Why homogeneous boundary conditions lead to heterogeneous internal strain in analogue simple shear experiments - explained by numerical modeling

Structural Processes Group Vienna

center for earth sciences, universität wien

Ulrike EXNER[1], Marcel FREHNER[1] , Neil S. Mancktelow[2], Djordje Grujic[3]

Department of Geodynamics and Sedimentology

INTRODUCTION

Pure and simple shear are useful end-member descriptions of 2D deformation, and represent practical geometries that can be attained in analogue model experiments. In addition to numerical models, physical experiments have been used to constrain e.g. the rotation of rigid particles, development of shear bands or folds in shear zones. Good boundary conditions are obtained for pure shear provided friction is adequately reduced by lubrication (e.g. Mancktelow, 1988). However, the results are less satisfactory for simple shear, where the opposite is desired, namely an effective transfer of shear stress at the model boundaries parallel to the shear direction.

Analogue modeling laboratories around the world have developed a range of linear simple and general shear rigs, e.g. at the HRTL in Uppsala (Ildefonse et al., 1992, Sengupta and Koyi, 2001), the ETH Zurich (Ildefonse and Mancktelow, 1993), CSIRO in Australia (Price and Torok, 1989) or at the Tectonophysics lab in Mainz (Piazolo et al., 2001). Despite the sometimes significant differences in design, all these analogue rigs show boundary effects to some degree, with a consequent inhomogeneous strain distribution within the models.

In this study, we use a finite element code to analyze the cause of the observed deviations from simple shear, employing both two- and three-dimensional models with variable boundary conditions. By comparing the results to the geometry of an initially rectangular marker grid on the analogue models, we identify the unintended boundary effects which lead to the bending of markers close to the shearbox walls and a back-rotation of the material in the box center.

Our results advise caution in the interpretation of rotation rates measured from such experiments, as the true internal shear strain is deviating significantly from the applied external shear strain.

