

Simulation of In-Plane Deformation Behavior in Components Induced by Defects

Master Project's Report | Interdisciplinary Engineering

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Foreword

This report completes my Interdisciplinary Project in the Department of Engineering at Trier University of Applied Sciences. The work was carried out during the 2025–2026 academic year and centers on developing, implementing, and analyzing my project, "Simulation of In-Plane Deformation Behavior in Components Induced by Defects."

I would like to thank my academic supervisor, Prof. Dr.-Ing. Michael Schuth, and my technical supervisor, Jessica Plaßmann, M. Eng., for giving me the chance to work on this topic. Their ongoing support, helpful advice, and feedback throughout the semester helped me overcome the challenges I faced during this project.

I am also thankful to the laboratory staff and fellow students at Trier University of Applied Sciences. Although this project did not involve practical laboratory experiments, the availability of laboratory resources, computational facilities, and technical assistance contributed significantly to the successful completion of my work.

Finally, I am deeply grateful to my family and friends. Their patience, encouragement, and constant support throughout my studies made it possible for me to finish this work.

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Declaration of Authorship for the Interdisciplinary Project

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Abstract

This master's project develops a numerical and computational approach to analyze how digital shearography (DS) can detect in-plane (IP) surface deformation gradients caused by structural defects and stiffness changes [1], [2], [3]. Traditional DS setups are much more sensitive to out-of-plane (OOP) displacement, which often hides the early, localized in-plane strains that can signal future structural failures in industrial parts [4], [5]. To address this, a back-mounted C-clamp welded-handle specimen was designed in CAD and analyzed using finite element method (FEM) simulations in ANSYS Mechanical Workbench [6].

The resulting 3D displacement data were processed with a custom MATLAB pipeline (InterShear), which restructured the spatial derivatives using a dual-beam 45-degree illumination setup to isolate pure in-plane gradients ($\partial u / \partial x$) [7], [8]. A detailed parametric study examined how different loading setups (60–360 N), boundary conditions, mesh refinements, and optical parameters such as illumination wavelengths ($\lambda = 450 \text{ nm}, 532 \text{ nm}, 620 \text{ nm}$) and image-shearing distances ($\delta = 2 \text{ mm}, 4 \text{ mm}, 5 \text{ mm}$) affected the results [5], [9].

The study found that the direction of mechanical loading relative to the stiffness boundary controls fringe formation [10]. Loading from the opposite side creates larger, clearer shear fields and increases fringe density by up to 71.8% compared to loading on the weld side, which is more restricted by local inertia [10]. Applying spatial Gaussian filters ($\sigma = 5$ to 15) to reduce noise in the numerical derivatives lowers the peak fringe signal by up to 60%, requiring mechanical loads to be increased to 360 N to compensate.

Comparing 2-edge and 3-edge fillet welds showed a small 7.1% drop in fringe count for the 3-edge design, likely due to additional stiffening from the transverse bead, confirming that overall loading has a larger effect than small boundary changes [11]. This research provides a validated simulation method, demonstrating that digital shearography can reliably measure in-plane deformation when mechanical and optical settings are optimized [12], [13]. It establishes a strong foundation for future experiments and industrial non-destructive testing (NDT) [14], [15].

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List of Abbreviations

Abbreviation	Description
FEA	Finite Element Analysis
FEM	Finite Element Method
ESPSI	Electronic Speckle Pattern Shearing Interferometry
CAD	Computer-Aided Design
NDT	Non-Destructive Testing
NDE	Non-Destructive Evaluation
MAPDL	Mechanical ANSYS Parametric Design Language
DS	Digital Shearography
IP	In-Plane
OOP	Out-of-Plane
WL	Wavelength
LED	Light-Emitting Diode
DIC	Digital Image Correlation
SNR	Signal-to-Noise Ratio

List of Formula Symbols

Symbol	Description	Unit
δ	Shear distance	mm
λ	Laser wavelength	nm
θ	Illumination angle	°
E	Young's modulus	GPa
ν	Poisson's ratio	–
N	Fringe order (number of fringes)	–
N_{ip}	In-plane fringe count	–
N_{oop}	Out-of-plane fringe count	–
u	In-plane (Y-axis) displacement	μm
w	Out-of-plane (X-axis) displacement	μm
$\partial u / \partial x$ ($\nabla \mathbf{u}$)	In-plane displacement gradient	$\mu\text{m}/\text{mm}$
$\partial w / \partial x$	Out-of-plane displacement gradient	$\mu\text{m}/\text{mm}$
σ	Gaussian smoothing parameter (sigma)	–
$\mathbf{S}$	Sensitivity vector	–

Introduction

In manufacturing industries, quality inspection is essential for ensuring component safety and service life[15]. Non-destructive testing (NDT) and non-destructive evaluation (NDE) are therefore widely used to assess structural integrity without damaging the component [2], [14].

Optical NDT methods are especially attractive because they provide non-contact, full-field inspection and can reveal deformation over a large surface area [2]. Among these methods, shearography is a full-field interferometric technique that is sensitive to displacement gradients rather than absolute displacement, which makes it useful for detecting near-surface defects and deformation anomalies. Shearography works by comparing two laterally shifted views of the same surface under different loading states [16].

The resulting interference pattern reflects changes in the displacement field, so defects, stiffness variations, or geometric irregularities can appear as fringe disturbances. This is particularly useful in industrial inspection, where small changes in strain distribution can indicate the presence of cracks, debonds, voids, or other flaws before visible failure occurs.

The technique is therefore well suited to structural health monitoring and defect detection in composite and metallic components [14]. A major challenge is that shearography is often more sensitive to out-of-plane deformation than to in-plane deformation [3]. Many structural components begin to deform within the material plane before bending becomes significant, so detecting these early-stage strain changes is difficult but valuable, as it can provide earlier warning of damage progression [2]. This project addresses the gap by investigating whether in-plane deformation induced by specific component geometries or defect types can be reliably detected using digital shearography [17].

The detectability of deformation is also influenced by mechanical and optical parameters, including shear distance, illumination wavelength, phase-shift processing, and loading direction [3], [9]. In this context, the project aims to identify the conditions under which in-plane deformation can be measured effectively and to determine which setup parameters improve the reliability of detection [3].

1.1 Background and Motivation

Digital shearography is widely used to detect out-of-plane deformation [1], [2], but many structural parts deform in their own plane when exposed to tension or shear before visible bending occurs [5]. This early in-plane deformation can signal more serious damage or fractures later on [14]. However, research on shearography's sensitivity to these early in-plane changes remains limited [12], and there is no clear, standardized method for detecting in-plane defects along the loading direction [8], [10], despite growing industrial interest in in-plane deformation measurement for structural and process validation [11].

This project aims to fill these gaps. It addresses the main challenge of measuring in-plane deformation and examines how defects, stiffness changes, or irregular shapes affect in-plane strain gradients [13]. It also studies how well shearography can detect these gradients [5].

1.2 Research Objectives

This project investigates the influence of mechanical and optical parameters on the formation and visibility of in-plane deformation, primarily induced by defects or geometric irregularities within a digital shearographic setup. It evaluates the effects of geometry selection, boundary constraints, loading direction, and mesh refinement on mechanical deformation. Once a stable in-plane response is established, the study assesses how optical parameters, such as wavelength, shear distance, and Gaussian smoothing, impact fringe behavior and detectability [9], [18]. The project also compares in-plane deformation across selected loading and geometric cases to assess how these variations influence fringe formation. The objective is to develop a validated workflow for analyzing in-plane deformation and its optical representation in geometrically constrained components.

To study this behavior systematically, finite element simulations are run in **ANSYS Workbench 2025 R2** [6] using CAD-generated component models. The resulting displacement fields are then processed in **MATLAB** [18], which converts the simulated deformation gradients into synthetic shearographic fringe patterns for optical analysis.

By combining mechanical and optical analyses, the project aims to establish detection limits for in-plane defects and identify shearographic setups that enable reliable inspection under real-world conditions [12].

1.3 Research Hypothesis

In-plane deformation behavior can be controlled and made optically visible by DS when the component geometry, boundary constraints, loading direction, and optical parameters are selected appropriately. Systematic variation of these mechanical and optical conditions is expected to produce measurable differences in in-plane fringe patterns, enabling reliable comparison between selected cases.

1.4 Report Structure

This report has seven chapters that follow the project from its initial motivation to the final evaluation. The introduction explains why in-plane deformation matters in industry, sets out the goals and hypothesis, and allows the project timeline to be decided. The theoretical background covers the optical and mechanical principles needed to understand digital shearography and to measure displacement gradients. The methodology section details how the component geometry, boundary conditions, and loading direction were chosen, how the FEM model was built, and how the optical parameters were set. The discussion examines the simulation results, focusing on how geometric constraints, loading direction, mesh refinement, and optical settings influence the outcomes. The results chapter compares different cases, such as weld-side versus opposite-side loading and two-edge versus three-edge welded geometries, and reviews the resulting fringe patterns. The final chapters summarize the main findings and suggest possible extensions and future work.

1.5 Project Timeline and Work Distribution

The project took place over eight and a half months, from November 2025 to mid-July 2026, and was organized into five main phases. Each phase built on the last to keep the work moving forward in a clear and logical way.

Phase One – Concept Development (Nov–Dec 2025)

The basics of in-plane deformation and digital shearography were learned at the start of the project. In this phase, the project scope, objectives, and hypothesis were defined, supported by an initial literature review and theoretical study.

Phase Two – Criteria Definition (Dec 2025–Jan 2026)

In this phase, the appropriate component shapes were selected, and the key mechanical and optical factors governing in-plane deformation were identified. Decision metrics and knockout criteria were also established to aid in selecting the final geometry and loading conditions.

Phase Three – Parametric Study and Simulation (Jan–Feb 2026)

Most of the technical work was completed in this phase. The finite element model was developed and improved by trying different approaches. Boundary conditions, loading directions, and mesh strategies were tested to create stable in-plane deformation. The optical parameter range was also set, and MATLAB was prepared for re-modulating phase shift generation.

Phase Four – Evaluation and Finalization (Feb 2026)

Once the simulations were completed, the mechanical and optical behavior was analyzed. Cases such as weld-side versus opposite-side loading and two-edge versus three-edge welded shapes were compared to observe fringe formation and ease of detection. The final results were checked against the previously set metrics.

Academic break – (March-May 2026)

During this period, project activities were paused due to an academic break. No further work was carried out, and the project resumed in June 2026, with report writing and data collection.

Phase Five – Documentation and Submission (Jun– July 2026)

The final phase involved writing and refining the project report, preparing the presentation, and structuring the research paper. The project was concluded with the submission of all deliverables in mid-July 2026.

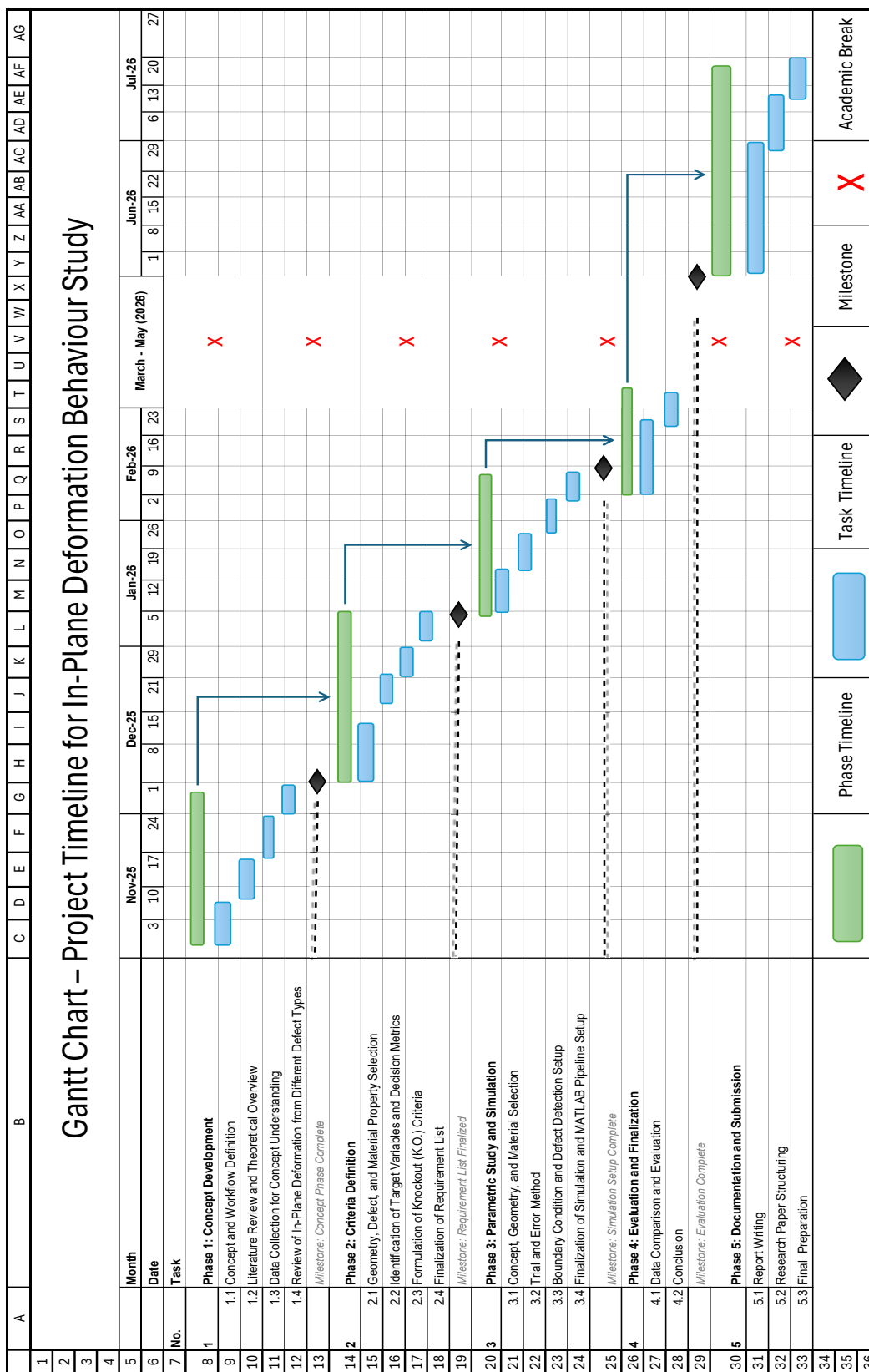


Figure 1.1.: Gantt Chart of the Project Schedule Within its Five Work Phases (Nov 2025 – July 2026)

Theoretical Background

At the start of this project, **Jessica Plaßmann** gave a practical demonstration of the shearographic setup. This helped introduce how deformation can be visualized and how loading direction affects fringe formation. After this, the key optical and mechanical principles were reviewed to build a solid theoretical foundation.

This chapter explains the basic ideas behind optical non-destructive testing (NDT) and interferometry. It covers how laser speckle forms, how holographic recording works, and what digital shearography is. The chapter also introduces the math behind phase modulation, the optical sensitivity vector, and temporal phase shifting, showing how displacement gradients create visible fringe patterns. Finally, it discusses the difference between in-plane and out-of-plane measurement sensitivity, which is important for both the simulation setup and later optical analysis.

2.1 Principles of Optical Interferometry and Speckle Metrology

Optical interferometry measures a surface's deformation by tracking changes in the phase of coherent light reflected from it [19]. This comparison between two states is the basis for several optical NDT methods, such as speckle interferometry, holography, and digital shearography [20].

As shown in Figure 2.1, the object is observed in both its original (unloaded) and deformed (loaded) states. When a rough surface is illuminated by coherent laser light, the scattered waves interfere, creating a pattern that reveals the displacement field [20]. Differences in material stiffness or hidden defects cause changes in how the object deforms, which in turn alters the phase of the reflected light and creates noticeable fringe patterns.



Figure 2.1.: Optical Observation (a) Deformation State of Before and After Loading, (b) Visible Defect Through Optical Interferometric Setup[20].

2.1.1 Laser Speckle Formation

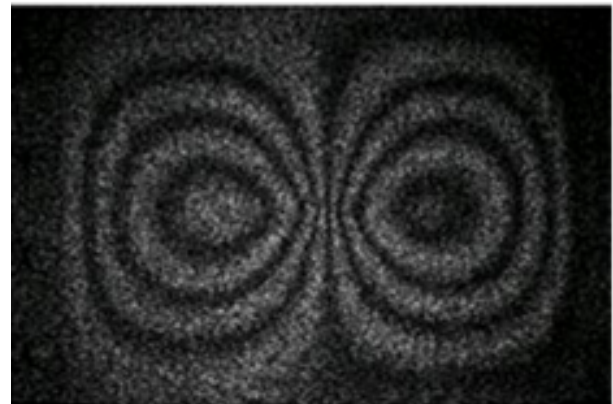
When a rough surface, with height variations larger than the optical wavelength, is lit by coherent laser light, the scattered waves interfere randomly. This creates a grainy pattern called a laser speckle pattern (Figure 2.2a) [2], [21].

If the object does not move, the phase differences between the scattered waves stay the same, so the speckle pattern does not change. In interferometry, these speckles can be described as either: Objective speckles, which are formed directly in free space on a screen without a lens, and subjective speckles, which are formed within the image plane of an optical imaging system (e.g., a camera lens) [20].

When the object deforms, the phase differences change, which shifts the speckle intensity. In interferometry, these changes turn into structured fringe patterns (Figure 2.2b) [3]. Random speckle patterns show local interference, while fringe patterns are larger, alternating bright and dark bands that mark lines of equal phase change.



(a)



(b)

Figure 2.2.: (a) Representative laser speckle pattern generated by coherent illumination of a rough surface [2]; (b) corresponding structured fringe pattern recorded with a shearography setup [3].

2.2 Comparison of Interferometric and Derivative-Based Methods

Holography and digital shearography both use coherent light interference to detect small deformations, but they use different optical setups and measure different types of movement.

2.2.1 Holographic Interferometry

Holography captures the complete optical wavefront (both amplitude and phase) of an object beam by interfering it with a coherent reference beam on a recording medium [20]. A representative holographic layout is illustrated in Figure 2.3.

