XV International Conference on Computational Plasticity. Fundamentals and Applications
COMPLAS 2019
E. Oñate, D.R.J. Owen, D. Peric, M. Chiumenti & Eduardo de Souza Neto (Eds)

FINITE ELEMENT ANALYSIS OF RESIDUAL STRESSES IN LARGE COLD-ROLLED THREADS

Julian Unglaub*, **Hendrik Jahns*** and **Klaus Thiele***

* Institute for Steel Structures
Technische Universität Braunschweig
Beethovenstraße 51, 38106 Braunschweig, Germany
e-mail: j.unglaub@stahlbau.tu-braunschweig.de, web page:
http://www.stahlbau.tu-braunschweig.de/

Key words: Computational Plasticity, Forming Process, Residual Stress, Bolt, Fatigue

Abstract. As a subproject of the DFG Research Training Group *Graduiertenkolleg 2075 - Modelling the constitutive evolution of building materials and structures with respect to aging* (GRK 2075), the fatigue behaviour of rolled-after heat-treatment and hot-dipped galvanized HT-bolts is examined.
Bolted joints are one of the most frequently used joining connections in mechanical and civil engineering. HT-bolts with large diameters (M 30 up to M 72) are widely used in wind power plants both on-shore and off-shore. During the cold-rolling process, compressive residual stresses are generated at the root of the thread in combination with strain hardening. Therefore, bolts rolled-after heat-treatment under tensile loading have a much longer fatigue life than rolled-before heat-treatment ones. In order to calculate the fatigue life of rolled-after heat-treatment bolts with a notch-strain concept, it is necessary to calculate the residual stresses and the material state from the forming process.
A simulation of the forming process of the M 48 thread will be presented. It is investigated if the residual stress and material state from the forming process can be captured with the transient cyclic material model of Chaboche et al.[1] implemented in the commercial FE program `Abaqus`. The forming process is simulated with remeshing and Mesh-to-Mesh-solution-Mapping [3] on an axisymmetric model. The result will be evaluated in terms of geometry, stress and strain state. The determined stress state is compared to measured residual stresses in Unglaub [2] and Fares [4]
The simulation of the forming process gives a good coincidence with the thread geometry in practice. The residual stress path corresponds qualitatively to the measured residual stresses. The plastic equivalent strain in the thread root is overestimated because of the chosen material model and the axisymmetric modeling.

1 Introduction

Bolts as elements are subject to aging. High-tensile (HT) bolts with large diameters (M 30 up to M 72) are widely used in wind power plants both onshore and offshore. Cyclic loading can lead to fatigue failure in the thread. The manufacturing process (rolled, cut, quenched tempered, galvanized) influences the fatigue strength. One of the fatigue strength governing parameters is the processing method used to manufacture those threads, shown in Figure 1 for an rolled-after heat-treatment (SG), hot-dip galvanized (tZn) HT-bolt.

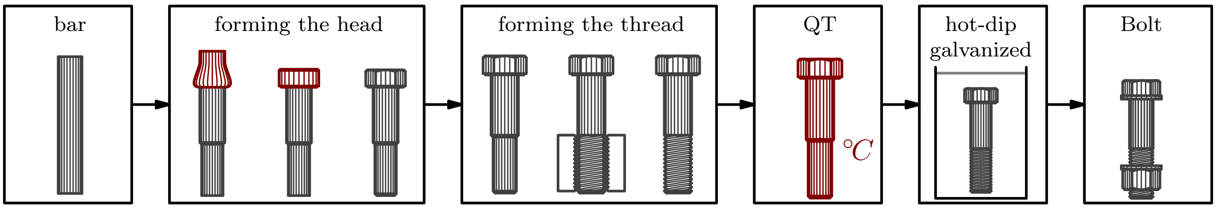


Figure 1: Manufacturing process steps for SG, hot-dip galvanized bolts [2]

During the cold-rolling process, compressive residual stresses are generated at the root of the thread in combination with strain hardening. Nearly all cracking due to cyclic loading occurs in this massively deformed area. Therefore, SG HT-bolts under tensile loading have a much longer fatigue life than rolled-before heat-treatment (SV) HT-bolts.