ANALOGUE MODELS

Fig. 1

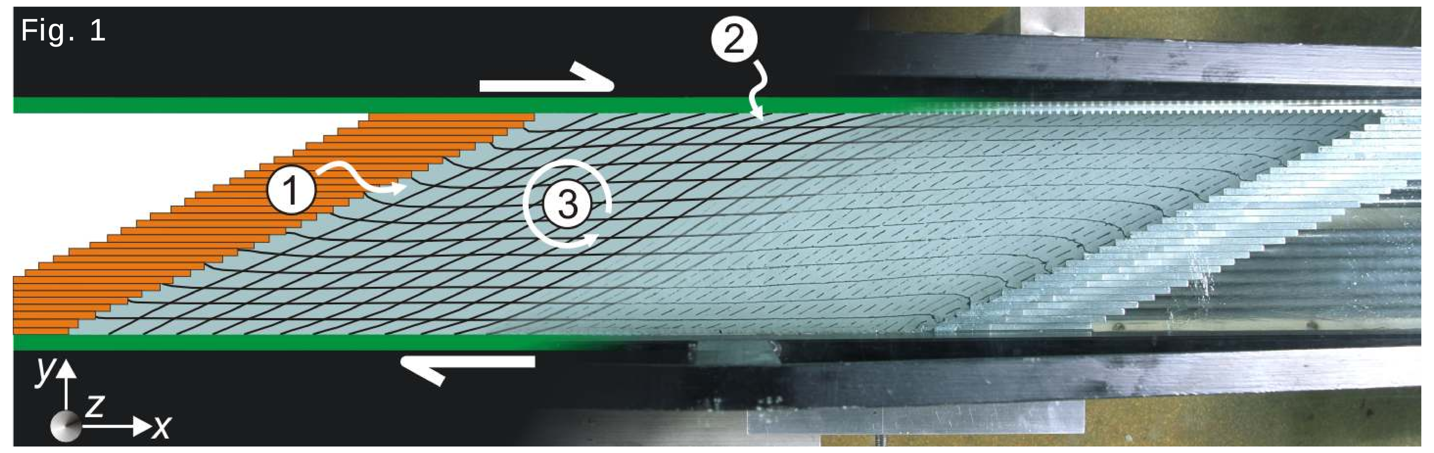
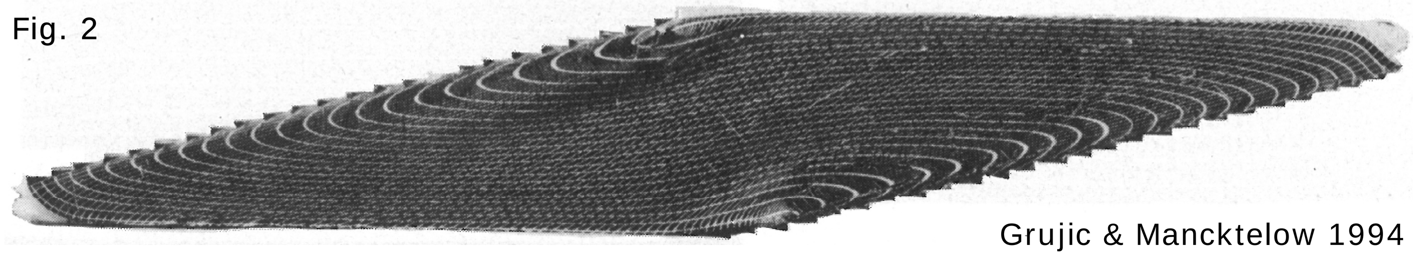
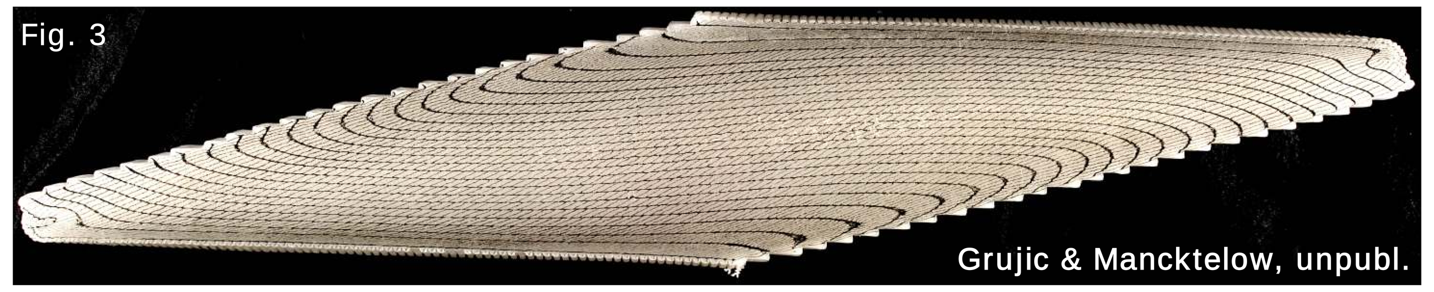


Fig. 2



Grujic & Mancktelow 1994

Fig. 3



Grujic & Mancktelow, unpubl.

Analogue experiments performed at the ETH Zurich. Three prominent effects can be observed (Fig. 1):

(1) Bending of markers close to x-boundaries, indicating less shear strain than applied at the boundaries

(2) Bending of markers close to y-boundaries, indicating more shear strain than applied at the boundaries

(3) Counter-rotation of the model center, indicating opposite vorticity than applied

These effects are present throughout the entire analogue material and do not vary in magnitude in the z-direction, as can be seen by comparing a marker layer in the model center (Fig. 2) and at the model top (Fig. 3).

Box configurations with higher aspect ratios in the x-y-plane do not eliminate the boundary effects (Fig. 1 & 3).