When the object deforms, the phase of the scattered light changes. Placing the deformed wavefront over the original hologram creates interference fringes that show the exact surface displacement.

Holography offers high spatial resolution, but because it relies on an absolute phase reference, it is highly sensitive to external noise, such as movement, vibration, or small misalignments. This sensitivity has limited its use in industrial settings [20].

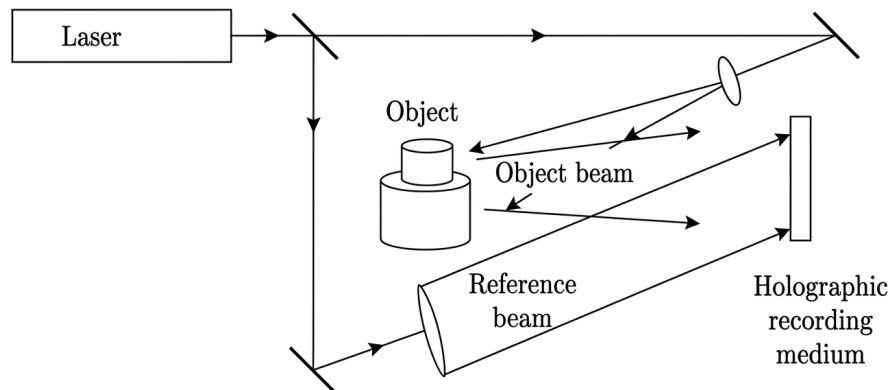


Figure 2.3.: Optical Layout of Holographic Recording and Reconstruction (adapted from [20]).

2.2.2 Digital Shearography

Digital shearography solves the vibration problem in holography by eliminating the need for an external reference beam [16], [22]. Instead, it uses a setup where the object serves as its own reference. As shown in Figure 2.4, the scattered light passes through an image-shearing device, such as a modified Michelson interferometer, placed in front of the camera lens [3].

The shearing device splits the object's image and shifts it slightly sideways (by a distance δ_x or δ_y). This means each point on the detector receives light from two nearby points on the object's surface (such as P_1 and P_2). When the object deforms, the system measures the phase change between these points, which shows the gradient of the displacement field. Since both light paths are nearly identical, any movement or vibration affects them equally and cancels out. This makes digital shearography very stable and suitable for industrial NDT [20].

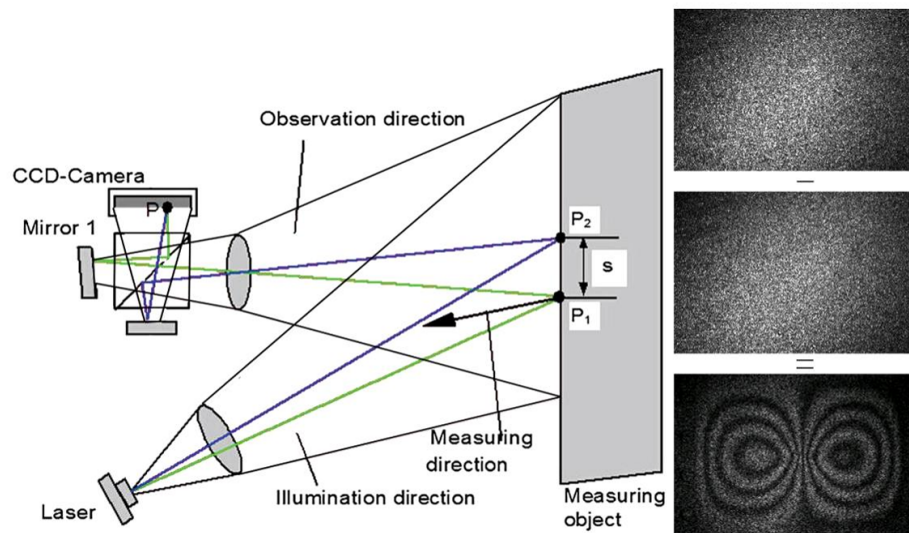


Figure 2.4.: Optical Layout of Digital Shearography (adapted from [3]).

2.2.3 Comparative Analysis: Absolute Displacement vs. Displacement Gradient

Figure 2.5 shows a schematic comparison of the results from holographic interferometry, which measures absolute displacement, and digital shearography, which measures displacement gradients, under the same loading conditions. When a subsurface defect is loaded, it usually produces a smooth, localized bulge that protrudes from the plane [3].

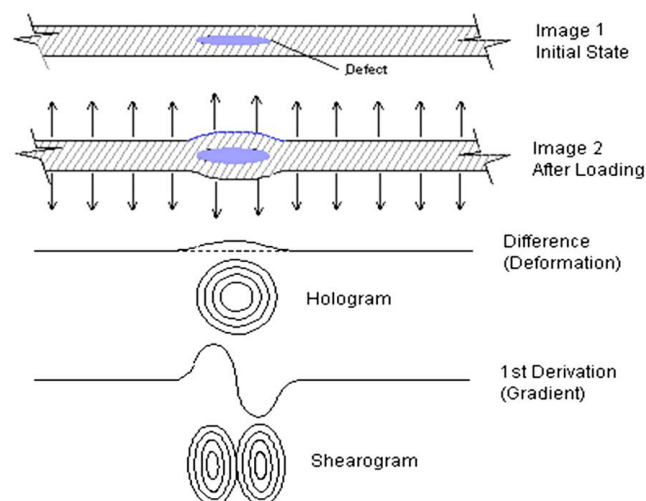


Figure 2.5.: Comparison of Deformation Interpretation in Holography and Shearography (adapted from [3]).

Holography measures the absolute change in optical path length, producing a set of concentric, circular fringe contours that represent lines of equal displacement (Figure 2.6a).

Shearography measures the spatial derivative of this displacement. On one side of the bulge, the slope is positive; on the other, it is negative. This leads to the characteristic double-lobed, symmet-

ric “butterfly” pattern (Figure 2.6b), displaying the direction and magnitude of the displacement gradient [3].

Figure 2.6 shows experimental results for three debonds in an aluminum plate, tested with both methods, as reported by **Zhao**[3].

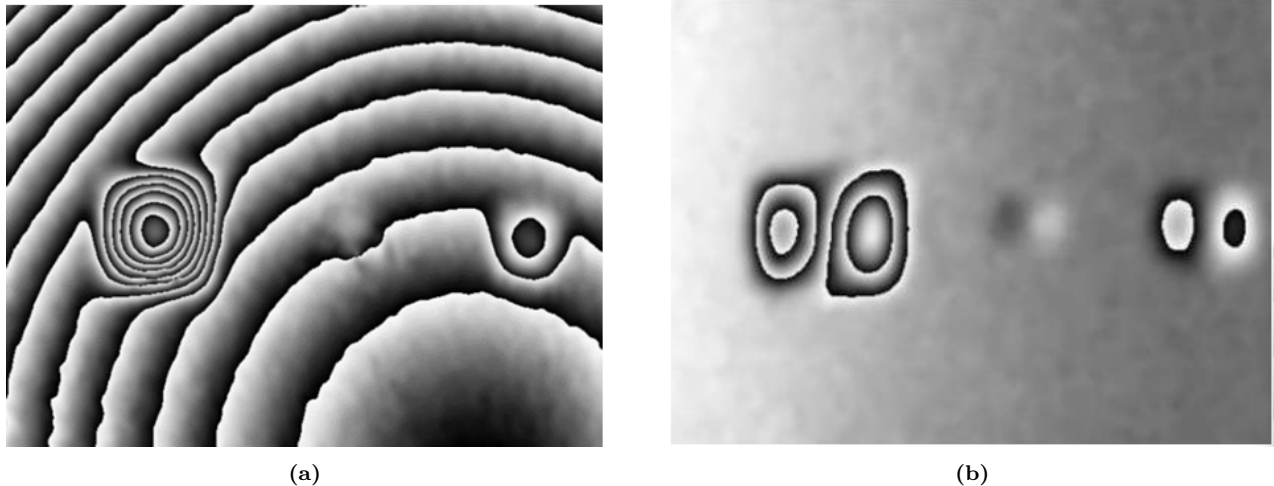


Figure 2.6.: NDT Results for Three Debonds in an Aluminum Plate: (a) holographic fringe pattern showing concentric contours of equal displacement; (b) shearographic fringe pattern showing the characteristic butterfly signature (adapted from [3]).

2.3 Phase Modulation and Fringe Formation

To use optical phase measurements as mechanical data, the phase changes in the light must be linked to how the material deforms.

2.3.1 The Optical Sensitivity Vector

The geometric arrangement of an interferometric setup determines its directional sensitivity as shown in Figure 2.4 [22]. For a specific illumination wave vector $\mathbf{k}_{\text{illumination}}$ and observation wave vector $\mathbf{k}_{\text{observation}}$, the optical sensitivity vector $\mathbf{S}$ is defined as:

$$\mathbf{S} = \mathbf{k}_{\text{illumination}} - \mathbf{k}_{\text{observation}} \quad (2.1)$$

The direction of $\mathbf{S}$ shows which components of displacement (u, v, w) influence the measured phase change. When $\mathbf{S}$ is parallel to the surface normal, the system detects only out-of-plane deformation (w). Angled, symmetric illumination increases sensitivity to in-plane (u, v) displacement gradients, which is elaborated in the chapter 2.4.3.

2.3.2 Principles of Temporal Phase Shifting

When an object deforms, the physical displacement vector $\mathbf{u}(x, y) = [u, v, w]^T$ alters the optical path length of the reflected light [23]. The resulting phase change $\Delta\phi(x, y)$ at a coordinate point is proportional to the projection of the displacement gradient onto the optical sensitivity vector $\mathbf{S}$:

$$\Delta\phi(x, y) \propto \mathbf{S} \cdot \nabla \mathbf{u}(x, y) \quad (2.2)$$

In a conventional digital shearography setup configured primarily for out-of-plane (OOP) sensitivity, Equation 2.2 simplifies to the standard relation:

$$\Delta\phi(x, y) = \frac{4\pi}{\lambda} w(x, y) \quad (2.3)$$

Here, λ is the wavelength of the laser.

In this project, finite element method (FEM) simulations [6] are used to get the full 3D displacement field $\mathbf{u}(x, y, z)$. Displacement gradients $\nabla\mathbf{u}$ are then calculated from this field. These gradients are mapped through the sensitivity vector $\mathbf{S}$ for each experimental setup, and synthetic shearographic fringe patterns are created in MATLAB [18]. This approach allows direct evaluation of in-plane deformations for different weld shapes and loading conditions.

2.4 Relationship Between Displacement Gradients and Shearographic Fringes

To connect optical fringe patterns to the mechanical strain fields beneath them, we first need to mathematically define how the surface moves. This section explains the coordinate changes and kinematic steps needed to relate physical displacements to the phase changes seen in an image-shearing interferometer.

2.4.1 Kinematics of Surface Deformation and the Strain Tensor

The mechanical state of a continuous solid is described by how its surface points move when it deforms. Each point on the original surface has coordinates $\mathbf{x} = [x, y, z]^T$. When the solid is loaded, this point moves to a new position, given by the displacement vector $\mathbf{u}(x, y, z) = [u, v, w]^T$. Here, u , v , and w are the displacements along the x , y , and z axes. According to Eq. 2.4 by Bömkes et al. [24], which is based on the classic elastostatic formulation by Gross et al. [25], the small-strain state of a continuous medium is described by the symmetric 3×3 linear strain tensor ε :

$$\varepsilon = \begin{bmatrix} \varepsilon_{xx} & \frac{1}{2}\gamma_{xy} & \frac{1}{2}\gamma_{xz} \\ \frac{1}{2}\gamma_{yx} & \varepsilon_{yy} & \frac{1}{2}\gamma_{yz} \\ \frac{1}{2}\gamma_{zx} & \frac{1}{2}\gamma_{zy} & \varepsilon_{zz} \end{bmatrix} = \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) & \frac{1}{2}\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right) \\ \frac{1}{2}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right) & \frac{\partial v}{\partial y} & \frac{1}{2}\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right) \\ \frac{1}{2}\left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right) & \frac{1}{2}\left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right) & \frac{\partial w}{\partial z} \end{bmatrix} \quad (2.4)$$

In this tensor, the diagonal entries (ε_{xx} , ε_{yy} , ε_{zz}) show stretching or compression along the main axes. The off-diagonal terms (γ_{ij}) represent engineering shear strains, which describe angular changes.

For digital shearography, we use a first-order Taylor series to describe how a surface point moves to a nearby neighbor at (dx, dy, dz) . As shown in Eq. 2.5 from Bömkes et al. [24], the total displacement $\mathbf{u}_{\text{ges}} = [u_{\text{ges}}, v_{\text{ges}}, w_{\text{ges}}]^T$ can be broken down as follows:

$$\begin{pmatrix} u_{\text{ges}} \\ v_{\text{ges}} \\ w_{\text{ges}} \end{pmatrix} = \begin{pmatrix} u \\ v \\ w \end{pmatrix} + \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{1}{2} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) & \frac{1}{2} \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \\ \frac{1}{2} \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) & \frac{\partial v}{\partial y} & \frac{1}{2} \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right) \\ \frac{1}{2} \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right) & \frac{1}{2} \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) & \frac{\partial w}{\partial z} \end{bmatrix} \begin{pmatrix} dx \\ dy \\ dz \end{pmatrix} \quad (2.5)$$

This kinematic mapping isolates three key deformation modes. This kinematic mapping highlights three main types of deformation that determine the sensitivity of the interferometric fringes: $\partial u/\partial x$ and $\partial v/\partial y$ represent parallel surface expansions or contractions. In-plane (IP) Shear/Slip: The coupling terms $\partial u/\partial y$ and $\partial v/\partial x$ characterize horizontal shearing sliding. Out-of-plane (OOP) Tilts: The transverse partial derivatives $\partial w/\partial x$ and $\partial w/\partial y$ define localized slopes or out-of-plane tilting.

2.4.2 Fringe Order Formulation and Sensitivity Vector Analysis

Digital shearography visualizes these spatial gradients of displacement rather than the displacement magnitudes themselves. When an image-shearing interferometer introduces a lateral shearing distance (Doppelbild-Versatz) δ_x along the x -direction, the light waves scattered from two adjacent surface points interfere on the sensor plane. The phase difference $\Delta\phi(x, y)$ generated by deforming the object manifests as a pattern of macroscopic interference fringes.

The mathematical relation mapping this phase change to the continuous fringe order N (the number of 2π phase cycles) is defined in Eq. 2.6 of Bömkes et al. [24]:

$$N = \frac{\delta_x}{\lambda} \left[\frac{\partial u}{\partial x} \sin(\theta_{xz}) + \frac{\partial w}{\partial x} (1 + \cos(\theta_{xz})) \right] \quad (2.6)$$

Where: N represents the continuous fringe order, δ_x is the lateral shearing distance along the x -axis, λ is the center wavelength of the coherent laser illumination, θ_{xz} is the illumination angle of the incident laser beam relative to the surface plane inside the xz -coordinate plane.

Under an orthogonal configuration where the illumination vector aligns exactly with the surface normal vector (i.e., the illumination angle $\theta_{xz} = 90^\circ$ relative to the surface plane), the coefficient $\sin(90^\circ)$ drops out. Consequently, Eq. (2.6) reduces to measure purely out-of-plane (OOP) deformation gradients:

$$N_{\text{oop}} = \frac{2\delta_x}{\lambda} \frac{\partial w}{\partial x} \quad (2.7)$$

In practice, compact shearographic heads constrain the illumination to a non-orthogonal angle ($\theta_{xz} < 90^\circ$). Under these non-ideal angles, the measured phase change includes minor coupling from the in-plane normal strain $\partial u/\partial x$, which must be mathematically decoupled or accounted for during quantitative post-processing.

2.4.3 In-Plane Fringe Formation Using Optical Decoupling

To measure in-plane displacement gradients ($\partial u/\partial x$) and eliminate out-of-plane coupling, the standard orthogonal illumination setup needs to be modified.

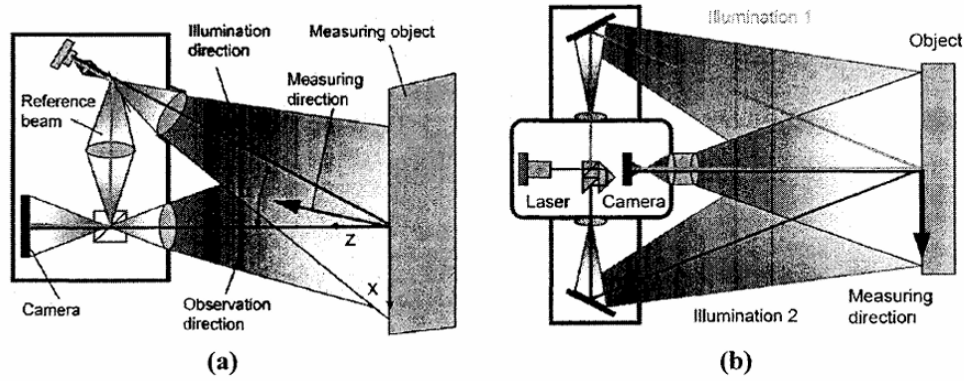


Figure 2.7.: ESPI Configurations for Out-of-Plane and In-Plane Displacement Measurement (adapted from [20]).

