

# Innovation of the “Cut-Clamp-Play” Concept for Robust and Efficient Sheet Metal Material Characterization

Andraž Maček<sup>1,a</sup>, Bojan Starman<sup>2,b</sup>, Miroslav Halilović<sup>2,c</sup>, Fabrice Pierron<sup>3,d</sup>,  
Pascal Lava<sup>3,e</sup> and Sam Coppieters<sup>1,f\*</sup>

<sup>1</sup>KU Leuven, Gent, Belgium

<sup>2</sup>Faculty of Mechanical Engineering, University of Ljubljana, Ljubljana, Slovenia

<sup>3</sup>MatchID, Gent, Belgium

<sup>a</sup>andraz.macek@kuleuven.be, <sup>b</sup>bojan.starman@fs.uni-lj.si, <sup>c</sup>miroslav.halilovic@fs.uni-lj.si,  
<sup>d</sup>fabrice.pierron@matchid.eu, <sup>e</sup>pascal.lava@matchid.eu, <sup>f</sup>sam.coppieters@kuleuven.be  
(\*corresponding author)

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**Abstract.** Material Testing 2.0 (MT2.0) couples full-field deformation measurements (Digital Image Correlation, DIC) with inverse identification methods (Virtual Fields Method, VFM) to extract constitutive parameters from a small number of heterogeneous experiments. This paper presents the *Cut-Clamp-Play* concept: an integrated industrial MT2.0 solution that unifies specimen design, automated testing hardware, and a computationally efficient VFM identification chain to deliver fast, user-friendly sheet-metal characterization. A perforated cruciform specimen is optimized for parameter identifiability of the Yld2000-2d anisotropic yield function and used in a single biaxial test. A working prototype has been built at KU Leuven and used to collect representative DIC data; the measured displacement/strain response is double-symmetric, confirming correct mechanical operation. Projected and early prototype results indicate that the Cut-Clamp-Play approach can reduce operator actions by roughly 70% and produce identification results within one hour for typical sheet-metal cases, while further work is required to make the fully automated “Play” stage robust for industrial deployment.

## Introduction

Accurate constitutive models are essential for predictive engineering simulation in automotive, aerospace, and consumer industries. Traditional material characterization (MT1.0) relies on multiple quasi-homogeneous tests and manual post-processing, which is time-consuming and resource intensive. MT2.0 replaces large test campaigns with a small number of carefully designed heterogeneous experiments - potentially two instead of seventeen [1] - combined with full-field measurement and inverse identification, enabling substantial reductions in experimental effort and improved parameter identifiability [2].

Two practical barriers limit industrial adoption of MT2.0: (i) computational cost of nonlinear inverse identification for anisotropic plasticity, and (ii) high user dependency across specimen preparation, DIC acquisition, and inverse processing. The Cut-Clamp-Play concept addresses these barriers by combining an identifiability-optimized perforated cruciform specimen, a computationally efficient stress-reconstruction strategy embedded in VFM, and an integrated testbed that minimizes operator actions. This paper summarizes the concept, specimen design and identifiability rationale, prototype implementation, representative DIC measurements, and the remaining steps required to industrialize the “Play” automation stage.

## Methodology

**System concept and scope.** The Cut-Clamp-Play concept targets sheet-metal biaxial characterization with minimal operator expertise. The operator performs three actions: *Cut* an optimized perforated cruciform from sheet stock, *Clamp* it into the fixture, and *Play* the automated test sequence. The system executes the biaxial loading, acquires stereo DIC images, computes kinematic fields, and runs a VFM-based identification chain designed for speed and robustness. A working prototype implementing the mechanical fixture and optical acquisition has been built and used for initial validation at KU Leuven.