Fig. 4

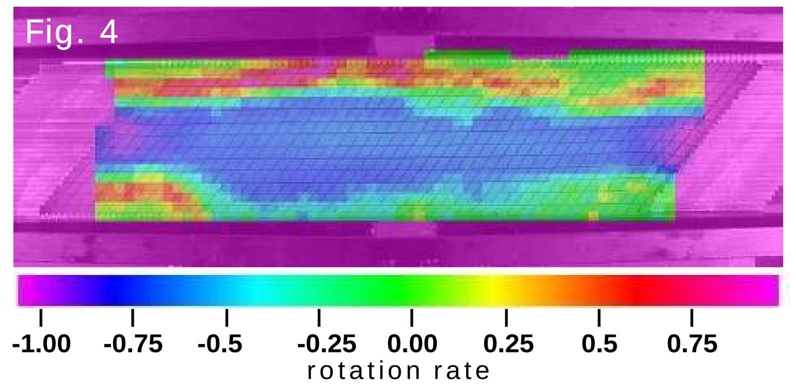
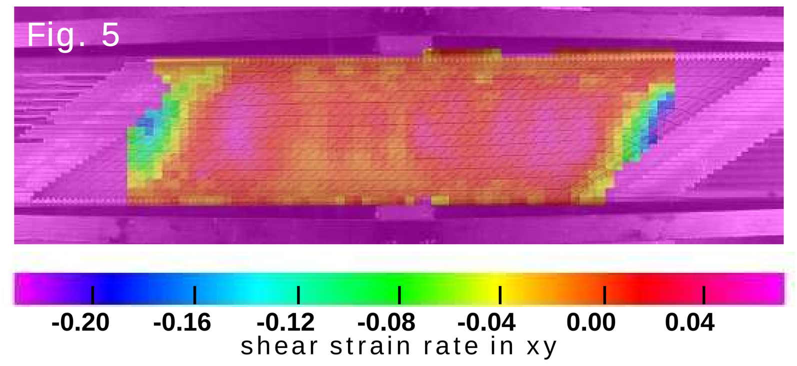


Fig. 5



Rotation rate and shear strain rate computed using *LaVision* particle imaging velocimetry software (Fig. 4 & 5).

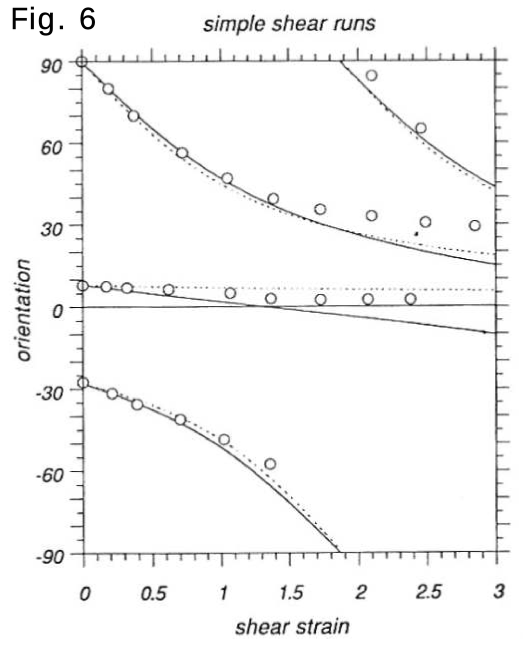
Access rotation at the y-boundaries corresponds to the observed bending to the initially y-parallel markers (Fig. 4). The bending at the x-boundaries reflects a reduced shear strain rate (Fig. 5).

WHY WORRY?

Analogue experiments in simple shear devices are frequently used to determine the rotation behavior of rigid or weak inclusions. They are especially useful, if complex rheological contrasts between clast and matrix (e.g. slipping boundaries, Fig. 6 &7) are to be investigated, where no analytical solution is available to verify numerical results.

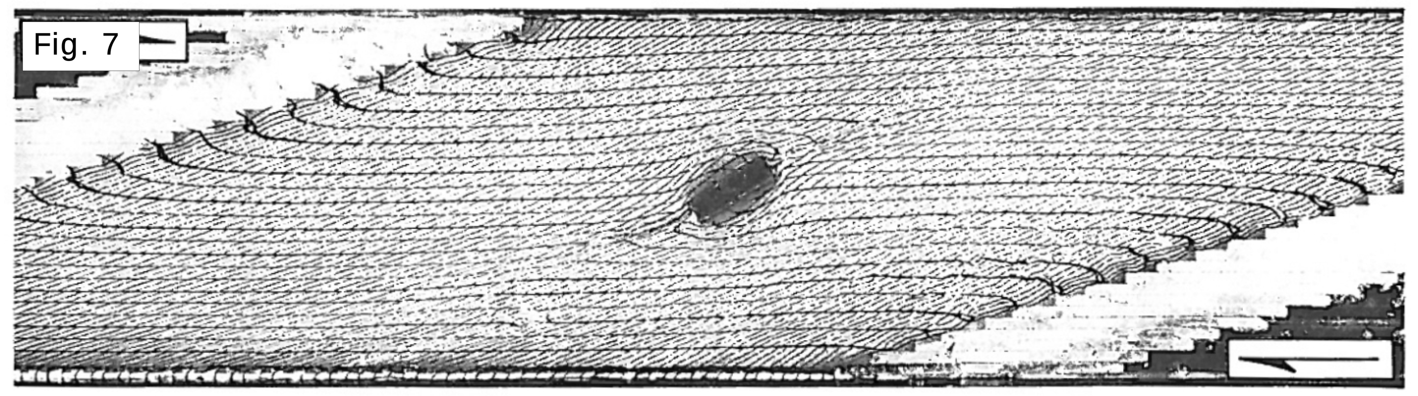
However, if the internal shear strain deviates from the externally applied shear strain, the orientation measurements potentially lead to erroneous conclusions.