Figure 2.7 shows that pure in-plane sensitivity is achieved by using a dual-beam illumination setup. The target surface is lit evenly from two opposite angles in the main measurement plane (at $+\theta$ and $-\theta$ in the xz -plane). Each beam creates its own separate fringe pattern on the detector:

$$N_{+\theta} = \frac{\delta_x}{\lambda} \left[\frac{\partial u}{\partial x} \sin(\theta) + \frac{\partial w}{\partial x} (1 + \cos(\theta)) \right] \quad (2.8)$$

$$N_{-\theta} = \frac{\delta_x}{\lambda} \left[-\frac{\partial u}{\partial x} \sin(\theta) + \frac{\partial w}{\partial x} (1 + \cos(\theta)) \right] \quad (2.9)$$

Since $\sin(-\theta) = -\sin(\theta)$ and $\cos(-\theta) = \cos(\theta)$, the out-of-plane (OOP) term is the same in both channels, but the in-plane (IP) term changes sign. By subtracting the two phase distributions, the out-of-plane effect is removed, and the in-plane sensitivity is doubled:

$$N_{\text{diff}} = N_{+\theta} - N_{-\theta} = \frac{2\delta_x \sin(\theta)}{\lambda} \cdot \frac{\partial u}{\partial x} \quad (2.10)$$

The in-plane displacement gradient can then be found as:

$$\frac{\partial u}{\partial x} = \frac{N_{\text{diff}} \lambda}{2 \sin(\theta)} \cdot \frac{1}{\delta_x} \quad (2.11)$$

In this project's optimized setup, the illumination source is set at $\theta = 45^\circ$. Plugging this value into Eq. (2.10) and solving for the fringe order gives the final formula for calculating the synthetic in-plane fringe patterns:

$$N_{\text{ip}} = \frac{2\delta_x \sin(45^\circ)}{\lambda} \cdot \frac{\partial u}{\partial x} \quad (2.12)$$

Equation (2.12) is the main analytical tool used in later chapters to create synthetic in-plane fringe patterns from finite element (FE) simulation displacement fields.

Methodology

This section provides a comprehensive overview of the simulation and post-processing pipeline implemented in this study. Section 3.1 defines the specimen geometry and outlines the approach for characterizing defects. Section 3.2 details the finite element method (FEM) simulation and its methodology, using ANSYS Workbench 2025 R2 [6]. Section 3.3 discusses the InterShear pipeline and its adaptation for in-plane fringe evaluation. Section 3.4 examines the influence of optical parameters on in-plane deformation.

3.1 Defect Types and Selection Criteria

The first step was to identify the most significant defects for detecting in-plane deformation. A defect is a local break or shape irregularity that changes how strain spreads.

Cracks are surface or subsurface gaps where stress concentrates. When a material is pulled, a crack blocks the load path, causing a sudden, steep change in strain at the crack tip. Shearography highlights this sharp, localized effect. The effect is highly localized and abrupt [12].

Voids are internal empty spaces that reduce the material's strength. Under load, the area above a void strains more than the rest. This local thinning increases strain above the void compared to the surrounding material. This strain difference creates a visible fringe pattern, though less sharp than with cracks. The fringe effect is subtler than with cracks[13].

Geometric irregularities, such as changes in weld shape or thickness steps, alter local stiffness [26]. These don't break the material but still cause measurable strain gradient changes, especially where stiffness shifts. Strain gradient changes are most evident at stiffness transitions. This is most noticeable at the border between different stiffness zones [13].

As shown in Table 3.1, geometric irregularities were chosen for this project because they offer a controlled, realistic means of studying in-plane strain changes. Unlike cracks or voids, geometric defects produce smoother, more predictable stiffness variation, making them ideal for this study.

Table 3.1.: Concept Screening Matrix for Defect-Type Selection

Criteria	Crack	Void	Geometric Change
In-plane strain visibility	Very sharp, highly localized (not suitable for systematic study)	Mixed in-plane/out-of-plane effects (difficult to isolate)	Clear, smooth stiffness-driven in-plane gradients (preferred)
Controllability of defect severity	Low (crack length unpredictable)	Medium (void size controllable)	High (stiffness variation fully controllable)
Suitability for parametric studies	Poor	Moderate	Excellent
Compatibility with shearography	Detectable but too localized	Detectable but noisy	Highly compatible (gradient-based response)
Overall suitability	Rejected	Rejected	Selected Concept

3.1.1 Evaluation of Initial Geometries

At first, the project's goal was to simulate a standard perforated Jig Fixture used in manufacturing industries because its ribbed, perforated web resembled the stiffening features. The L-shaped jig fixture measured roughly 120 mm × 80 mm with 3 mm plate thickness and a 70 mm stiffening rib. This seemed like a good starting point for studying how geometric stiffening affects in-plane deformation. But the welded joints made the bracket more stiffer and caused most of the deformation to occur as out-of-plane bending rather than in-plane strain. It makes sense to choose another geometry with a different defect to achieve clearer, more controlled in-plane strain changes. Figure 3.1 below illustrates the concept of jig fixtures with a welded rib alongside as a support structure.

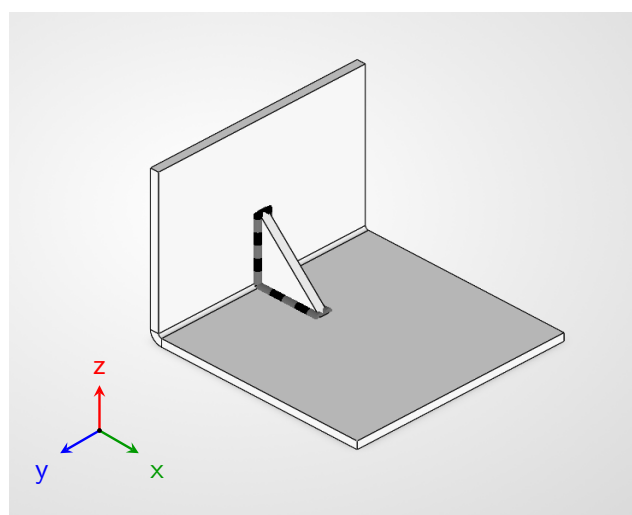


Figure 3.1.: CAD Model of the Initially Considered Perforated L-shaped Jig Fixture from SolidWorks 2026.[27]

3.1.2 Transition to Final Geometry Concept

After the perforated jig-fixture idea was set aside, the weld area became the main focus for developing a new specimen. A basic simulation was performed in SolidWorks to observe the movement of test objects, and it showed that the original shape led to bending instead of useful in-plane stretching or shear. This finding led us to design a specimen in which the weld would help generate measurable in-plane strain.

The first approach was to weld two strips together and test their response by pulling both plates. This setup showed greater stretching but lacked stable boundaries and failed under conditions of geometric change.

From the last decision, a handle-shaped specimen with one welded side was created. This design let the weld produce clear in-plane stretching when the specimen was pulled or pushed. The simple load path, flat surface, and local stiffness change made it much better for shearographic analysis and for studying the chosen geometric-change defect.

3.1.3 Morphological Matrix and Concept Screening

The morphological matrix guided the choice of geometric change for the simulation, leading to Option B as per Table 3.2. This option uses a dual welded-edge stiffness transition at the handle-to-plate junction. It creates a clear and controllable geometric change along the weld, resulting in a distributed in-plane strain gradient that follows the main load path. Because it is easy to observe and works well with the loading direction, Option B was the best choice for the welded handle-type specimen.

3.1.4 Final Geometry Synthesis and CAD Implementation

The final specimen geometry was created based on the design requirements in Table 3.3. This approach ensured that all required geometric, defect-integration, loading, and optical criteria were met.

Table 3.4 shows the main dimensions and material details of the final specimen, and an isometric view of the 3D geometry is shown in Figure 3.2. The detailed CAD drawings with all measurements are available in Appendix VI.1, VI.2, VI.3, and VI.4.

Table 3.2.: Morphological Matrix for Geometric-Change Defect Implementation

Subfunction	Option A	Option B	Option C	Option D
Defect Type (Geometric Change)	Single welded-edge transition	Dual welded-edge transition	Localized thinning region	Step-change in plate thickness
Defect Severity Control	Edge height variation (1–3 mm)	Edge count variation (2–3 edges)	Thickness reduction (0.5–2 mm)	Step height variation (1–2 mm)
Defect Location	Clamp–plate junction	Handle–plate junction	Central plate region	Side-wall transition
Expected In-Plane Strain Response	Moderate, directional gradient	High, distributed gradient	Localized but smooth gradient	Broad stiffness transition
Optical Accessibility	Excellent (flat plate surface)	Good (near clamp boundary)	Excellent (central region)	Moderate (side curvature)
Compatibility with Loading Direction	High (aligned with main load path)	High (load path bifurcation)	Medium (requires symmetric load)	Medium (requires angled load)
Overall Suitability	High potential	Selected Concept	Moderate suitability	Low suitability

Table 3.3.: Design Requirements for the Handle-Type Specimen

Group	Type	Requirement	Metric
Geometry	Must	Parameterized Handle & Base Plate: Grip length (L), flat base plate surface dimensions ($W_b \times L_b$), and plate thickness (t) must be fully adjustable.	Active design parameters > 5
Geometry	Must	Back-Mounted C-Type Clamp: A C-clamp structure integrated directly behind the flat base plate for secure, zero-slip from one end mechanical anchoring.	Throat clearance: 10–50 mm
Defects	Must	Localized Defect Integration: Capability to simulate stress-concentrating defects	defect length: 5–20 mm; Void $\varnothing$: 2–10 mm; Thinning depth: 0.5–2 mm
Forces	Must	Gripping & Preload Force Simulation: Dual-mode load application combining C-clamp pre-tensioning behind the plate with multi-directional user gripping forces on the handle.	Gripping load: 0–2 kN; Clamping torque up to 15 Nm
Optical	Should	Shearographic Compatibility: Under applied load, the front-facing flat base plate surface must yield clear in-plane and out-of-plane displacement gradients.	Surface strain gradient $\nabla \epsilon \geq 100 \mu\epsilon/\text{mm}$

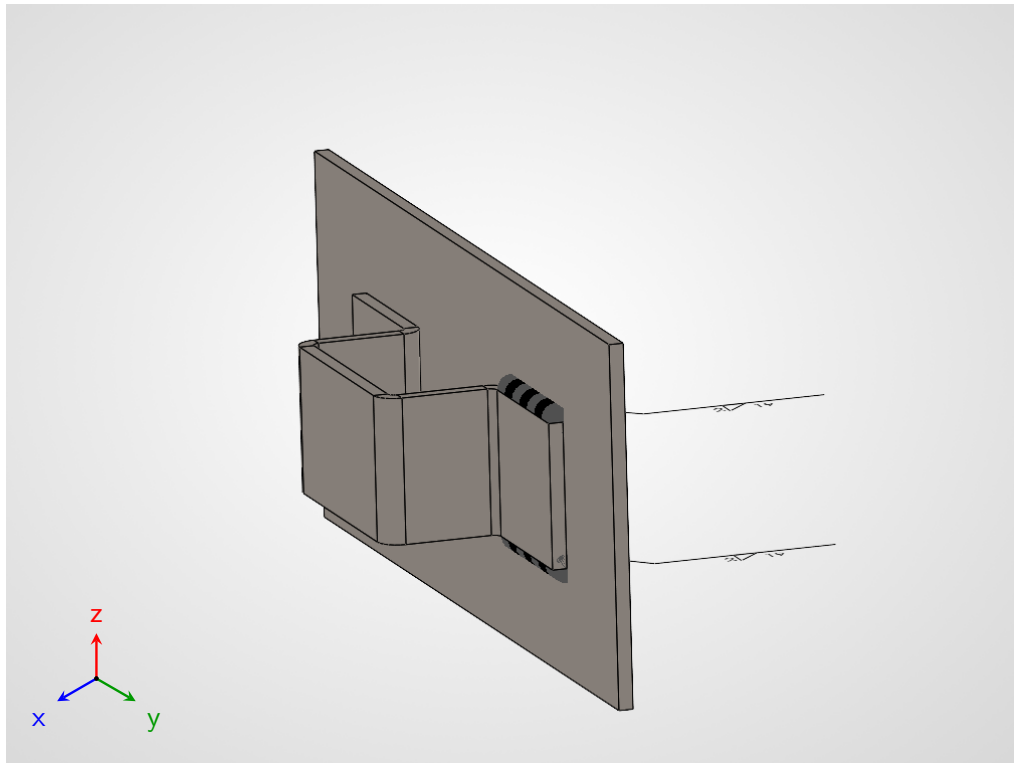


Figure 3.2.: Final Specimen Assembly with Base Plate and Back-Mounted C-Clamp, joined by fillet welds. From SolidWorks 2026. [27]

Table 3.4.: Specimen Geometry and Material Parameters

Parameter	Value
Base Plate (DWGSPC2)	
Length (Y-direction)	120 mm
Width (X-direction)	80 mm
Thickness (Z-direction)	2 mm
Material	Structural Steel
Weight	94.20 g
C-Type Clamp (DWGSPC1)	
Overall height	108.6 mm
Clamp width	37.7 mm
Throat clearance	22.6 mm
Radius transitions	R10.0 mm
Material	Structural Steel
Weight	34.12 g
Welded Assembly (DWGSPA1, DWGSPA2)	
Assembly length	120 mm
Assembly height	50 mm
Assembly width	15 mm
Weld fillet radius	R0.74 mm
Material Properties (Structural Steel)	
Young's Modulus	200 GPa
Poisson's Ratio	0.3
Yield Strength	250 MPa

3.2 Finite Element Simulation

The simulation procedure was taken into account when deciding on the structure of the final FEM strategy. The simulation overview set the main requirements for the project, such as loading direction, load magnitude, boundary conditions, and the types of deformation fields to study. These requirements shaped the kinematic strategy, which determined the specimen's position, the fixed and loaded boundaries, and the direction of the applied load to keep the deformation mostly in-plane. The simulation overview defined what needed to be evaluated, while the kinematic strategy explained how to arrange and load the specimen to meet those goals, as shown in Figure 3.3.

The workflow in Figure 3.4 shows how the simulation procedure developed as the project progressed. Each step corresponds to a decision made earlier: the geometry definition follows concept screening, boundary conditions are based on the kinematic strategy, and the loading direction is chosen to match the desired deformation in the specimen. The mesh-refinement load case, the full simulation set, and the export of displacement fields were organized so that FEM results could be consistently

analyzed in MATLAB for optical analysis. The workflow not only lists the steps but also shows how the simulation strategy was built from earlier decisions.

3.2.1 Kinematic Strategy for Targeted In-Plane Deformation

To study in-plane deformation, the first step was to set the specimen's orientation relative to the observation direction. The flat base plate faced the camera, making the deformation field visible and suitable for shearographic evaluation. This setup guided all subsequent FEM decisions, including the specimen's position, the fixed boundary, and the loading direction and magnitude.

After setting the observation geometry, the loading strategy matched the main stiffness change at the clamp-plate junction. The load was applied along the $\pm y$ -direction, which matches the handle's gripping axis. This setup ensured that most of the deformation occurred in the material plane, creating measurable displacement gradients across the welded-edge defect area.

The camera line of sight was oriented normal to the flat front plate surface to maximize optical sensitivity to in-plane gradients. This unified kinematic setup, consisting of the specimen orientation, boundary conditions, and loading direction, included positioning the camera perpendicular to the flat front plate to maximize sensitivity to in-plane gradients. This consistent setup, including specimen orientation, boundary conditions, and loading direction, was used in all simulations to ensure results could be compared. Figure 3.3 shows the loading options and observation direction used for in-plane deformation analysis.

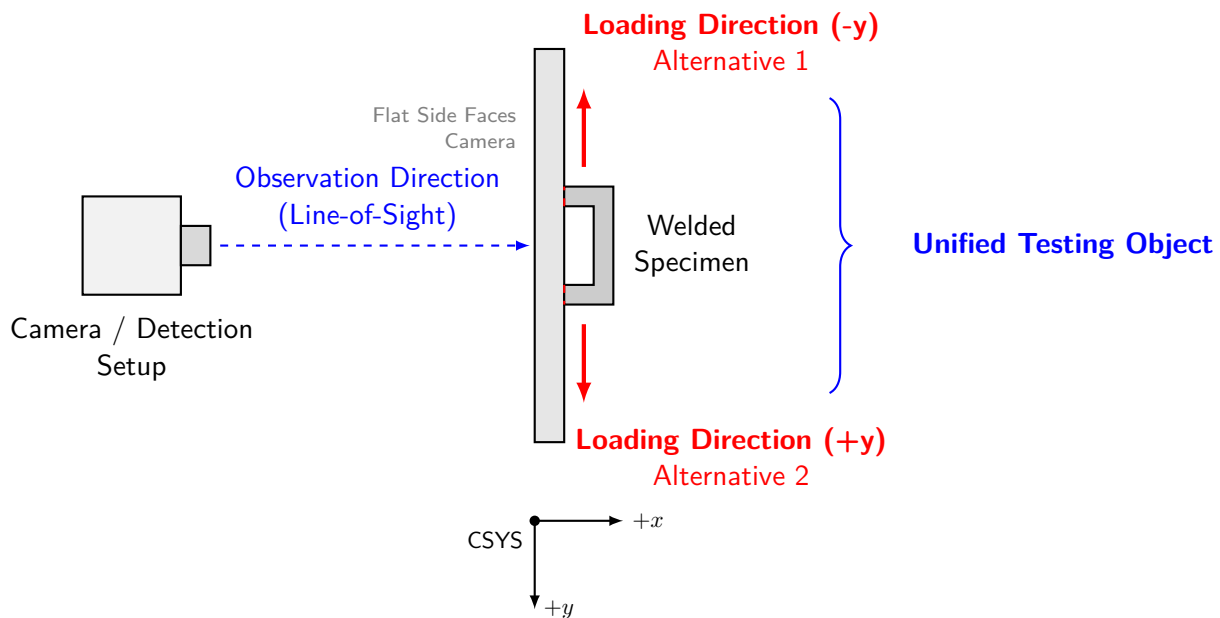


Figure 3.3.: Test Configuration Showing Camera Line-of-Sight and Loading Directions

3.2.2 Simulation Workflow Development

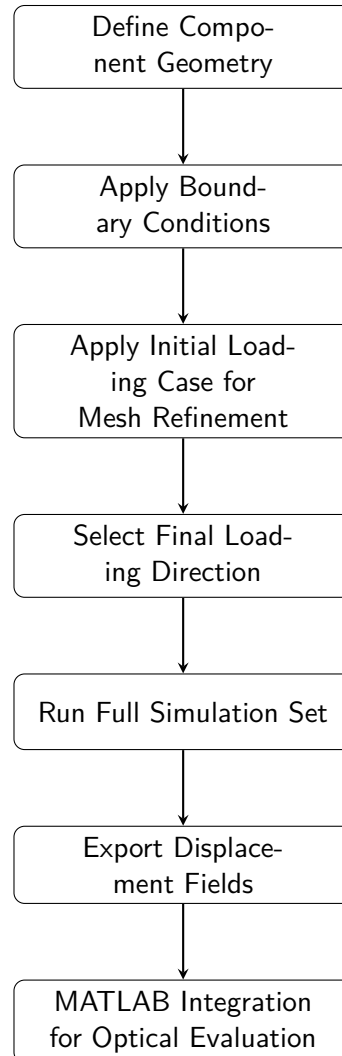


Figure 3.4.: FEM-to-Optical Evaluation Workflow

Once the specimen orientation and observation direction were set, the sequential workflow in Figure 3.4 was used to guide the FEM simulations. This workflow outlines each step of the simulation, starting with geometry definition and boundary-condition assignment, followed by loading selection, running the full simulation, and exporting the displacement field for MATLAB-based optical evaluation. The reasons behind each step in this workflow are explained in detail in the Discussion chapter.