**Identification framework.** Identification is based on the nonlinear Virtual Fields Method (VFM) applied to measured kinematic fields. For a chosen set of virtual fields  $\mathbf{u}^*$ , the equilibrium statement reads

$$\left[ - \int_S \boldsymbol{\sigma} \cdot \boldsymbol{\varepsilon}^* \, dS - \int_{L_f} \bar{\mathbf{T}} \cdot \mathbf{u}^* \, dl \right]^2 = 0, \quad (1)$$

where  $\boldsymbol{\sigma}$  is the Cauchy stress and  $\boldsymbol{\varepsilon}^*$  the virtual strain associated with  $\mathbf{u}^*$ . The stresses  $\boldsymbol{\sigma}$  are reconstructed using the measured strain field  $\boldsymbol{\varepsilon}$  and the constitutive material model (Yld2000-2d [3]) parameterized by  $\boldsymbol{\theta}$  parameters. By using optimization methods, we identify a set of  $\boldsymbol{\theta}$  parameters which fulfil equilibrium (Equation 1) as close as possible. A detailed theoretical development of the sensitivity-based VFM employed in this work is provided by Marek [4].

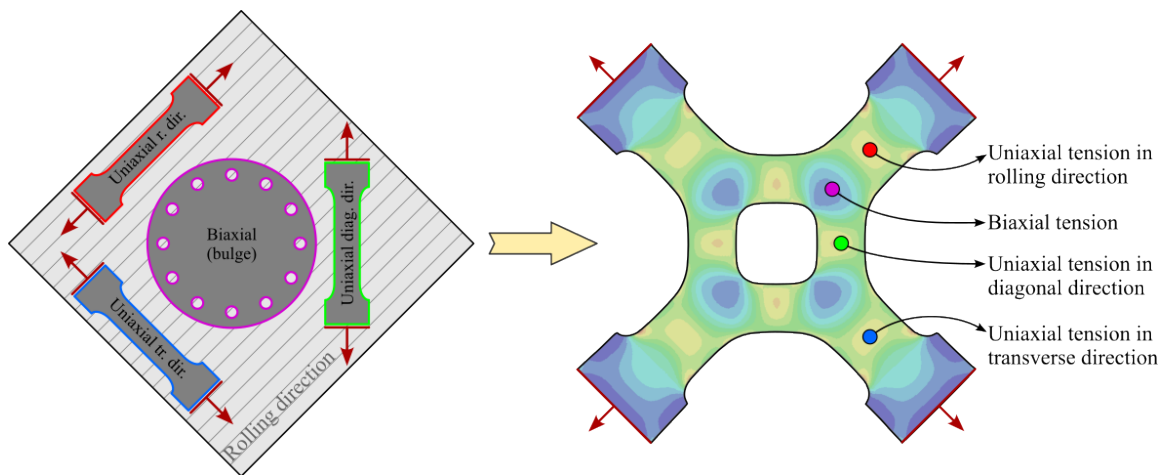
Following Equation 1, the stresses need to be reconstructed in every VFM iteration for every measured material point, for every time step and in the case of gradient-based optimization techniques for every constitutive parameter. Meaning that in a typical identification procedure we need to reconstruct the stresses approximately 100-million-times. To reduce runtime, the explicit stress-reconstruction operator *NICE* [5] is employed to compute stresses and sensitivities explicitly at the measurement points (both spatially and temporally), thereby avoiding nested implicit stress solves within the identification loop. The *NICE* operator has been seamlessly integrated into the *MatchID* software package and is available in version 2026.1, implemented in both the Results module (for stress calculation) and the VFM module.

**Specimen design and identifiability.** A *perforated cruciform* specimen was chosen because it can reproduce, within a single heterogeneous region of interest, the variety of stress states that are normally obtained from multiple homogeneous tests. The geometry conceptually originated from engineering judgement: *combine three standard uniaxial tests and one biaxial test (four homogeneous tests) into a single heterogeneous biaxial tensile experiment* by arranging local features that produce distinct local stress-strain responses. In practice, the perforations and fillets create zones with different stress types and strain gradients so that, under a single global biaxial loading path, the region of interest simultaneously samples stress states analogous to the separate homogeneous tests (e.g., uniaxial along rolling direction (RD), uniaxial along transverse direction (TD), uniaxial along 45° direction to RD, and biaxial tension, as shown in Figure 1). This engineered heterogeneity increases the information content of one experiment and reduces the number of separate tests required to identify anisotropic plasticity parameters.