Fig. 6



Ildefonse & Mancktelow 1993

Fig. 7

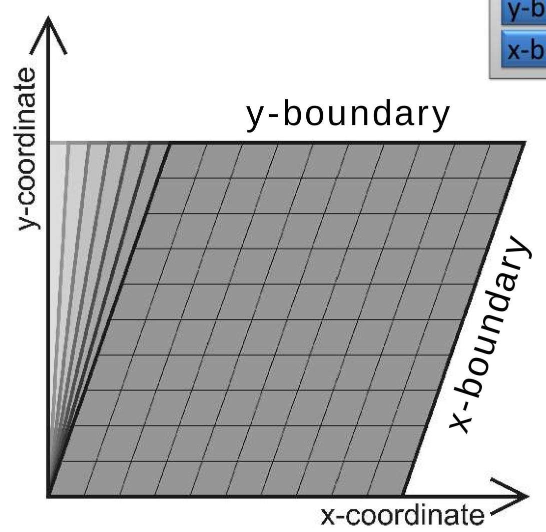


Ildefonse & Mancktelow 1993

HOW DOES PERFECT SIMPLE SHEAR WORK?

Fig. 8

Boundary \ Condition	$v_x = \dot{\gamma}_{ext} y$	$v_y = 0$
y-boundaries	✓	✓
x-boundaries	✓	✓



Definition:
x-Boundary: Initially perpendicular to x-axis
y-Boundary: Perpendicular to y-axis

Perfect homogeneous simple shear with no rotation parallel to the x-coordinate. All lines remain straight, and there is no stretching or shortening of lines paralle to the x-coordinate (Fig.9) .

Only two fundamental boundary conditions need to be respected, i.e. zero velocity in the y-direction, and a velocity in the x-direction dependent on the position along y. All four boundaries of the shear box need to fulfill these two conditions to produce homogeneous simple shear.

