattern with physical tests, and then adjust material and contact parameters, such as stiffness, friction, damage behaviour, and local compaction, until the model reproduces the measured response. Thereby, finding the relevant material parameters which can be used for any board geometry. In this way, mechanical testing, μ CT, DVC, and simulation can be used together to move testing forwards.

5.5 Conclusions

This thesis investigated the pull-out behaviour of thermoplastic expander dowels in particleboard using mechanical testing, μ CT imaging, and DVC. The work was carried out in collaboration with IKEA Components AB and aimed to evaluate whether μ CT can be used as a tool for product development. An experimental methodology was developed in which continuous pull-out tests were used to characterise the global force-displacement response, while ex-situ and in-situ tomography were used to relate this response to the internal structure and deformation of the particleboard around the dowel. DVC was applied to the tomographic image volumes to obtain displacement and strain fields during selected loading stages.

The results show that pull-out resistance is governed by localised interactions between individual dowel teeth and the surrounding particleboard. The dowel does not act as a uniformly loaded component along its embedded length. Instead, load transfer occurs through local contact, frictional interaction, compaction, and mechanical interlocking around specific teeth. The vertical displacement and strain fields showed localised deformation and coning around the dowel, indicating that resistance is obtained not only through direct tooth contact but also through movement and compaction of the surrounding board volume.

The mechanical tests showed similar overall pull-out behaviour across the testing systems, but with differences in peak force, curve shape, and post-peak response. These differences were influenced by local particle-board structure, dowel assembly, testing setup, and loading rate. The results indicate that the heterogeneous structure of the particleboard strongly affects the measured response, since teeth located in dense regions or near pores can contribute differently to the load-transfer mechanism. The lower teeth were often associated with the largest displacement and strain concentrations, indicating that their engagement was particularly important for the pull-out response in the investigated specimens.

The research questions can therefore be answered as follows. μ CT can be used in product development by revealing the actual assembled state, local board structure, and deformation mechanisms that cannot be obtained from force-displacement curves, CAD geometry, or visual inspection alone. A suitable methodology is to combine conventional pull-out testing with ex-situ tomography before and after loading, in-situ tomography at selected loading stages, and DVC-based displacement and strain analysis. Together, these methods show that thermoplastic expander dowels interact with particleboard through a local and progressive load-transfer process in which tooth

engagement, compaction, slip, and redistribution between teeth control the global pull-out response.

Overall, the thesis demonstrates that combining mechanical testing with μ CT and DVC is a valuable approach for analysing interactions between particleboard and thermoplastic expander dowels. The method does not replace conventional pull-out testing, but complements it by explaining why a certain mechanical response occurs. For product development, this means that dowel performance can be evaluated not only by maximum pull-out force but also by the internal mechanisms that produce that force. This provides a stronger basis for future optimisation of dowel geometry, material selection, testing procedures, and simulation models.