The specimen geometry was further constrained by a simple force-equilibrium requirement under the assumption of a homogeneous, isotropic material: all ligaments that carry load in the rolling and transverse directions are designed to be subjected to the same nominal stress, therefore they must have the same cross-sectional area. Ligaments oriented at 45° to the RD carry the same axial force component only if their cross-section is scaled by  $1/\sqrt{2}$  relative to the rolling/transverse ligaments. This scaling follows directly from resolving forces on a 45° ligament and enforcing equal nominal stress levels across ligament families.

After imposing these cross-section constraints the remaining geometric degrees of freedom reduce to ligament lengths and internal/external radii (fillets). These parameters were selected to maximize the approach to an equibiaxial stress state in the region of interest while preserving a steep-gradient-free measurement area for DIC and delaying localization. In practice the ligament lengths control the strain gradient and the spatial extent in the region of interest, whereas the fillet radii control stress concentration and the smoothness of the strain field used for correlation.

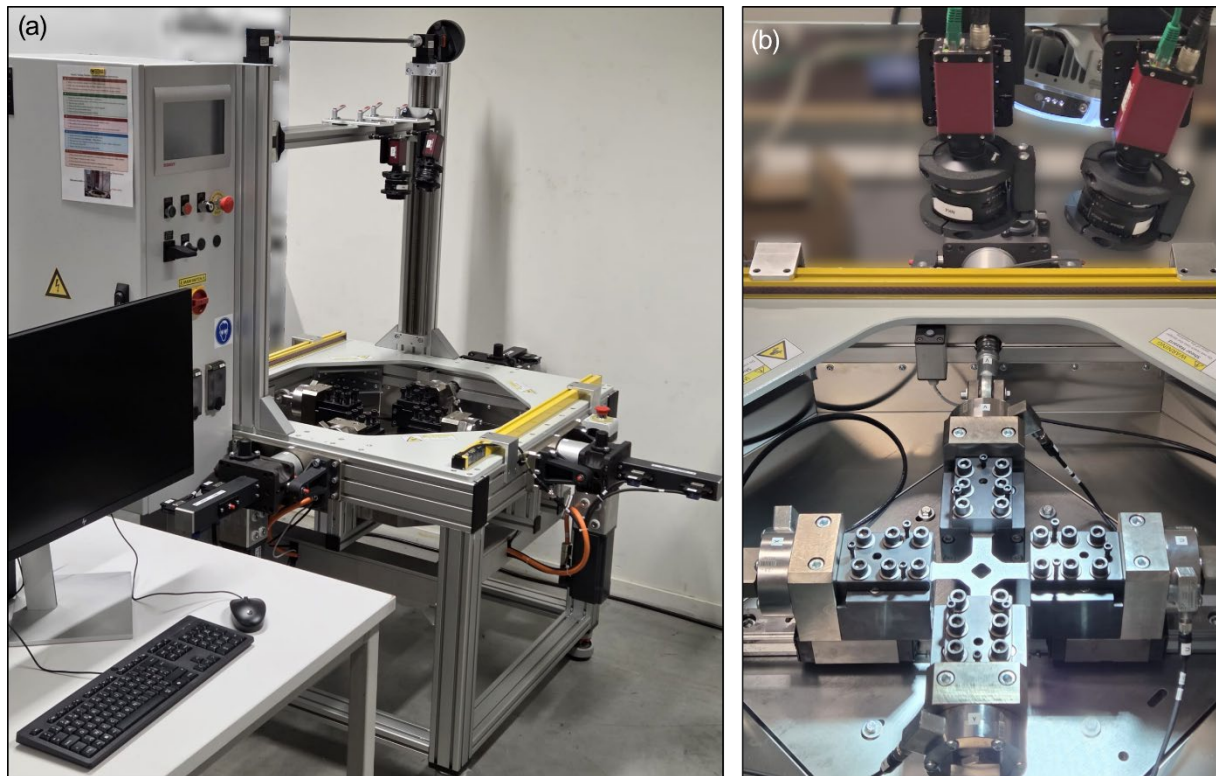
Design selection proceeded by evaluating the resulting stress maps under the intended global biaxial load and adjusting ligament lengths and fillets until the biaxial regions exhibited near-equibiaxial stress conditions. The final geometry balances three practical requirements: (1) broad, smoothly varying strain fields with small strain gradients for robust DIC correlation; (2) delayed necking by reducing stress concentrations; and (3) sufficient heterogeneity to encode the equivalent information of the four homogeneous tests into one experiment.