3.3 Data Post-Processing Framework

The original InterShear framework, introduced by Jessica Plassmann [7], was developed for out-of-plane (OOP) shearography, where the phase distribution is computed from the gradient of the displacement component $w(x, y)$. The Intershear pipeline framework can be seen as per the flow diagram 3.5. For this project, the workflow was adapted and agreed by Jessica Plassmann to operate on the in-plane displacement component $u(x, y)$, allowing the pipeline to evaluate in-plane deformation behavior.

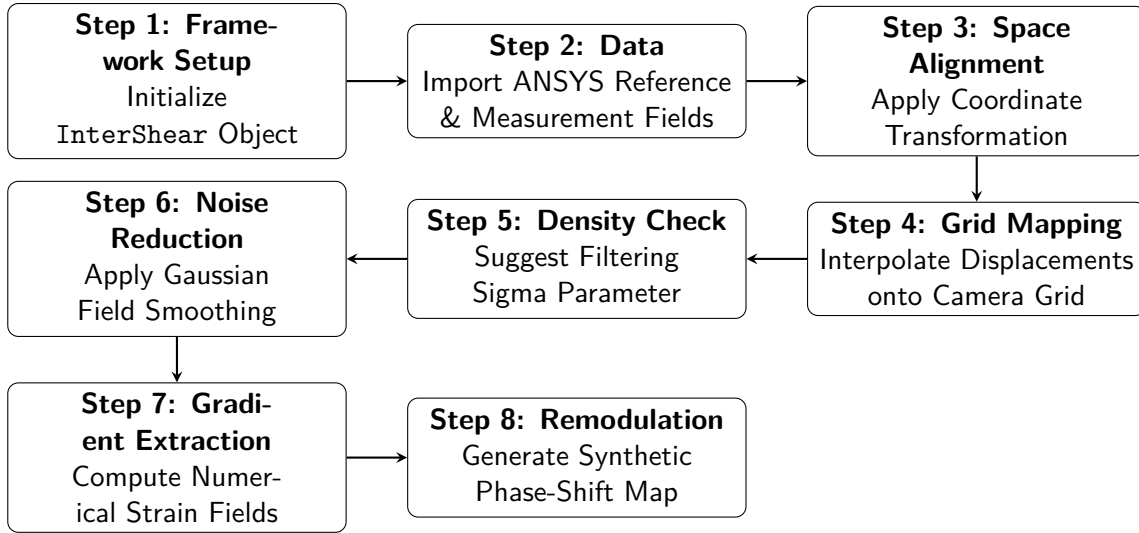


Figure 3.5.: Processing Stages of the InterShear Pipeline

Although the internal variable names of the original code remain unchanged, the mathematical operations correctly compute the in-plane gradient $\partial u / \partial x$, which is required for in-plane shearography under the dual-beam 45° illumination used in this setup. This modification enables InterShear to generate synthetic in-plane fringe patterns using the same computational structure as the original OOP implementation, which is described in the next chapter.

3.3.1 Mathematical Formulation for In-Plane Sensitivity

In the theoretical formulation presented earlier, out-of-plane (OOP) shearography evaluates deformation by transferring the displacement field into the camera coordinate system and computing the gradient of the out-of-plane component $u_z(x, y)$ along the shear direction. With shear applied in the x -direction, the resulting phase distribution is obtained from the term $\partial u_z / \partial x$, producing the classical OOP fringe pattern shown in Figure 3.6a.

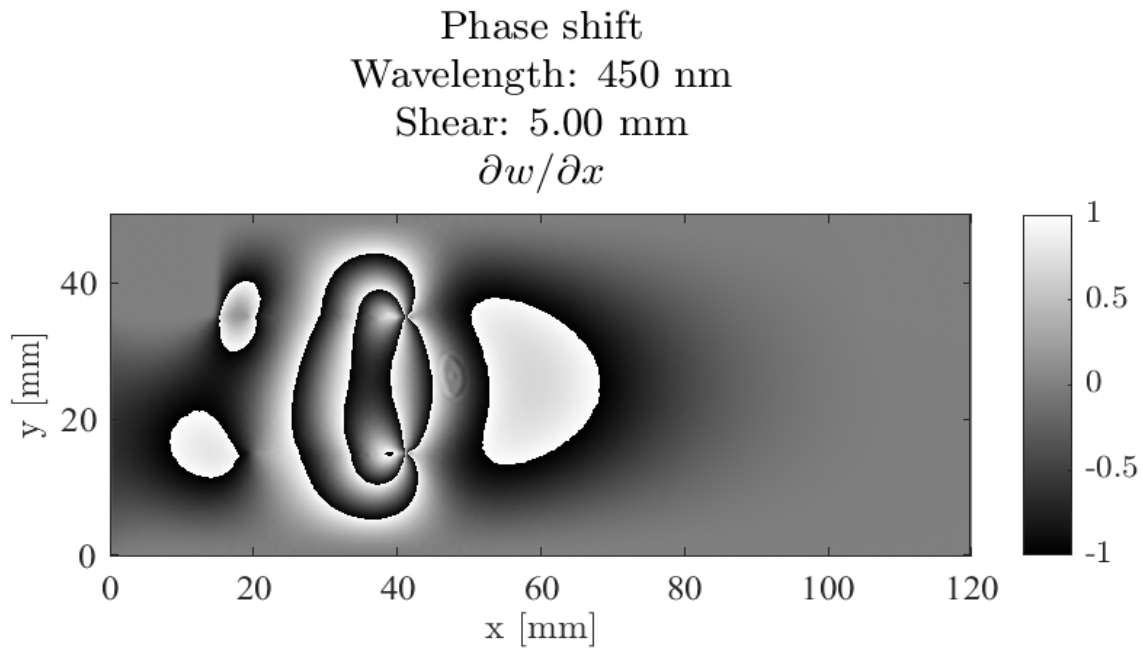
$$N_{oop} = \frac{\Delta \varepsilon_{SPSI_{ezz}}}{2\pi} = \frac{2\delta_x}{\lambda} \frac{\partial w}{\partial x}, \quad (3.1)$$

For in-plane (IP) shearography, the same mathematical structure is retained, but the displacement variable supplied to the pipeline is changed. Instead of using the out-of-plane component $w_x(x, y)$,

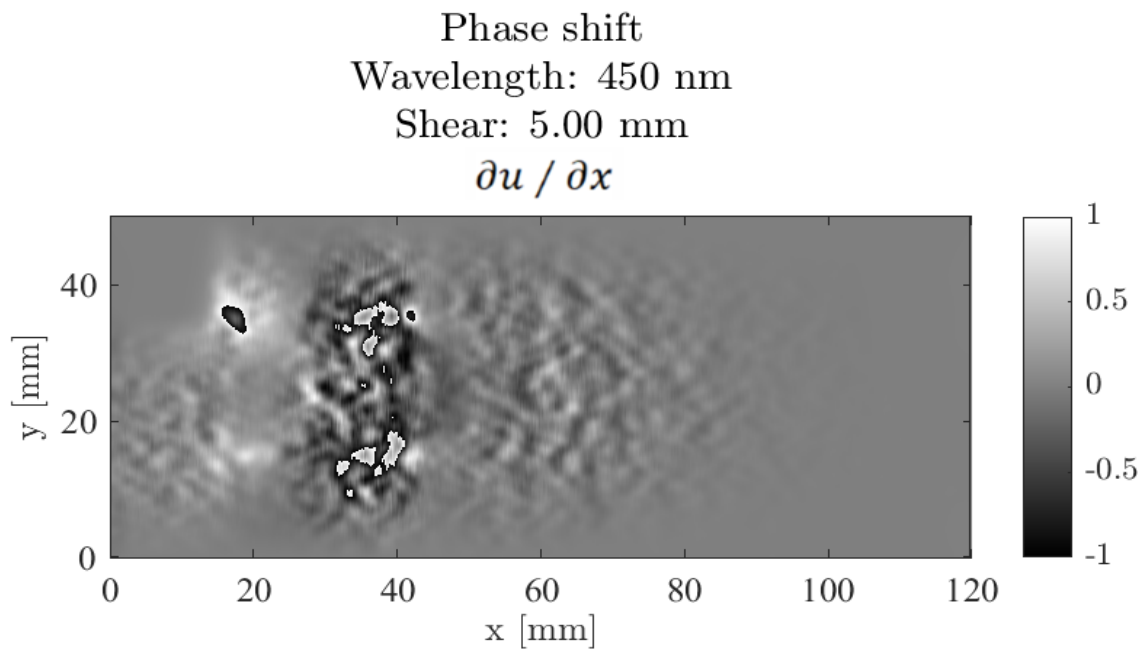
the in-plane displacement component $u_y(x, y)$ is transferred into the camera coordinate system. The shear direction remains aligned with the x -axis, meaning the pipeline evaluates the in-plane gradient $\partial u_y / \partial x$, which is required for IP sensitivity. This substitution transforms the OOP phase formulation into the in-plane expression.

$$N_{ip} = \frac{2\delta \sin(45^\circ)}{\lambda} \cdot \frac{\partial u}{\partial x} \quad (3.2)$$

consistent with the dual-beam illumination geometry described in the theoretical chapter 2.4.3. The resulting in-plane fringe pattern is shown in Figure 3.6b. The comparison between Figures 3.6a and 3.6b demonstrates how changing the displacement component from w_x to u_y directly alters the phase distribution and enables in-plane deformation evaluation using the same InterShear computational workflow.



(a)



(b)

Figure 3.6.: Synthetic Phase-Shift Maps for Out-of-Plane and In-Plane Gradients from MATLAB. [18]

3.4 Definition of the Parametric Domain

Equation 3.2 shows that the optical parameters of the shearographic system are important for evaluating synthetic phase maps. The illumination wavelength and spatial shear distance both affect the sensitivity term in the phase formula, which controls the size and density of the reconstructed fringe pattern. Shorter wavelengths make the phase more sensitive, while a larger shear distance increases the gradient response but can also introduce more noise. For this reason, the parametric domain in this chapter includes these optical parameters and the mechanical deformation field to ensure that the map evaluation is consistent with the theoretical sensitivity model.

For this project, three standard illumination wavelengths were used. These correspond to green, red, and infrared laser colors, and were combined with a standard shear distance. These optical parameters directly influence the sensitivity of the phase map. The values used are listed below.

$$\delta = 2 \text{ mm}, 4 \text{ mm}, 5 \text{ mm} \quad (3.3)$$

$$\lambda = 450 \text{ nm}, 532 \text{ nm}, 620 \text{ nm} \quad (3.4)$$

4

Discussion

This chapter looks at how simulated deformation responds to different conditions. The results are grouped into separate cases. Each case builds on the last, showing how decisions develop over time. This step-by-step approach makes the conclusions stronger by showing how each factor affects the results. The factors considered are boundary condition, loading direction, loading magnitude, mesh refinement, and optical parameters. The chapter explores how these factors affect the ability to detect in-plane deformation with digital shearography.

Note on Coordinate System Convention

All simulations in this project used the global coordinate system defined in **ANSYS Workbench 2025 R2** [6]. This system was set up in the **ANSYS Mechanical** environment. The global coordinate triad (X, Y, Z) is shown in its reference orientation in Figure 4.1, which applies to the entire finite element workflow. The specimen's longitudinal axis is aligned with the global Y-direction. This direction is also used for loading in all cases. The global Z-direction matches the specimen height, and the global X-direction represents the thickness. Due to the fixed global coordinate system used in ANSYS Mechanical, the displacement measurements required for in-plane and out-of-plane evaluation must be transferred according to the global axes. In-plane deformation is therefore taken from the global Y-direction, which represents the specimen's longitudinal axis, while the out-of-plane deformation corresponds to the global X-direction rather than the local Z-direction. All displacement gradients and phase-map evaluations in this project follow this global-axis interpretation.

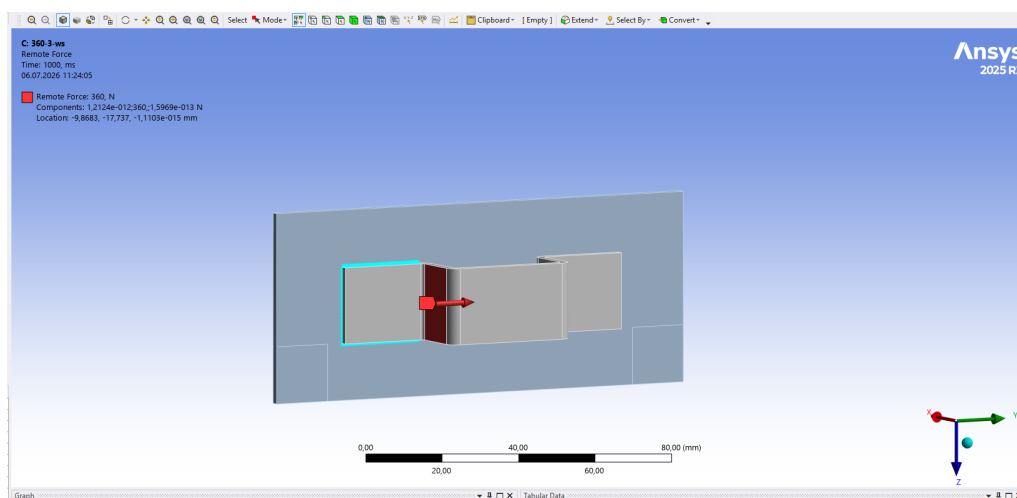


Figure 4.1.: Global Coordinate System Used in ANSYS Mechanical [6]

4.1 Structural Evaluation of Candidate Geometries

In this case, a few geometric configurations were modeled and analyzed under static structural loads to find the best spatial orientation and load-path transmission.

Case 1: Vertical Base Plate Orientation (Rejected)

The foremost idea was to set the base plate orientation to simplify the load path. The bottom edge was fixed, and a uniaxial load was applied vertically along the global Y -direction.

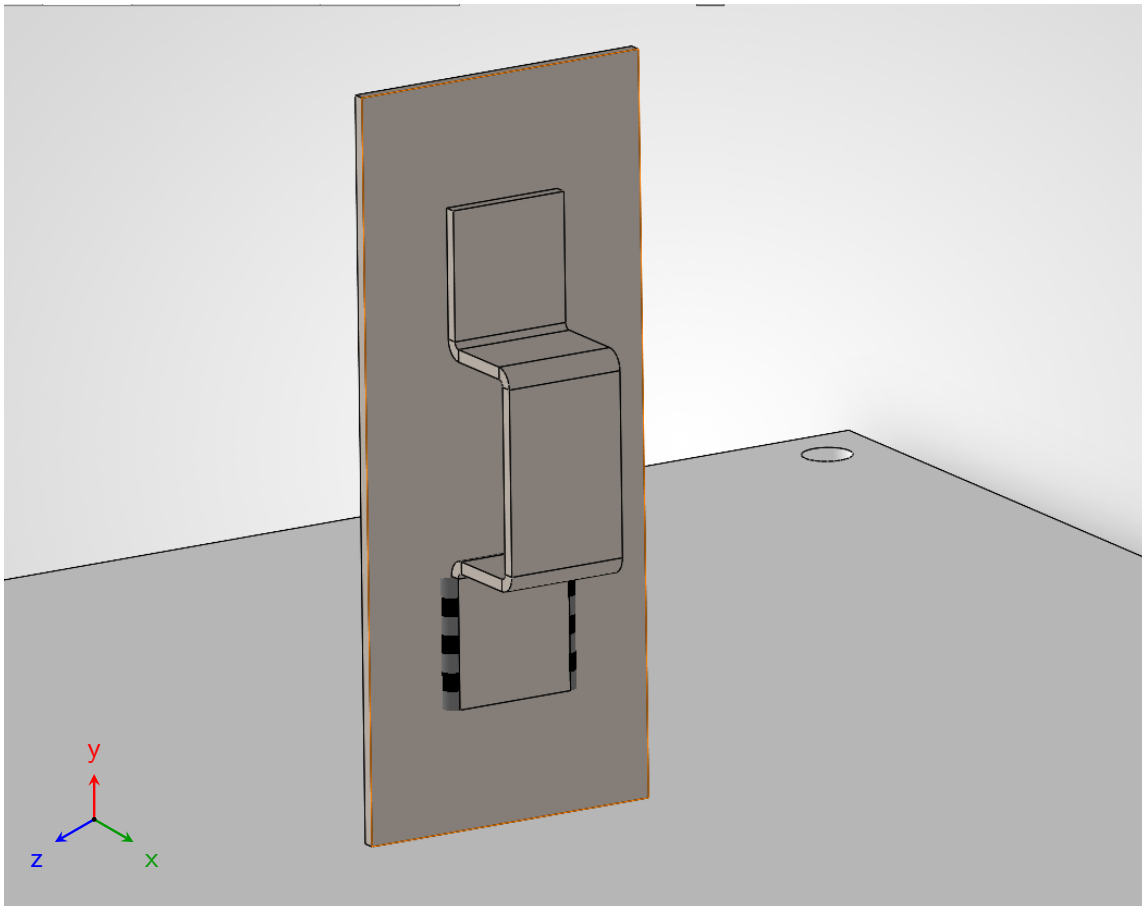


Figure 4.2.: Vertically Oriented Base Plate in ANSYS [6]

The vertical orientation, shown in Figure 4.2, was highly unstable. When loaded to clamp the part in the Y -direction, the plate's thin aspect ratio ($t = 2$ mm) led to localized buckling. Instead of transmitting force evenly through the weld toe to create a pure in-plane gradient ($\partial u / \partial x$). This was observed from deformation pattern which was in the middle of base plate. This instability caused out-of-plane displacements ($X_{\max} = 5.49 \times 10^{-4}$ mm) that were much larger than the in-plane displacements ($Y_{\max} = 9.27 \times 10^{-5}$ mm). Since the out-of-plane phase from bending (N_{oop}) would overwhelm the optical sensor, the vertical orientation was not used for future study.