BOUNDARY CONDITIONS IN THE X-Y-PLANE

Fig. 9

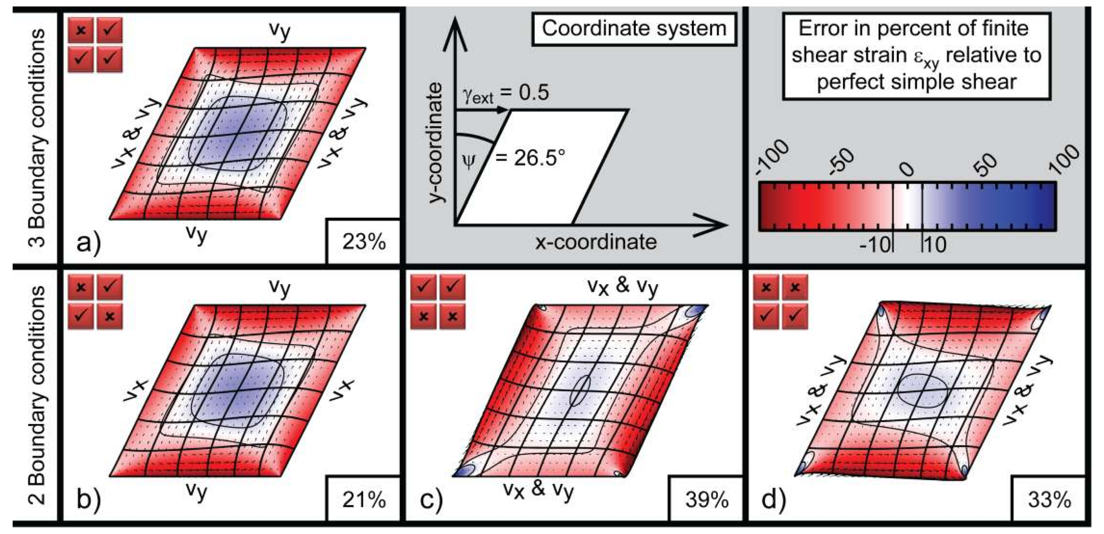
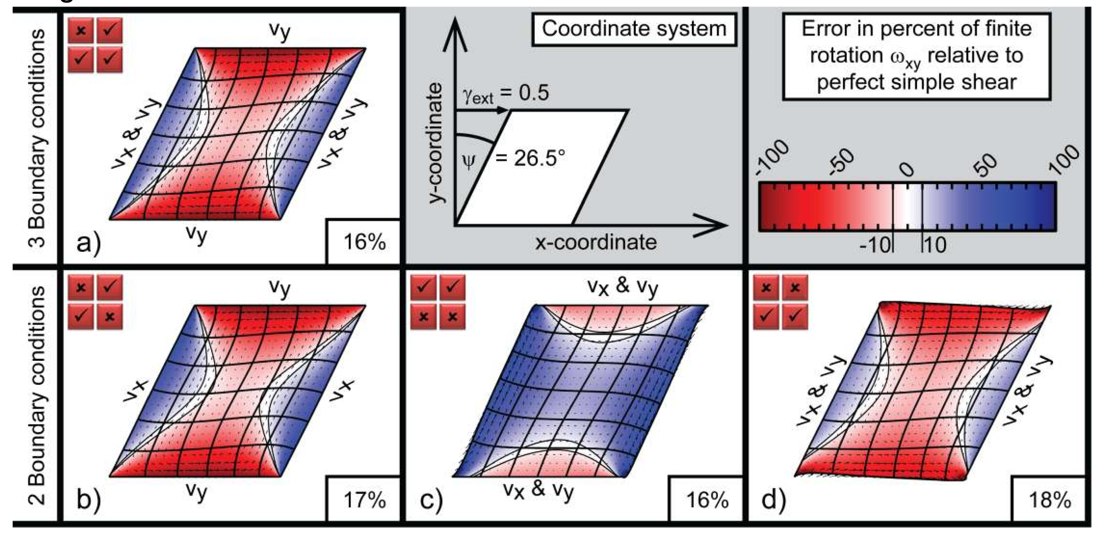


Fig. 10



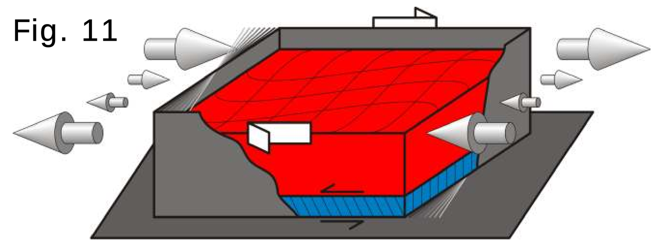
In a 2D finite element model, we investigate all possible combinations of imperfect boundary conditions at all four boundaries. The meaningful combinations (Fig. 9 & 10) display the same bending of markers at x-boundaries as in laboratory experiments, and most of them (apart from Fig. 9c & 10c) show a counter-rotation of the model center. However, the bending of markers close to y-boundaries

cannot be reproduced by imperfect x-y-boundary conditions.

Contoured errors of finite shear strain (Fig. 9) and finite rotation angle (Fig. 10) show that a dramatically high percentage of the model area strongly deviates from the intended rotation and shear strain values. Given percent-values represent the area of the model with less than 10% absolute error. Arrows indicate the finite perturbation displacement field relative to homogeneous simple shear.

BOUNDARY CONDITIONS IN Z-DIRECTION

Fig. 11



A lubricating layer at the base (e.g. Vaseline in analogue models) reduces the transfer of shear stresses. This 3D setup is approximated by introducing a velocity-dependent friction-term in the 2D model.

FEM results (Fig. 12 & 13) indicate that heterogeneous strain patterns observed in analogue models

can be reproduced by adhesive boundary conditions in the z-direction

The area of error <10% from the intended values of shear strain increases with time.