**Fig. 1.** Preliminary specimen design of perforated biaxial test, following the engineer's practical insight of replacing 3 standard uniaxial and one equibiaxial (e.g., bulge) test to one heterogeneous biaxial tensile test.

### Prototype and Experimental Procedure

**Prototype implementation.** A prototype cruciform biaxial testing machine and fixture were fabricated and assembled at KU Leuven (see Figure 2). The prototype includes gripping clamps, alignment guides, and stereo camera mounts positioned to capture the gauge region. Mechanical stops and repeatable fixturing ensure consistent specimen placement between tests. The prototype was used to collect representative DIC data for validation and demonstration purposes.

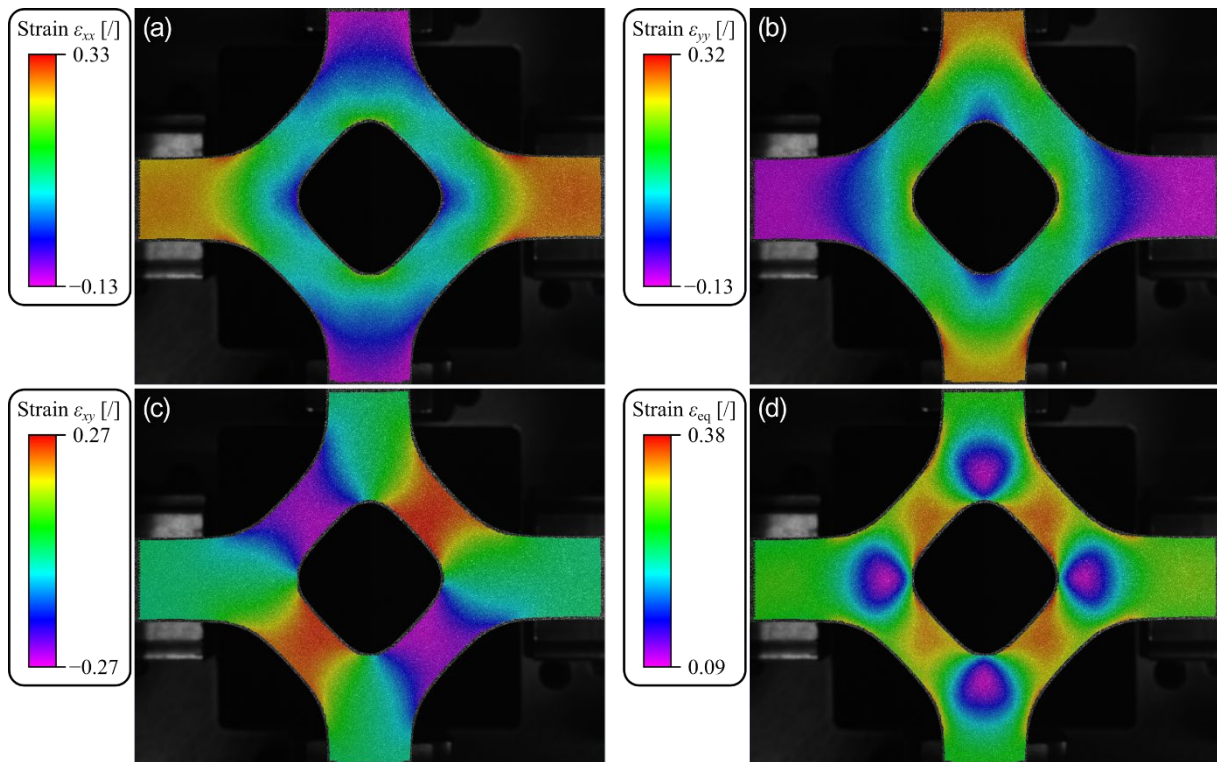


**Fig. 2.** Prototype biaxial testing machine with integrated cameras for stereo DIC: (a) complete testbed with camera mounts and electrical cabinet and (b) clamped specimen with camera setup. The machine represents a research platform for performing biaxial experiments on sheet-metal. The control logic of the machine enables early adoption into the “Cut-Clamp-Play” concept using an additional computer seen in the bottom-left corner of the image (a).