Case 3: Horizontal Base Plate Orientation

To eliminate the buckling and bending instabilities of Case 1, the specimen was rotated into a

horizontal orientation, and a central grip handle was integrated on the back of the base plate (as shown in Figure 3.2). In this setup, the flat base plate lies within the $Y-Z$ plane, with the central handle extending along the global X -axis.

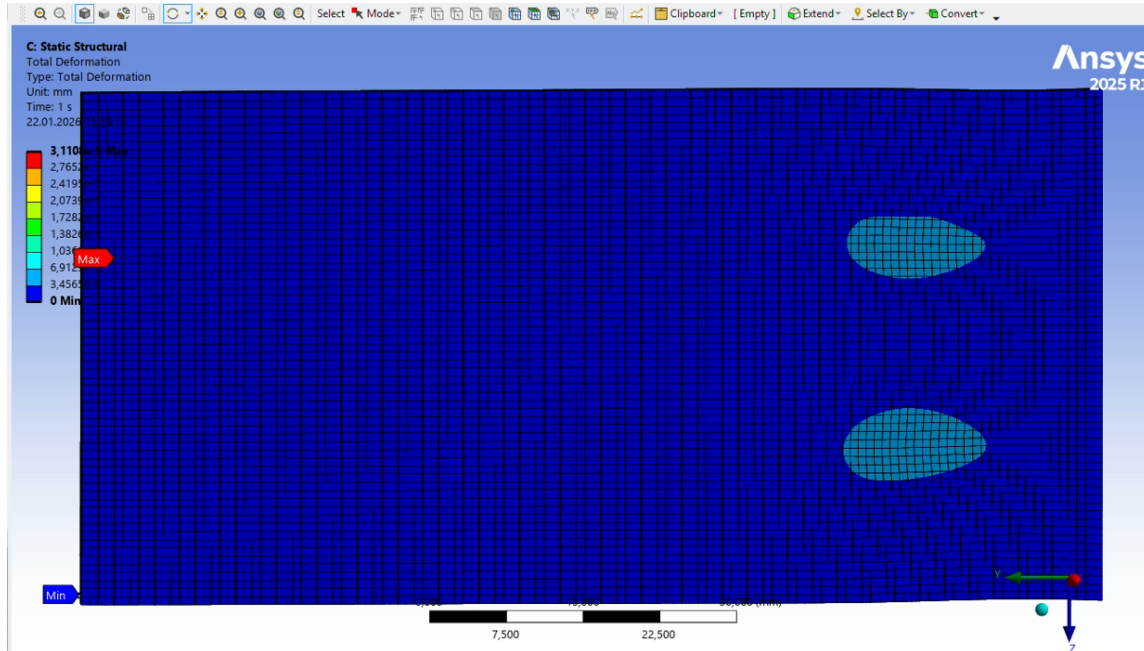


Figure 4.3.: Finite Element Strain Plot of the Horizontal Weld Zone from ANSYS Mechanical.[6]

The horizontal configuration addresses these mechanical instabilities by aligning the primary loading axis parallel to the flat surface of the base plate. By applying the force along the longitudinal axis (Y -direction), the load path passes directly through the weld joint, localizing the resulting strain field right at the stiffness transition boundary (Figure 4.3).

Furthermore, this orientation minimizes the out-of-plane bending moment because the loading vector remains coplanar with the plate's neutral axis. This configuration effectively suppresses parasitic out-of-plane displacements (X -direction), ensuring that horizontal in-plane displacement (u) remains the dominant deformation mode.

Consequently, orienting the base plate horizontally and applying the load along the longitudinal Y -direction stabilizes the overall structural response. This setup successfully isolates the horizontal displacement gradient ($\partial u / \partial x$), making this geometry the most suitable candidate for generating clean input data for the synthetic in-plane shearographic imaging pipeline.

4.2 Boundary Condition

Two boundary condition configurations were tested to determine how the specimen should be constrained for generating measurable in-plane deformation at the weld.

Case 3: Continuous Full-Strip Fixation (Rejected)

In the first test, a continuous, rigid displacement constraint was used along the entire rear and

front strip at the bottom of the base plate (Figure 4.4). This setup anchored the specimen under load but caused significant boundary-induced artifacts.

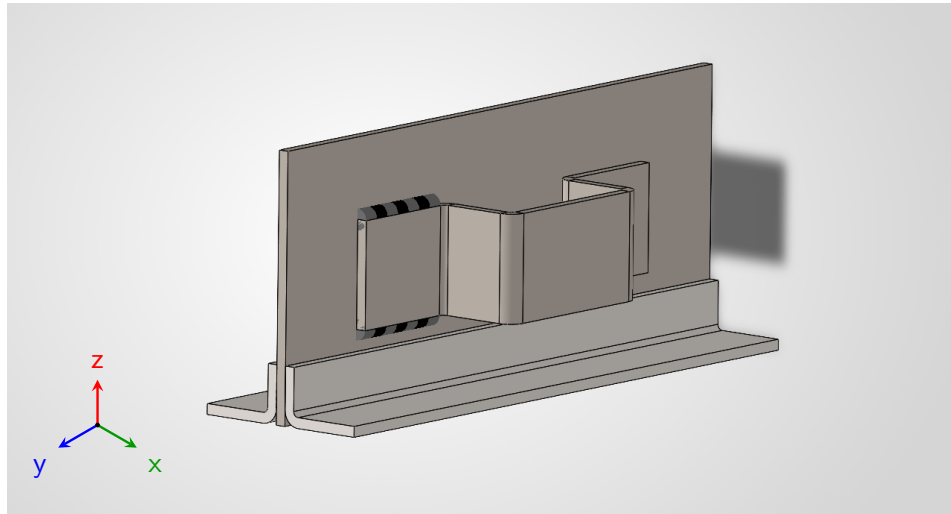


Figure 4.4.: Isometric View of the Considered Boundary Condition From SolidWorks 2026[27]

After applying this boundary condition, the deformation pattern did not focus on the welded region. Instead, it spread mostly to the outer areas of the base plate. The strain field was controlled by global bending and boundary effects, not by local deformation at the weld, which is the main focus of this study. As shown in Figure 4.5, the displacement gradients needed for weld evaluation could not be separated in this setup. Because of this, the configuration was considered unsuitable for in-plane deformation analysis and was not used further.

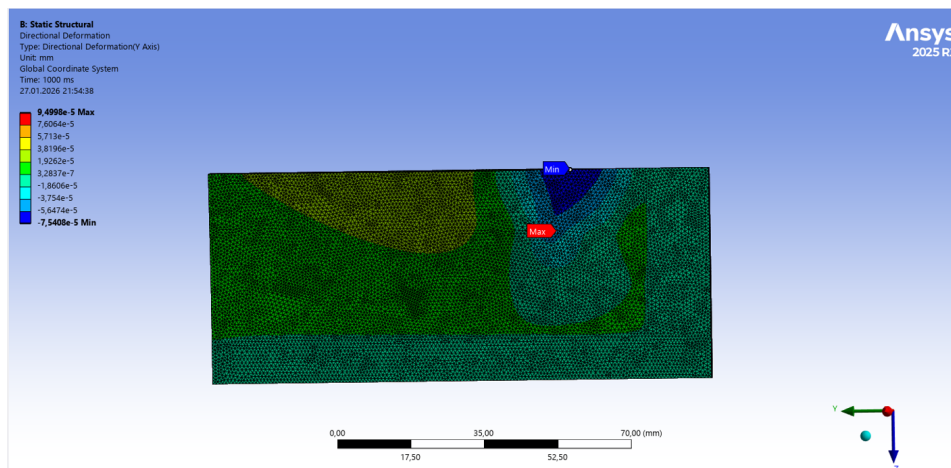


Figure 4.5.: Directional Deformation for the Full-Strip Fixation Boundary Condition From ANSYS Mechanical [6] .

Case 4: C-Clamp Fixation (Final Setup)

The final boundary condition was set by placing fixed supports at the two C-clamp areas at each end of the specimen. This approach holds the plate only where it is actually clamped, so the rest of the structure can deform naturally under load. Unlike the full-strip fixation, which was not used, the C-clamp setup prevents the rear surface from being over-constrained and allows the welded region

to deform naturally. This method closely matches the real experimental clamping and ensures that artificial bending from the boundaries does not affect the deformation field.

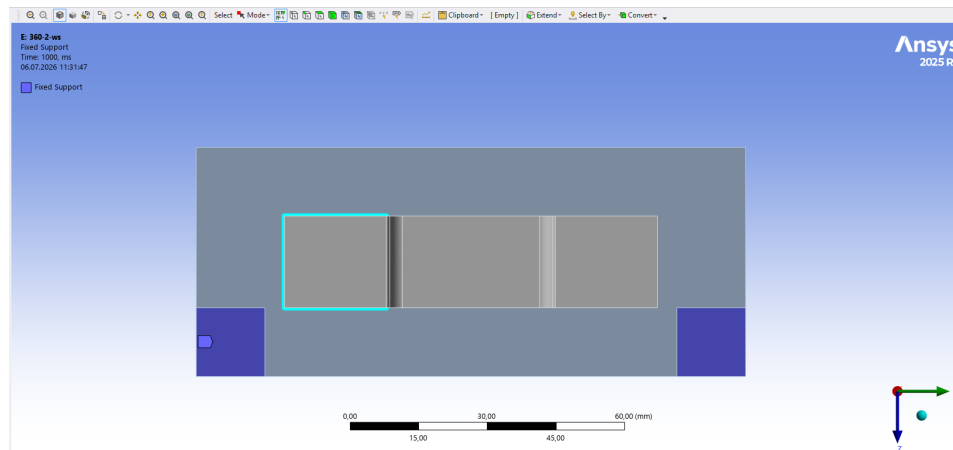


Figure 4.6.: Final Boundary Condition with Fixed Supports at the C-Clamp Regions in ANSYS Mechanical [6]

The Y-direction deformation field indicates that the C-clamp fixation produces a clear, localized strain concentration at the weld. The deformation remains localized near the welded edge and does not spread across the plate, which means the boundary condition effectively isolates the in-plane displacement gradients required for evaluation. Figure 4.7 shows that the deformation is mainly caused by the material change at the weld, with very little unwanted out-of-plane bending. This result aligns with the simulation goal and confirms that the C-clamp setup is the appropriate boundary condition for further analysis.

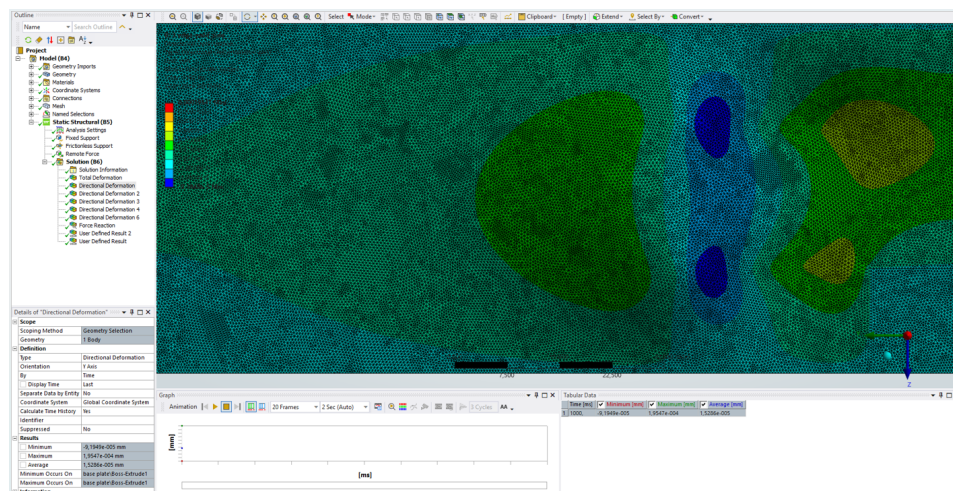


Figure 4.7.: Resultant Y-Direction Deformation for the C-Clamp Fixation Configuration in ANSYS Mechanical [6].

4.3 Loading Condition Evaluation

The loading evaluation began with a test load of 100 N to assess whether the specimen exhibited any in-plane deformation. The weld exhibited measurable in-plane deformation, but the difference

between the Y- and X-directional deformations was too large. The values were not selected using a specific mechanical criterion. Instead, it simply subtracted and added 20 N from the previous simulation to make a basic two-point comparison of how loading position and direction affect the Y-direction deformation gradient.

Case 5: Loading Magnitude and Direction

The deformation data in Table 4.1 show that where the load is applied has a strong effect on the mechanical response. This effect appears in both in-plane and out-of-plane behaviors in the weld zone, regardless of the applied load level. At 60 N and 80 N, loading on the 3-edge weld side consistently produces the lowest $X_{\max}$ (out-of-plane bending) and the most localized $Y_{\max}$ at the weld line. This result points to a mainly in-plane deformation pattern. In contrast, loading on the opposite side (3-edge opposite and 2-edge opposite) leads to higher $Z_{\max}$ values and much larger $X_{\max}$ values. This shows that when the load is applied to the opposite side, the deformation moves away from the weld and becomes mainly controlled by out-of-plane bending.

While the 3-edge weld-side setup produces the strongest in-plane gradient (Y-direction), the opposite-side loading was chosen for the experimental fringe observation. This choice is based on how the optical shearography system works, since it is much more sensitive to out-of-plane displacement gradients than to in-plane shifts. Opposite-side loading creates a strong bending component ($X_{\max}$), which leads to dense, clear, and high-contrast interference fringe patterns. These fringes are easily detected by the shearing camera system, making this setup the best option for finding subsurface defect anomalies.

Table 4.1.: Directional Deformation for Different Loading Positions and Magnitudes

Simulation	Edge / direction	Load	$Y_{\max}$ [mm]	$Z_{\max}$ [mm]	$X_{\max}$ [mm]
1	3-edge (weld side)	60 N	9.2736×10^{-5}	7.4115×10^{-5}	5.4991×10^{-4}
2	3-edge (opposite side)	60 N	1.5165×10^{-4}	1.3128×10^{-4}	3.9126×10^{-4}
3	2-edge (weld side)	60 N	1.1566×10^{-4}	7.7918×10^{-5}	5.6708×10^{-4}
4	2-edge (opposite side)	60 N	1.3895×10^{-4}	1.3134×10^{-4}	5.2391×10^{-4}
5	3-edge (weld side)	80 N	7.4204×10^{-5}	1.9231×10^{-5}	4.1285×10^{-5}
6	3-edge (opposite side)	80 N	2.0220×10^{-4}	1.7504×10^{-4}	5.2168×10^{-4}
7	2-edge (weld side)	80 N	1.5421×10^{-4}	1.0389×10^{-4}	7.5611×10^{-4}
8	2-edge (opposite side)	80 N	1.8527×10^{-4}	1.7513×10^{-4}	6.9855×10^{-4}

4.4 Mesh Refinement and Gradient Formation

This chapter explains the main ideas behind mesh refinement and controlled gradient formation. It describes how mesh density influences deformation accuracy and why it is important to refine the mesh near the weld. All numerical assessments, including different mesh setups, deformation results, and convergence behavior, are shown in Case 6. This approach allows the chapter to focus on the methods, while the case study provides the full technical reasoning behind the final mesh selection.

Case 6: Mesh Convergence Evaluation

Table 4.2 shows the full mesh-convergence evaluation for the global body and welded-edge region. The deformation values remain within a very narrow range across all mesh types, indicating that the model is not very sensitive to global mesh density. The coarse 1 mm quadrilateral and tetrahedral meshes give $Y_{\max}$ deformation values of 0.00097032 mm and 0.00098174 mm, setting the upper limit for deformation. When the mesh is refined to 0.5 mm and 0.6 mm, the deformation drops slightly, with values approaching 0.000957 mm.

A fully refined 0.2–0.2 mm mesh was also tested to see whether using a fine mesh throughout would make a real difference. This setup yielded the lowest deformation value (0.00095501 mm), but the improvement over the chosen 0.6–0.2 mm mesh (0.00095589 mm) was only 0.09 %, which is much less than what is meaningful for gradient extraction or weld-region deformation analysis. However, the computational time increased by about 30 minutes, a significant increase for almost no gain in accuracy.

The final setup uses a 0.6 mm global body mesh with a locally refined 0.2 mm weld mesh, which gives the best balance between accuracy and efficiency. This mesh yields a deformation of 0.00095589 mm, within 0.1 % of the fully refined 0.2–0.2 mm mesh, but at much lower computational cost. The fine tetrahedral mesh at the weld captures the deformation gradients well, while the moderately dense global mesh keeps computational cost down in areas with low sensitivity to gradients.

Based on these results, the 0.6–0.2 mm fine tetrahedral mesh was chosen as the final mesh strategy for all subsequent simulations.

Table 4.2.: Mesh Strategy Overview and Resulting Deformation

Body Mesh Size	Weld Mesh Size	Mesh Type	$Y_{\max}$ deformation
1 mm	1 mm	Quadrilateral - Coarse	0.00097032 mm
1 mm	1 mm	Tetrahedral - Coarse	0.00098174 mm
0.5 mm	0.5 mm	Tetrahedral - Coarse	0.00095845 mm
0.2 mm	0.2 mm	Tetrahedral - Coarse	0.00095501 mm
0.6 mm	0.2 mm	Tetrahedral - Coarse	0.00095708 mm
0.6 mm	0.2 mm	Tetrahedral - Fine	0.00095589 mm

4.5 Optical Parameters Evaluation

After establishing a stable structural displacement field with the optimized finite element model, this section examines how the spatial and optical settings of the shearographic setup affect the visibility, density, and detectability of the fringe patterns. Displacement data from the ANSYS mechanical solver were used to generate synthetic phase-difference maps with the modified InterShear post-processing pipeline.