Bibliography

- [1] IKEA. *From humble origins to global brand: A brief history of IKEA*. URL: <https://www.ikea.com/us/en/this-is-ikea/about-us/from-humble-origins-to-global-brand-a-brief-history-of-ikea-pubad29a981/> (visited on 18/05/2026).
- [2] Jean-Yves Buffière, Eric Maire, Jérôme Adrien, Jean-Paul Masse and Elodie Boller. “In Situ Experiments with X ray Tomography: An Attractive Tool for Experimental Mechanics”. In: *Experimental Mechanics* 50.3 (2010), pp. 289–305. DOI: 10.1007/s11340-010-9333-7.
- [3] Simone Carmignato, Wim Dewulf and Richard Leach, eds. *Industrial X-Ray Computed Tomography*. Cham: Springer International Publishing, 2018. ISBN: 978-3-319-59573-3. DOI: 10.1007/978-3-319-59573-3.
- [4] Philip J. Withers, Charles Bouman, Simone Carmignato, Veerle Cnudde, David Grimaldi, Charlotte K. Hagen, Eric Maire, Marena Manley, Anton Du Plessis and Stuart R. Stock. “X-ray computed tomography”. In: *Nature Reviews Methods Primers* 1.1 (2021), p. 18. DOI: 10.1038/s43586-021-00015-4.
- [5] Marek Zemek, Pavel Blažek, Jan Šrámek, Jakub Salplachta, Tomáš Zikmund, Petr Klapetek, Yoshihiro Takeda, Kazuhiko Omote and Jozef Kaiser. “Voxel Size Calibration for High-resolution CT”. In: *10th Conference on Industrial Computed Tomography (iCT 2020)*. Vol. 25. 2. Wels, Austria, 2020. DOI: 10.58286/25109.
- [6] Stephen Hall. *X-Ray Tomography in Experimental Mechanics I*. PowerPoint slides, Division of Solid Mechanics, Lund University. 2025. URL: https://canvas.education.lu.se/courses/36480/files/7135022?module_item_id=1674516 (visited on 18/05/2026).
- [7] Olga Stamati, Edward Andò, Emmanuel Roubin, Rémi Cailletaud, Max Wiebicke, Gustavo Pinzon, Cyrille Couture, Ryan C. Hurley, Robert Caulk, Denis Caillerie, Takashi Matsushima, Pierre Bésuelle, Félix Bertoni, Tom Arnaud, Alejandro Ortega Laborin, Riccardo Rorato, Yue Sun, Alessandro Tengattini, Olumide Okubadejo, Jean-Baptiste Colliat, Mohammad Saadatfar, Fernando E. Garcia, Christos Papazoglou, Ilija Vego, Sébastien Brisard, Jelke Dijkstra and Georgios Birmipilis. “span: Software for Practical Analysis of Materials”. In: *Journal of Open Source Software* 5.51 (2020), p. 2286. DOI: 10.21105/joss.02286.
- [8] Dennis Jones and Christian Brischke, eds. *Performance of Bio-based Building Materials*. Woodhead Publishing, 2017. ISBN: 978-0-08-100982-6. DOI: 10.1016/C2015-0-04364-7.
- [9] Joanna Izdebska-Podsiadły and Sabu Thomas, eds. *Printing on Polymers: Fundamentals and Applications*. William Andrew, 2015. ISBN: 978-0-323-37468-2. URL: <https://shop.elsevier.com/books/printing-on-polymers/izdebska-podsiadly/978-0-323-37468-2> (visited on 18/05/2026).

- [10] Sanjay Krishna, I. Sreedhar and Chetan M. Patel. “Molecular dynamics simulation of polyamide-based materials: A review”. In: *Computational Materials Science* 200 (2021), p. 110853. DOI: 10.1016/j.commatsci.2021.110853.
- [11] M. G. D. Geers, R. de Borst and W. A. M. Brekelmans. “Computing strain fields from discrete displacement fields in 2D-solids”. In: *International Journal of Solids and Structures* 33.29 (1996), pp. 4293–4307. DOI: 10.1016/0020-7683(95)00240-5.
- [12] John Ashburner and Karl J. Friston. “Rigid Body Registration”. In: *Human Brain Function*. Ed. by Richard S. J. Frackowiak, Karl J. Friston, Christopher D. Frith, Raymond J. Dolan, Cathy J. Price, Semir Zeki, John Ashburner and William D. Penny. 2nd ed. Academic Press, 2003. Chap. 2, pp. 12–35. URL: <https://www.fil.ion.ucl.ac.uk/spm/doc/books/hbf2/pdfs/Ch2.pdf> (visited on 18/05/2026).
- [13] Sheila Widnall and Jaime Peraire. *Lecture L5: Other Coordinate Systems*. MIT OpenCourseWare, 16.07 Dynamics. 2008. URL: https://ocw.mit.edu/courses/16-07-dynamics-fall-2009/resources/mit16_07f09_lec05/ (visited on 18/05/2026).
- [14] Richard G. Budynas and J. Keith Nisbett. *Chapter 8: Screws, Fasteners, and the Design of Nonpermanent Joints*. Lecture slides based on *Shigley’s Mechanical Engineering Design*, 9th ed. 2012. URL: https://web.itu.edu.tr/~halit/Makel/Ch_8_slides_m.pdf (visited on 18/05/2026).