**Measurement and test protocol.** Representative tests follow a controlled biaxial loading path selected to excite anisotropic responses in the gauge region. Stereo DIC captures surface displacements at a sampling rate sufficient to resolve the quasi-static loading sequence. Typical processing yields displacement fields  $\mathbf{u}$  and derived strain fields  $\boldsymbol{\varepsilon}$  across the region of interest. Identifiability checks are performed prior to full identification to confirm that the measured fields contain sufficient information for the targeted parameter set of the Yld2000-2d constitutive model.

### Initial Results

**Measured DIC response.** The representative DIC fields from the prototype exhibit clear double symmetry in both displacement and strain maps across the whole specimen region (see Figure 3). This symmetry confirms that the mechanical fixture and loading paths produce the intended boundary conditions and that the optical setup provides consistent measurements suitable for inverse identification.



**Fig. 3.** Measured DIC strain response for a representative test: (a) strain  $\varepsilon_{xx}$  in RD, (b) strain  $\varepsilon_{xx}$  in TD, (c) shear strain  $\varepsilon_{xy}$  and (d) Von Mises Equivalent Strain  $\varepsilon_{eq}$ . The response is double-symmetric about both principal axes, confirming correct mechanical alignment and symmetric loading in the prototype.

**Identification performance.** Early numerical benchmarks and synthetic tests using the NICE-extended stress reconstruction indicate approximately 30% reduction in CPU time for the VFM identification chain compared to a baseline implicit integration approach. On the prototype hardware and typical desktop, end-to-end identification (from processed DIC fields to parameter estimates with confidence intervals) is achievable within the target of one hour for standard sheet-metal cases, subject to DIC processing time and chosen temporal discretization.

**Operator action reduction.** Laboratory trials with technicians unfamiliar with MT2.0 workflows show a substantial reduction in required operator actions when using the Cut-Clamp-Play protocol and prototype fixture. Prognosed reductions in manual steps will be approximately 70% relative to a conventional MT2.0 chain that requires specimen-specific fixturing, manual camera alignment, and multi-software data transfers.

## Discussion

Key advantages:

- **Efficiency:** The combination of an identifiability-optimized specimen and a fast stress-reconstruction strategy enables dense temporal discretization and rapid parameter estimation without prohibitive runtimes.
- **Usability:** The Cut-Clamp-Play workflow minimizes operator expertise required for routine sheet-metal characterization, lowering the barrier for industrial adoption.
- **Validation readiness:** Double-symmetric DIC responses from the KU Leuven prototype confirm mechanical and optical integrity of the testbed, supporting reliable inverse identification.

Limitations and remaining work:

- “Play” robustness: While the prototype automates many steps, further engineering is required to make the fully automated “Play” stage robust under industrial variability (e.g., variable speckle quality, lighting conditions, and non-ideal user actions). Additional work is needed on automated speckle quality assessment, adaptive correlation settings, and assessing robust experiment parameters.
- Model-identifiability trade-offs: Increasing constitutive complexity (more parameters) reduces identifiability; practical deployments must balance model expressiveness and the number of reliably recoverable parameters. Current targets aim for reliable identification of at least 7 of 9 Yld2000-2d parameters for typical sheet metals.
- DIC sensitivity: Although the workflow reduces operator influence, DIC image quality remains a limiting factor. Robust pre-test checks and automated image-quality metrics are necessary to ensure consistent identification accuracy.
- Expanding and validating the whole inverse identification on other metallic sheets.

## Conclusions

The Cut-Clamp-Play MT2.0 concept demonstrates a practical pathway to industrialize full-field inverse material characterization for sheet metals. By combining an identifiability-optimized perforated cruciform specimen, a computationally efficient VFM identification chain (NICE-extended), and a prototype cruciform testbed built at KU Leuven, the approach reduces operator actions by roughly 70% and achieves representative end-to-end identification within one hour for typical cases. Measured DIC fields from the prototype show double symmetry, confirming correct mechanical operation. Remaining development focuses on making the automated “Play” stage robust enough to handle industrial variability and on broadening validation across materials and process conditions. Once these steps are completed, the Cut-Clamp-Play system can substantially lower the barrier for MT2.0 adoption in industrial simulation workflows.

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