This analysis addresses the well-known trade-off in digital shearography: balancing the numerical

noise introduced by spatial differentiation against the loss of fringe density from smoothing filters. By systematically changing the smoothing scale (σ), applied mechanical load (F), laser wavelength (λ), and shearing distance (δ), the study identifies a clear range of settings for reliable in-plane defect detection.

4.5.1 Synthetic Fringe Generation and Noise Reduction

Case 7: In-Plane Fringe Pattern Detection and Filter Effect

The initial synthetic fringe reconstruction was performed using the displacement field obtained from a baseline compressive load of 80 N, as illustrated in Figure 4.8. The objective was to evaluate whether a standard low-load configuration could yield clear, readable phase-difference maps under typical laboratory configurations.

Using a green laser with a wavelength of $\lambda = 532$ nm and a shear distance of $\delta = 5$ mm, the theoretical maximum in-plane fringe order (N_{ip}) from the main shearographic phase equation is:

$$N_{ip} = \frac{2}{\lambda} \sin \theta \left(\frac{\partial u}{\partial x} \right) \delta \approx 2.6896 \quad (4.1)$$

The raw gradient plot shows that the structural displacement gradient is concentrated near the weld toe. However, the synthetic fringe pattern has high-frequency spatial noise. This noise arises from taking numerical derivatives of discrete FE node displacements ($\partial u / \partial x$), which is similar to the laser speckle noise observed in real experiments [21].

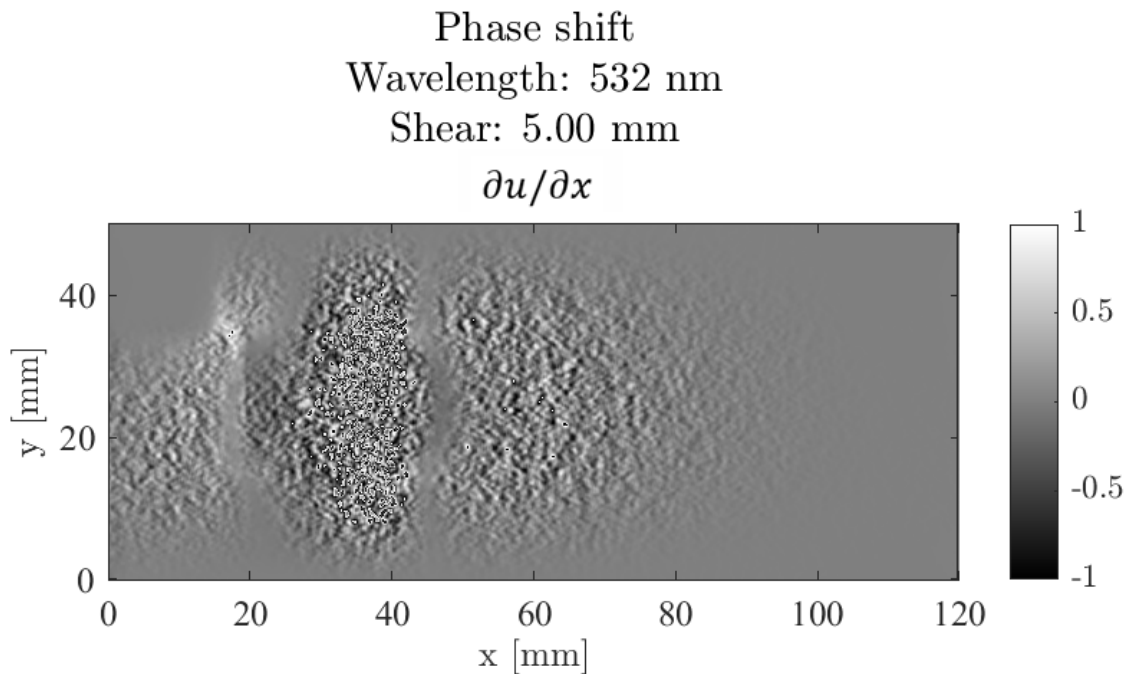


Figure 4.8.: Raw Horizontal Displacement Gradient at 80 N Load Before Filtering, Generated From Matlab [18].

A spatial Gaussian smoothing filter was used on the displacement fields to make the fringe map easier to read [28]. Setting the smoothing parameter to $\sigma = 8$ removed most of the high-frequency noise and cleaned up the phase boundaries, as shown in Figure 4.9. However, this filter also smoothed out the peak values near the stiffness transition, reducing the effective peak fringe order by about 60%:

$$N_{ip, \text{reduced}} \approx 1.07584 \quad (4.2)$$

Because of this large reduction in fringe order, only a small density of fringes appears across the whole region of interest. With so few fringes, it is not possible to find defect boundaries or measure strain fields accurately. This shows that although an 80 N load is structurally stable, it does not induce sufficient deformation for the spatial filtering required to produce clear fringes.

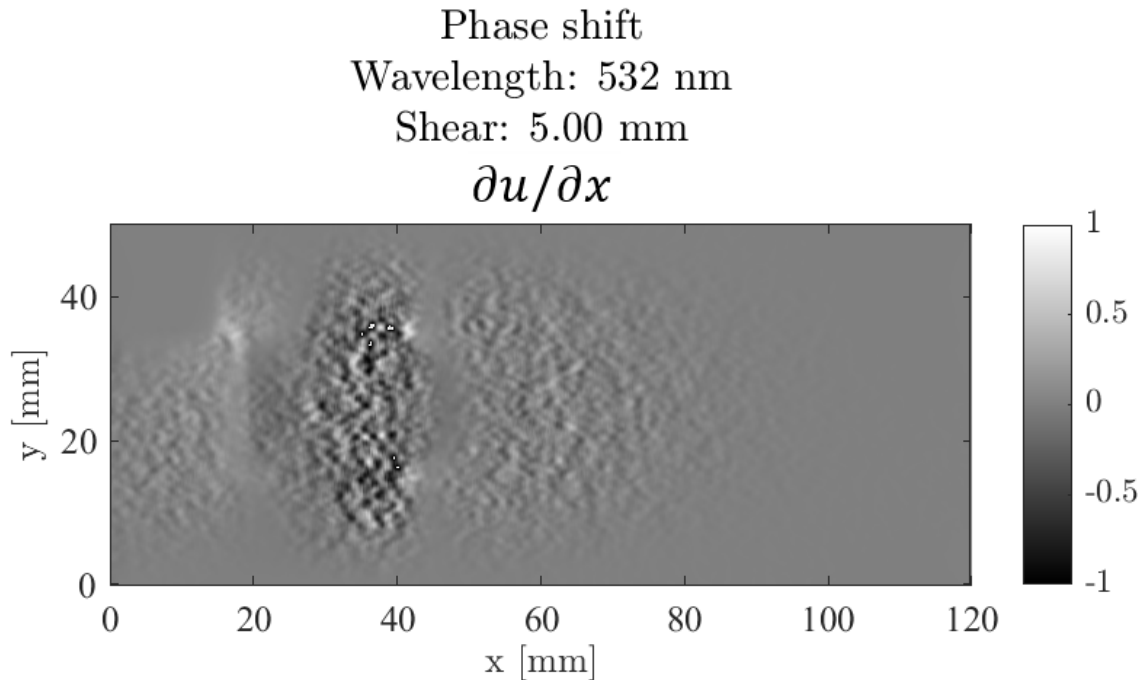


Figure 4.9.: Synthetic In-Plane Fringe Pattern After Gaussian Smoothing $\sigma = 8$, Generated From Matlab [18].

4.5.2 Mechanical Compensation for Signal Reduction

Case 8: Effect of Increased Loading Magnitude

Case 7 showed that using a Gaussian filter to reduce numerical noise also removed about 60 % of the useful displacement gradient signal. Since spatial smoothing is needed to get usable phase-difference maps, this loss had to be offset by increasing the specimen's physical deformation.

In the finite element model, which assumes linear elastic material behavior, both the displacement field (u) and its spatial derivative increase in direct proportion to the applied force (F). As a result, the number of fringes is directly proportional to the load:

$$N \propto \left(\frac{\partial u}{\partial x} \right) \propto F \quad (4.3)$$

To make up for the 60 % signal loss from the $\sigma = 8$ Gaussian filter and reach an evaluating fringe pattern that standard shearing cameras can clearly resolve. As it was already visible in 60 N loading, with lower fringe density condition, therefor, it is the base load to perform evaluation with 60 % increased load. This meant increasing the mechanical load by a factor of 6, from the original 60 N to 360 N.

Tests with the 360 N load confirmed that the resulting displacement gradient was sufficient to produce high-contrast, multi-fringe patterns. This setup also kept the structural details of the weld-toe transition visible, even after strong noise-reduction filters were applied.

4.6 Combined Effect of Wavelength and Shear Distance

Case 9: Co-Influence of Wavelength and Shear Distance

With the optimized 360 N loading setup, a final parametric study explored how both the laser wavelength (λ) and the physical shear distance (δ) together affect the sensitivity of the shearographic measurement.

Effect of Illumination Wavelength

The wavelength of the laser light sets the scale for the phase-difference maps. Since phase change is measured against the light source's wavelength, the fringe density goes up as the wavelength gets shorter:

$$N \propto \frac{1}{\lambda} \quad (4.4)$$

To test this sensitivity, three common laser wavelengths were used with the same loading (360 N) and shearing distance ($\delta = 5$ mm): blue ($\lambda = 450$ nm), green ($\lambda = 532$ nm), and red ($\lambda = 620$ nm) lasers.

Table 4.3.: Optical Sensitivity and Fringe Order for Standard Laser Wavelengths at 360 N Load

Laser Source	Wavelength (λ)	Relative Optical Sensitivity
Blue Helium-Cadmium	450 nm	118.2%
Green DPSS	532 nm	100.0% (Baseline)
Red Helium-Neon	620 nm	85.8%

As shown in Table 4.3, the blue laser ($\lambda = 450$ nm) produced the highest fringe density, giving the best spatial resolution for mapping strain. The red laser ($\lambda = 620$ nm) produced a much sparser fringe pattern, resulting in lower measurement sensitivity.

Although the blue laser gives the highest sensitivity, green lasers ($\lambda = 532$ nm) are usually chosen in experiments because they are more power-efficient and work better with standard silicon-based CCD sensors. This makes green the most practical choice for validation.

Effect of Shear Distance

The physical shear distance (δ) is the distance by which the two overlapping images are shifted on the camera sensor[4]. This distance sets the spatial gauge length for the measurement:

$$\Delta\phi_x \approx \frac{4\pi}{\lambda} \sin \theta \left(\frac{\partial u}{\partial x} \right) \delta \quad (4.5)$$

To find the best setup, shear distances of 2 mm, 4 mm, and 5 mm were tested. The simulations showed that a small shear distance of 2 mm resulted in a very sparse, low-sensitivity fringe pattern, making it difficult to distinguish the weld-toe strain from background noise.

When the shear distance was increased to 4 mm and 5 mm, the phase difference became stronger. This produced clear, high-density fringe patterns with strong visual contrast near the stiffness transition.

Results and Parametric Evaluation

The last evaluation of the synthetic shearographic imaging pipeline uses two detailed structural cases. These cases help separate the effects of loading direction, weld boundary shape, and optical setup on the in-plane fringe patterns. The complete data for all evaluated cases can be found in the Appendix VI.5 to VI.8.

All simulations used the optimized 360 N compressive load setup described in Section 4.5. To test how the phase-extraction pipeline handles numerical noise, synthetic phase-difference maps were generated and evaluated at three Gaussian smoothing levels ($\sigma = 5$, $\sigma = 10$, and $\sigma = 15$). This shows how the results change from noisy, high-frequency gradients to clear, easy-to-read interference fringes.

5.1 Evaluation 1: Effect of Loading Direction (Weld-Side vs. Opposite-Side)

The position of the load relative to the stiffness boundary strongly affects the specimen's behavior. This section compares Case 10, where the load is applied on the weld-side edge, with Case 11, where the load is applied to the edge opposite the weld. Both cases use the 3-edge welded specimen.

Table 5.1 and Table 5.2 show the calculated fringe counts (N_{ip}) for different illumination wavelengths (λ) and shear distances (δ).

Table 5.1.: Synthetic In-Plane Fringe Counts for Weld-Side Loading on a 3-Edge Welded Specimen (360 N)

Wavelength [nm]	Shear Distance [mm]	Fringe Count N_{ip}
450	2.0	0.82
450	4.0	1.65
450	5.0	2.06
532	2.0	0.70
532	4.0	1.39
532	5.0	1.74
620	2.0	0.60
620	4.0	1.20
620	5.0	1.49

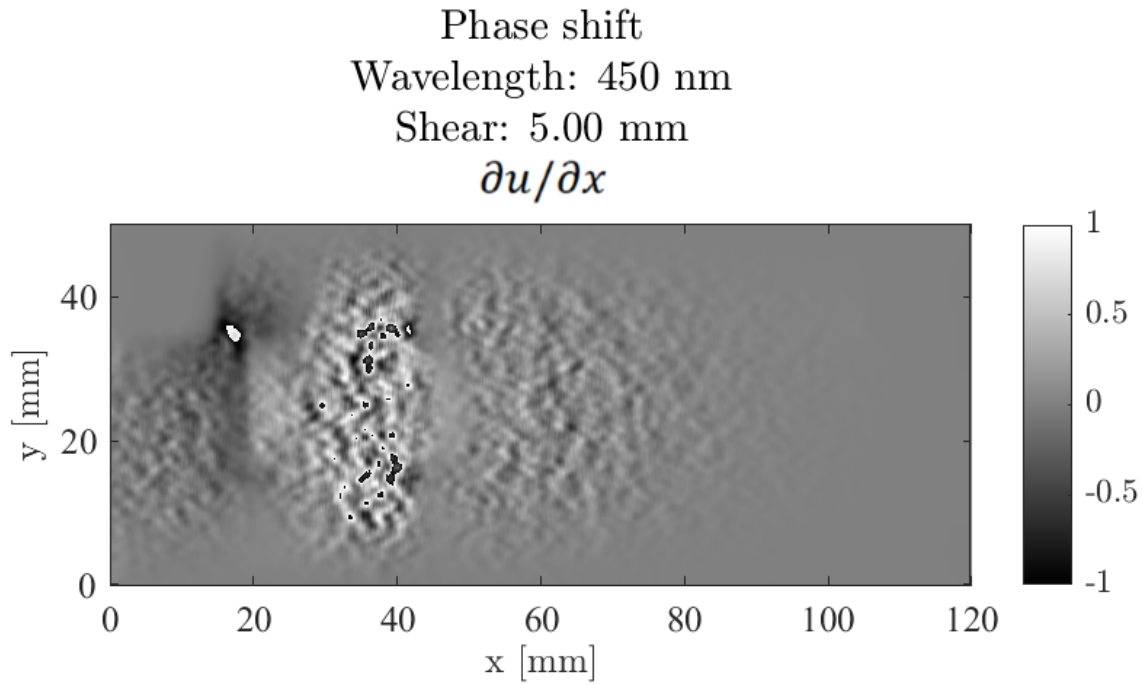
Table 5.2.: Synthetic In-Plane Fringe Counts for Opposite-Side Loading on a 3-Edge Welded Specimen (360 N)

Wavelength [nm]	Shear Distance [mm]	Fringe Count N_{ip}
450	2.0	1.42
450	4.0	2.83
450	5.0	3.54
532	2.0	1.20
532	4.0	2.40
532	5.0	3.00
620	2.0	1.03
620	4.0	2.06
620	5.0	2.57

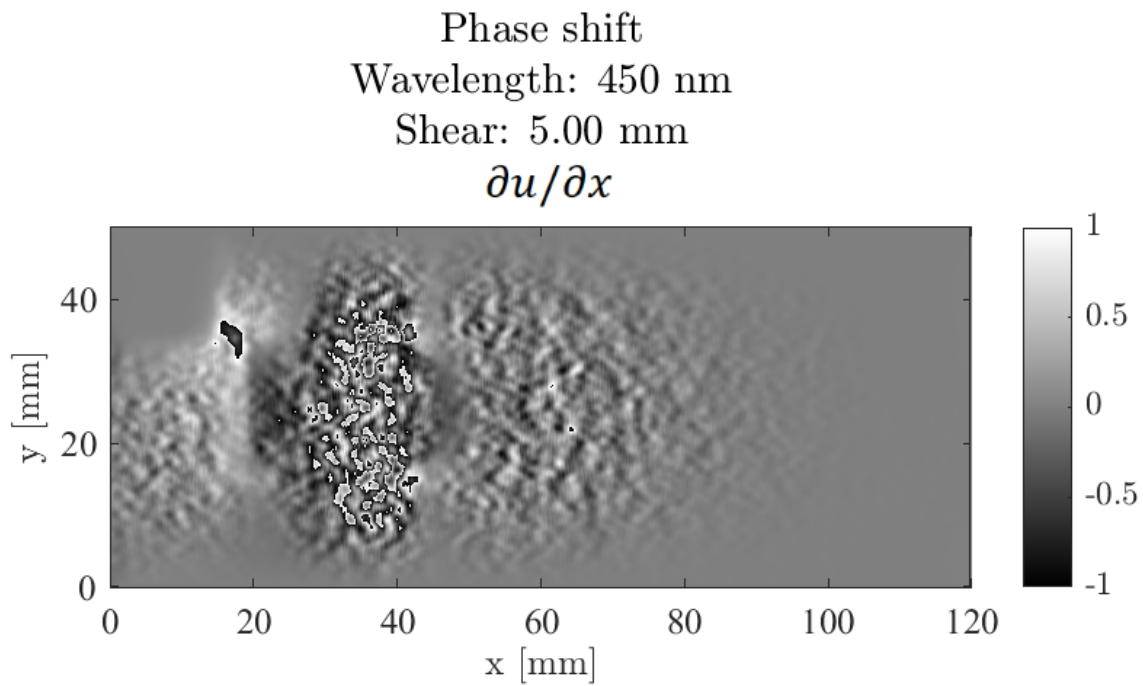
Comparing these datasets shows a clear difference in mechanical response. When the load is applied to the opposite side of the weld (Case 11), the fringe density is consistent across all setups. For example, at $\lambda = 450$ nm and $\delta = 5.0$ mm, the fringe count is $N_{ip} = 3.54$ for opposite-side loading, but only $N_{ip} = 2.06$ for weld-side loading.