Fig. 12

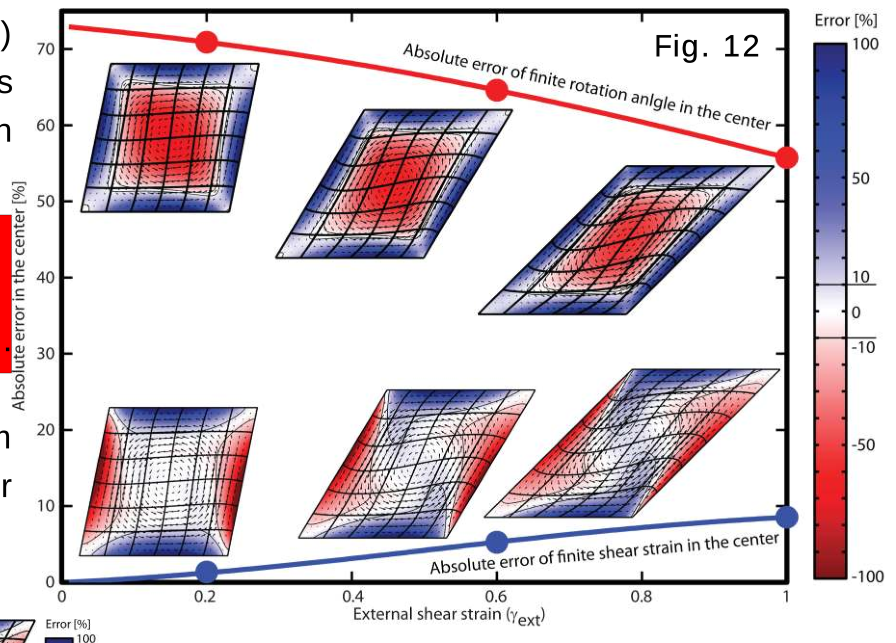
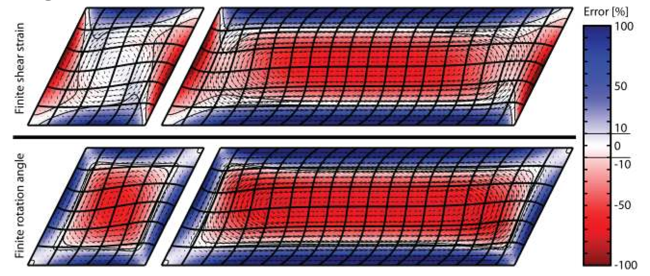


Fig. 13



Increasing the shearbox aspect ratio does not increase the area of true simple shear, but increases the central area of low shear strain and back-rotation, and does not reduce the bending of marker at x- and y-boundaries.

CONCLUSIONS

- Simple shear is not homogeneous in analogue models.
- Bending of marker lines at the shearbox boundaries and counter-rotation of the model center are a consequence of viscous drag at the bottom and top of the shearbox, but cannot be explained by slip at the vertical walls.
- Viscous drag at the bottom and top should be avoided by using lubricating material with significantly lower viscosity.
- Shear strain and rotation values inside the model are not necessarily equal to externally applied values.
- Therefore, strain or rotation values in analogue models need to be measured inside the model.

REFERENCES

Bons, P. D., E. Druguet, et al. (2004). Journal of Structural Geology 26: 625-636.

Grujic, D. and N. S. Mancktelow (1995). Journal of Structural Geology 17(279-291).

Ildefonse, B., Sokoutis, D., Mancktelow, N.S. (1992). Journal of Structural Geology 14: 1253-1266.

Ildefonse, B. and N. S. Mancktelow (1993). Tectonophysics 221: 345-359.

Mancktelow, N. S. (1988). Journal of Structural Geology 10(1): 101-108.

Piazolo, S., S. M. ten Gotenhuis, et al. (2001). GSA Bulletin, Special Volume. 193: 235-244.

Price, G. P. and P. A. Torok (1989). Tectonophysics 158: 291-309.

Sengupta, S., Koyi, H.A. (2001). Tectonic Modeling: A Volume in Honor of Hans Ramberg.

1) Department for Geodynamics and Sedimentology, University of Vienna, Austria
2) Geological Institute, ETH Zurich, Switzerland
3) Department of Earth Sciences, Dalhousie University, Halifax, Canada