This difference comes from the specimen's boundary conditions. When the load is applied to the weld-side edge, the forces act near the stiff welded area. The fillet weld increases the local area moment of inertia, so the structure resists in-plane shear and instead bends slightly in a small, localized area.

In contrast, loading the opposite, unreinforced edge creates a larger moment arm compared to the fixed side. This causes a strong, large-scale shear gradient ($\partial u / \partial x$) across the main plate. As a result, opposite-side loading is much better for studying in-plane deformation with shearography. This difference is easy to see in the phase-difference maps in Figure 5.1, which use a wavelength of 450 nm, a shear distance of 5.0 mm, and a smoothing value of $\sigma = 10$. The weld-side loading map (Figure 5.1a) has broad, low-density fringes that are hard to see clearly. In contrast, the opposite-side loading map (Figure 5.1b) shows high-density, well-defined fringes that follow the stiffness change at the weld toe.



(a) Weld-side loading (Case 10)



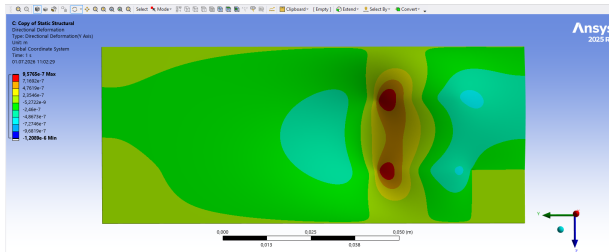
(b) Opposite-side loading (Case 11)

Figure 5.1.: Synthetic Phase-Difference Maps for Weld-Side and Opposite-Side Loading From Matlab [18]

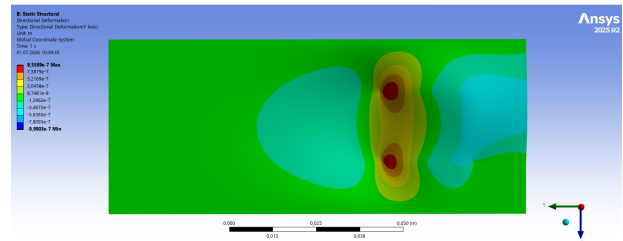
5.2 Evaluation 2: Effect of Weld Geometry (2-Edge vs. 3-Edge Welded Specimens)

The second evaluation examines how differences in geometric weld profiles affect the deformation profile. It compares a 2-edge welded joint with a 3-edge welded joint, both under the same loading conditions (360 N, opposite-side loading).

The FEA deformation profiles in Figure 5.2 show that the overall displacement fields are quite similar. In the 2-edge welded specimen (Figure 5.2a), the displacement spreads more evenly along the free edge, resulting in a slightly higher peak displacement. Adding an extra transverse-welded edge increases the local bending stiffness and slightly restricts the displacement path, thereby concentrating the strain gradients directly along the vertical fillet toe.



(a) 2-edge welded profile



(b) 3-edge welded profile

Figure 5.2.: Finite Element Deformation Plots for 2-Edge and 3-Edge Welded Specimens From ANSYS Mechanical [6].

To see how these structural differences manifest in the optical results, synthetic fringe maps were generated with a high smoothing level of $\sigma = 15$. This high smoothing helps separate the main, low-frequency structural response from local numerical noise. The results are shown in Table 5.3 and Table 5.4.

Table 5.3.: Synthetic In-Plane Fringe Counts for the 2-Edge Welded Specimen (360 N, $\sigma = 15$).

Wavelength [nm]	Shear Distance [mm]	Fringe Count N_{ip}
450	2.0	0.84
450	4.0	1.68
450	5.0	2.11
532	2.0	0.71
532	4.0	1.43
532	5.0	1.78
620	2.0	0.61
620	4.0	1.22
620	5.0	1.53

Table 5.4.: Synthetic In-Plane Fringe Counts for the 3-Edge Welded Specimen (360 N, $\sigma = 15$).

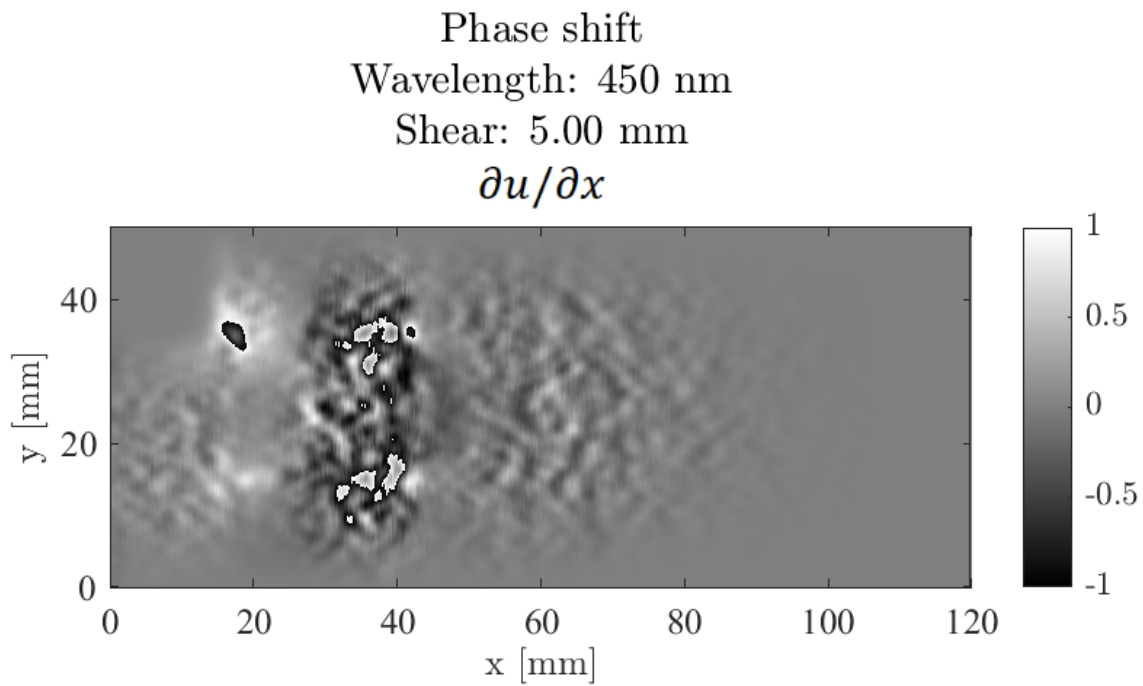
Wavelength [nm]	Shear Distance [mm]	Fringe Count N_{ip}
450	2.0	0.78
450	4.0	1.57
450	5.0	1.96
532	2.0	0.96
532	4.0	1.33
532	5.0	1.66
620	2.0	0.57
620	4.0	1.14
620	5.0	1.42

Comparing the numbers shows that adding the 3-edge weld slightly lowers the overall fringe density. For example, at a blue wavelength ($\lambda = 450$ nm) and a 5.0 mm shear distance, the 2-edge specimen has $N_{ip} = 2.11$, while the 3-edge specimen has $N_{ip} = 1.96$.

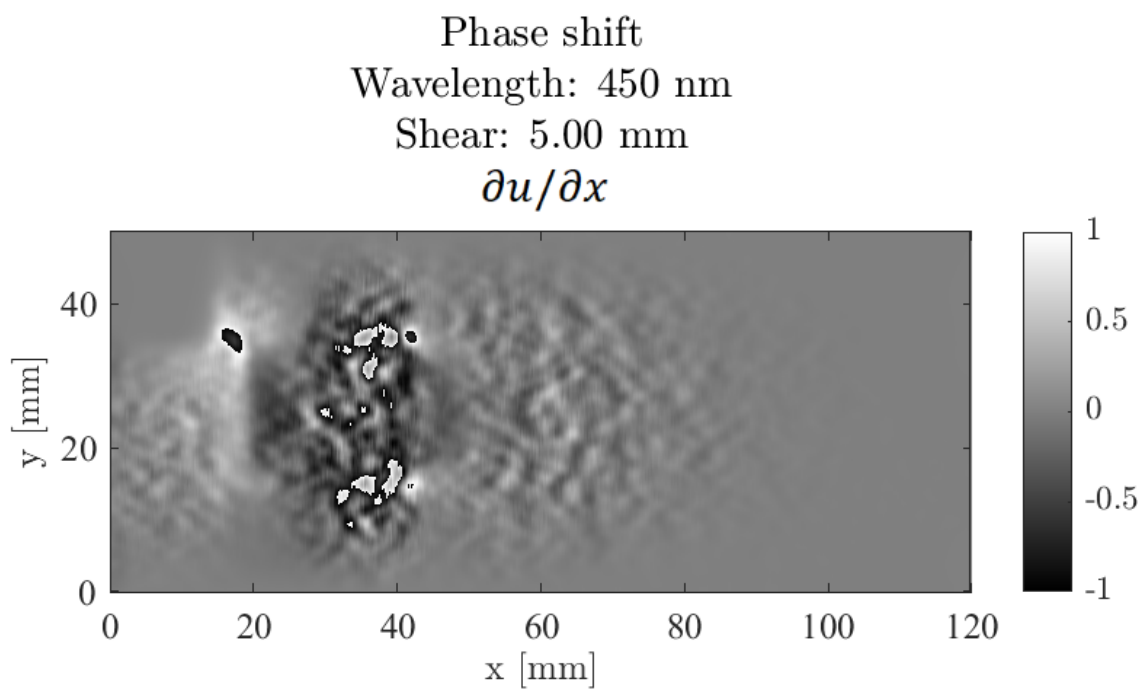
This 7.1% drop in optical sensitivity is caused by the transverse weld bead, which acts as a stiffening rib that limits local material contraction and shear deformation along the main loading axis.

The phase-difference maps in Figure 5.3 confirm that the overall fringe geometry and orientation stay very consistent between the two cases. While the 3-edge welded geometry provides higher structural restraint, causing the fringe pattern to remain confined near the center, whereas the 2-edge welded case lacks this resistance, allowing the deformation and as result, the fringe shift to transfer more freely toward the loading direction.

This finding is important for experimental validation. It shows that small geometric changes in the weld profile, such as switching from a double-sided fillet weld to a three-sided pocket weld, have only a minor effect on the overall in-plane displacement gradients. The main factor affecting the shearographic fringe pattern remains the direction of the loading vector relative to the main stiffness boundary.



(a) 2-edge welded configuration



(b) 3-edge welded configuration

Figure 5.3.: Synthetic Phase-Difference Maps for 2-Edge and 3-Edge Welded Configurations From MATLAB [18]

Conclusions

This research developed and tested a complete workflow to evaluate in-plane surface deformation gradients ($\partial u/\partial x$) caused by changes in structural stiffness, using digital shearography. By connecting finite element analysis (FEA) in ANSYS with synthetic fringe pattern reconstruction in MATLAB, the study measured the key mechanical and optical factors that affect the sensitivity of gradient-based non-destructive testing. One main finding is that the direction of the applied load has a much greater effect on high-contrast fringe formation than local structural features. When a 360 N compressive load is applied to the unreinforced edge, the fringe density is much higher ($N_{ip} = 3.54$ at $\lambda = 450$ nm and $\delta = 5.0$ mm) than when the load is applied to the weld side ($N_{ip} = 2.06$). This happens because loading the weld side adds local reinforcement, which reduces in-plane shearing and shifts strain energy into local bending. In contrast, loading the opposite side produces a larger moment arm, resulting in wider and more measurable strain fields. The study also found that optical sensitivity rules control fringe visibility and resolution. According to the interferometer phase formula, the density, contrast, and clarity of the synthetic fringe patterns increase as the illumination wavelength decreases ($\propto 1/\lambda$) and as the spatial shearing gauge length increases ($\propto \delta$). Using short-wavelength blue lasers ($\lambda = 450$ nm) and larger shear distances ($\delta = 4$ to 5 mm) gives the best sensitivity to small strain changes, but a gauge length of $\delta = 4$ mm is the best compromise in the lab to balance strong phase mapping with image clarity. The study also measured how much signal is lost due to noise-reduction filters. Digital differentiation of finite element nodes creates high-frequency noise similar to laser speckle, and smoothing it with a Gaussian filter ($\sigma = 5$ to 15) reduces the peak fringe amplitude. A standard filter of $\sigma = 8$ lowers the peak fringe order by about 60%, making lower-load profiles (60 N to 80 N) hard to see. Therefore, a load of 360 N is needed to produce clear, multi-fringe phase maps that can track defect boundaries without changing the basic elastic behavior. Comparing 2-edge and 3-edge welded-handle specimens showed that changes in the weld profile only slightly affect overall deformation. Adding a third, transverse weld bead acts as a local stiffener, limiting material contraction along the main loading path and causing a small 7.1% drop in peak fringe count (from $N_{ip} = 2.11$ to 1.96 at $\lambda = 450$ nm, $\delta = 5.0$ mm, and $\sigma = 15$). Despite this small decrease, the overall shape and direction of the fringe patterns remain very stable, indicating that the main loading condition is more important than minor geometric changes.

7

Outlook

Several preliminary geometries explored during the development phase revealed local weld discontinuities, where short segments of the weld line were intentionally omitted. These configurations, visible in the early ANSYS models, introduce localized stiffness reductions that are highly relevant for industrial components. Although these cases were not included in the final validated results, they represent a promising direction for future work. A systematic investigation of partial weld interruptions, such as 0.5 mm to 2 mm missing weld segments, could provide deeper insight into how small geometric defects influence in-plane deformation fields and fringe formation. Extending the simulation framework to include these discontinuities would allow the identification of detectability thresholds [12] and support the development of shearographic inspection strategies tailored to real welded structures. Future studies may also combine weld discontinuities with multi-directional loading to evaluate more complex strain interactions [8].

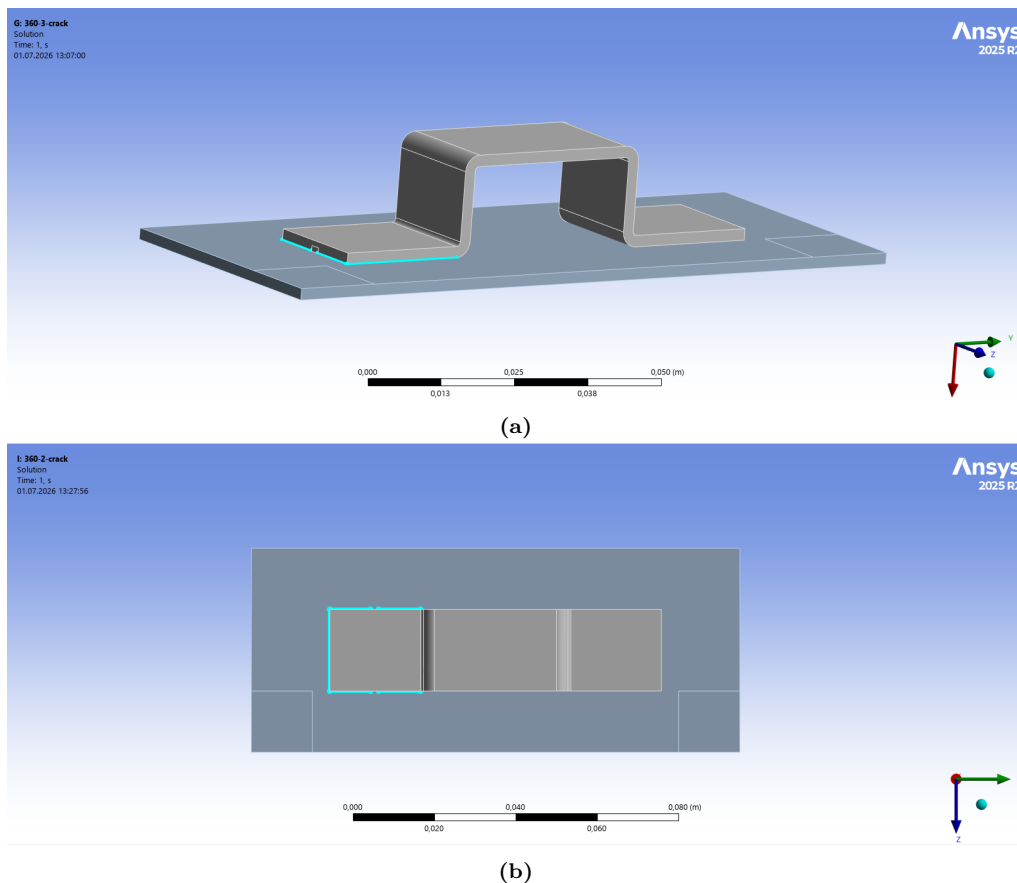


Figure 7.1.: Weld Discontinuity Geometry Configuration From ANSYS Mechanical [6]

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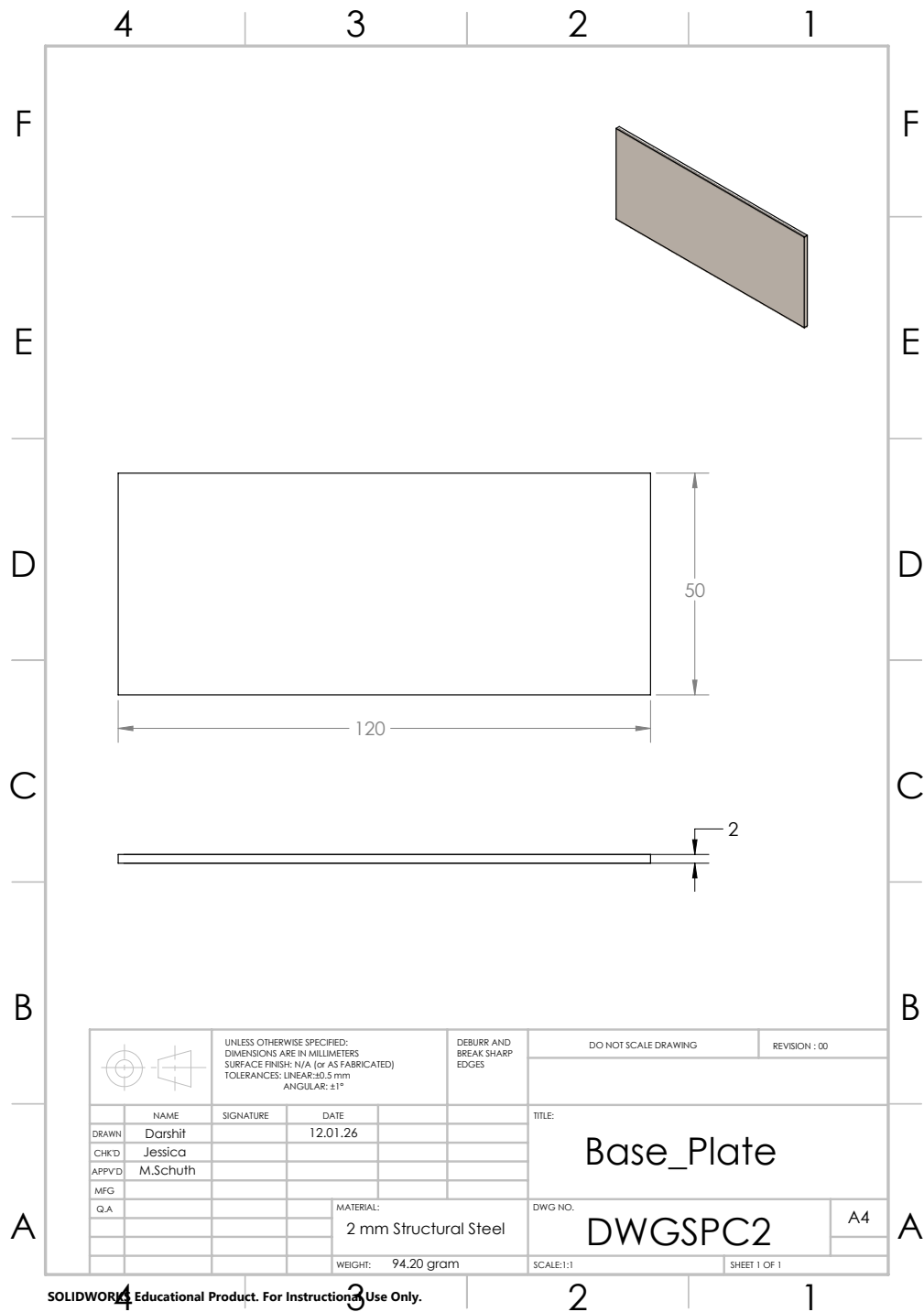
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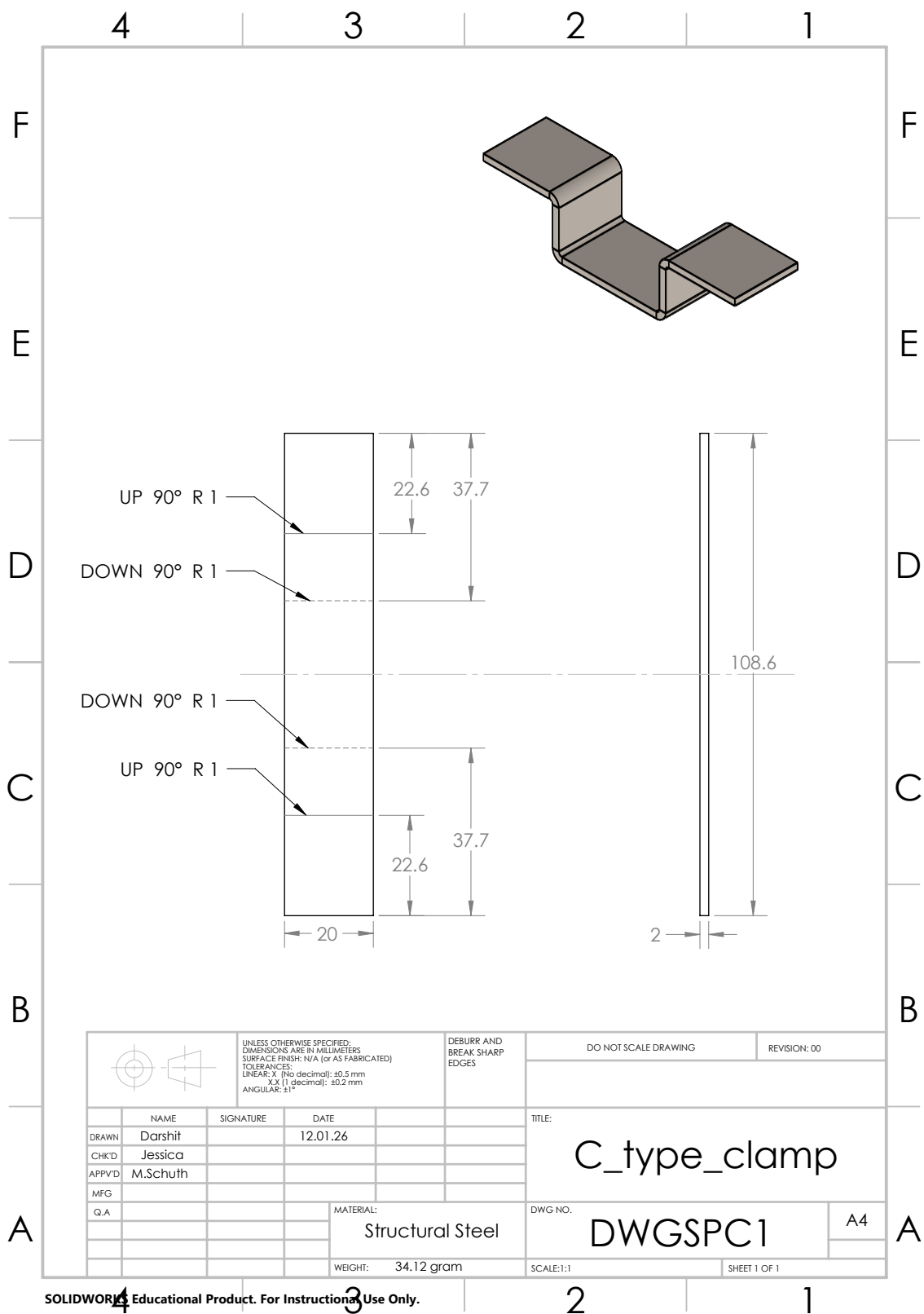
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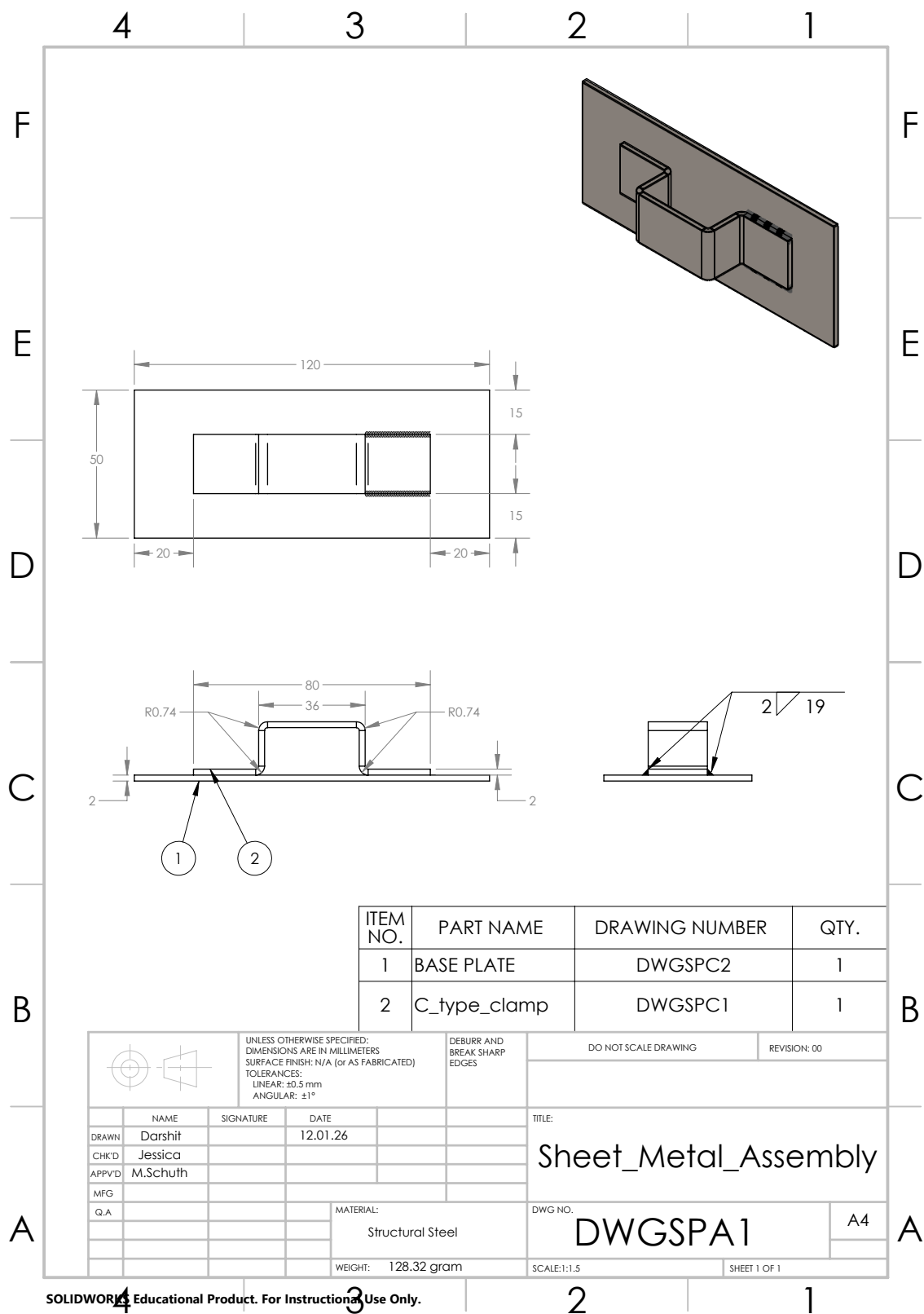
VI.1 Technical Drawing: Base Plate (DWGSPC2)



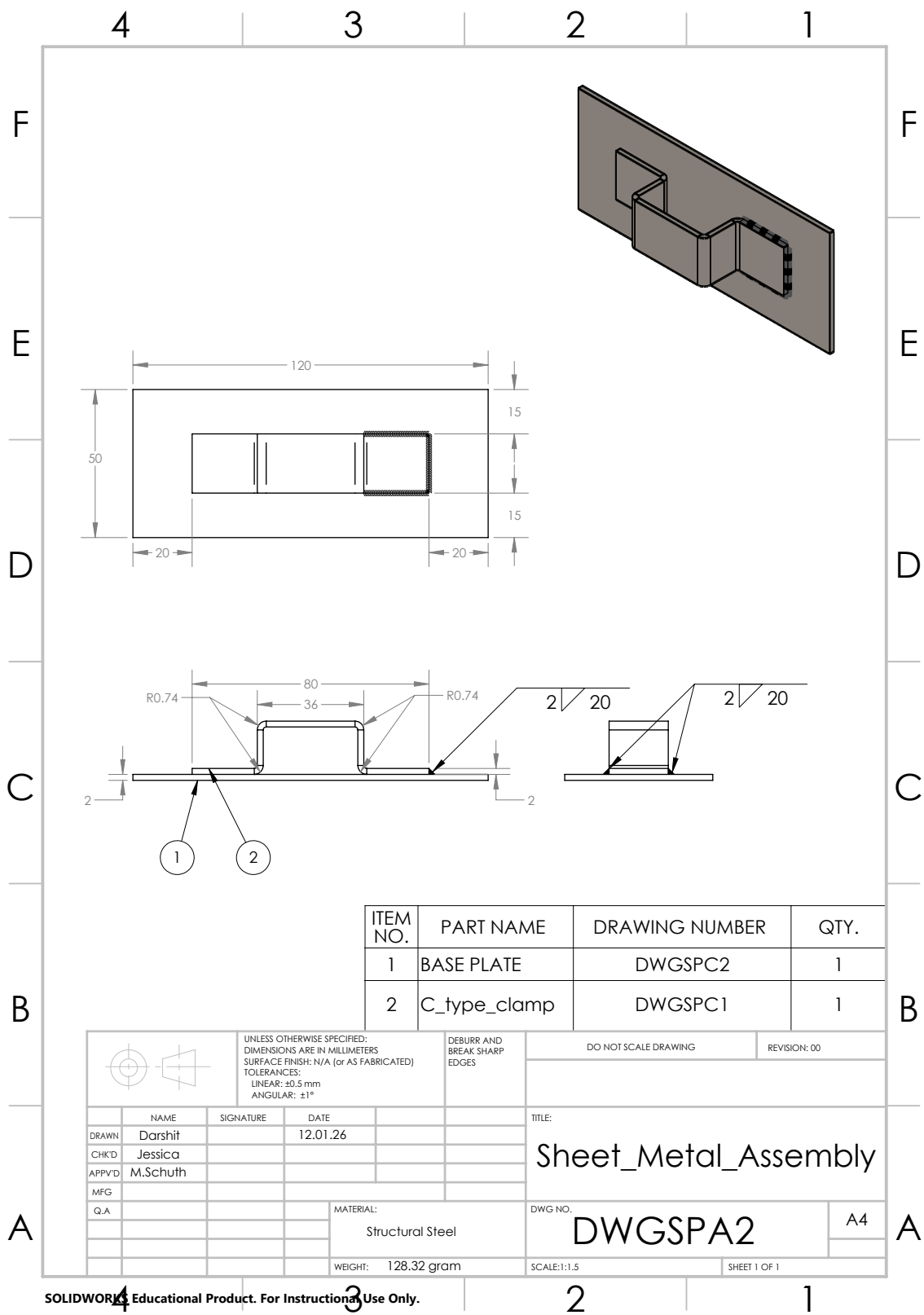
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VI.3 Technical Drawing: Assembly Sheet 1 (DWGSPA1)



VI.4 Technical Drawing: Assembly Sheet 2 (DWGSPA2)



VI.5 Optical Parameter Variation: 3-Edge Specimen, Opposite-Side Loading

Table VI.1.: Optical Parameter Variation for a 3-Edge Welded Specimen, Opposite-Side Loading (360 N)

Wavelength (nm)	Shear (mm)	Sigma	Fringe Count
450	2.0	5	4.05
450	4.0	5	8.10
450	5.0	5	10.12
532	2.0	5	3.42
532	4.0	5	6.85
532	5.0	5	8.56
620	2.0	5	2.94
620	4.0	5	5.88
620	5.0	5	7.35
450	2.0	10	1.42
450	4.0	10	2.83
450	5.0	10	3.54
532	2.0	10	1.20
532	4.0	10	2.40
532	5.0	10	3.00
620	2.0	10	1.03
620	4.0	10	2.06
620	5.0	10	2.57
450	2.0	15	0.78
450	4.0	15	1.57
450	5.0	15	1.96
532	2.0	15	0.66
532	4.0	15	1.33
532	5.0	15	1.66
620	2.0	15	0.57
620	4.0	15	1.14
620	5.0	15	1.42

VI.6

Optical Parameter Variation: 3-Edge Specimen, Weld-Side Loading

Table VI.2.: Optical Parameter Variation for a 3-Edge Welded Specimen, Weld-Side Loading (360 N)

Wavelength (nm)	Shear (mm)	Sigma	Fringe Count
450	2.0	5	2.33
450	4.0	5	4.66
450	5.0	5	5.83
532	2.0	5	1.97
532	4.0	5	3.95
532	5.0	5	4.93
620	2.0	5	1.69
620	4.0	5	3.39
620	5.0	5	4.23
450	2.0	10	0.82
450	4.0	10	1.65
450	5.0	10	2.06
532	2.0	10	0.70
532	4.0	10	1.39
532	5.0	10	1.74
620	2.0	10	0.60
620	4.0	10	1.20
620	5.0	10	1.49
450	2.0	15	0.46
450	4.0	15	0.93
450	5.0	15	1.16
532	2.0	15	0.39
532	4.0	15	0.78
532	5.0	15	0.98
620	2.0	15	0.34
620	4.0	15	0.67
620	5.0	15	0.84

VI.7 Optical Parameter Variation: 2-Edge Specimen, Weld-Side Loading

Table VI.3.: Optical Parameter Variation for a 2-Edge Welded Specimen, Weld-Side Loading (360 N)

Wavelength (nm)	Shear (mm)	Sigma	Fringe Count
450	2.0	5	2.56
450	4.0	5	5.12
450	5.0	5	6.41
532	2.0	5	2.17
532	4.0	5	4.33
532	5.0	5	5.42
620	2.0	5	1.86
620	4.0	5	3.72
620	5.0	5	4.65
450	2.0	10	0.90
450	4.0	10	1.80
450	5.0	10	2.25
532	2.0	10	0.76
532	4.0	10	1.52
532	5.0	10	1.90
620	2.0	10	0.65
620	4.0	10	1.30
620	5.0	10	1.63
450	2.0	15	0.51
450	4.0	15	1.03
450	5.0	15	1.28
532	2.0	15	0.43
532	4.0	15	0.87
532	5.0	15	1.08
620	2.0	15	0.37
620	4.0	15	0.74
620	5.0	15	0.93

VI.8

Optical Parameter Variation: 2-Edge Specimen, Opposite-Side Loading

Table VI.4.: Optical Parameter Variation for a 2-Edge Welded Specimen, Opposite-Side Loading (360 N)

Wavelength (nm)	Shear (mm)	Sigma	Fringe Count
450	2.0	5	4.39
450	4.0	5	8.78
450	5.0	5	10.98
532	2.0	5	3.71
532	4.0	5	7.43
532	5.0	5	9.28
620	2.0	5	3.19
620	4.0	5	6.37
620	5.0	5	7.97
450	2.0	10	1.53
450	4.0	10	3.06
450	5.0	10	3.82
532	2.0	10	1.29
532	4.0	10	2.58
532	5.0	10	3.23
620	2.0	10	1.11
620	4.0	10	2.22
620	5.0	10	2.77
450	2.0	15	0.84
450	4.0	15	1.68
450	5.0	15	2.11
532	2.0	15	0.71
532	4.0	15	1.43
532	5.0	15	1.78
620	2.0	15	0.61
620	4.0	15	1.22
620	5.0	15	1.53