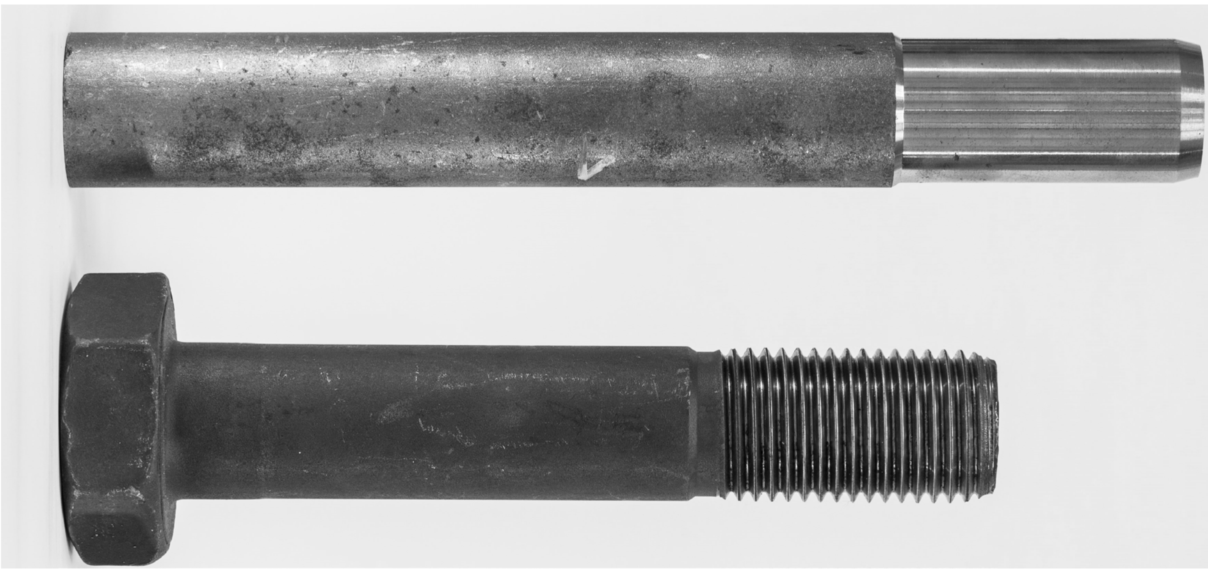


Figure 2: Workpiece for M48x255 SG 10.9 HT-Bolt (above) and final geometry of M48x255 SG 10.9 HT-Bolt (below)

To describe the fatigue behaviour of SV HT-bolts locally, notch-strain-concepts are frequently used [7]. The cyclic transient elastic-plastic material behaviour is estimated with the help of experiments. Previous local concepts for SG bolts take residual stresses

into account via phenomenological parameters [8].
The reason for this situation is the description of the complex residual stress state and hardening condition in the thread root. In order to develop a comprehensive notch-strain-concept for SG bolts, it is necessary in a first step to understand the cyclic transient elastic-plastic behaviour in finite element simulation during the forming process. On this basis a further loading behavior can be investigated.
In the following the calculation of the residual stress state is carried out by means of forming simulation of a M48x255 SG 10.9 HT-bolt, cf. Figure 2. The result will be evaluated in terms of geometry, stress and strain state. The determined stress state is compared to measured residual stresses in Unglaub [2] and Fares [4].

2 Principle of thread rolling

The piercing process rolls the thread on the workpiece by shifting two thread-dies on both sides, cf. Figure 3. The workpiece is mounted on additional rollers so that it can rotate freely in the rolling direction. In addition, the workpiece is continuously lubricated and cooled via suspension. The manufacturing process can be divided into two phases: In a first step, plastic deformation takes place as a result of the displacement and rotation of the die rollers. Once the dies have completely penetrated the workpiece, the displacement is kept constant in a second step and a defined number of roll-overs are applied [2].
The diameter of the raw workpiece is smaller than the diameter of the actual thread, cf. Figure 2. This can be attributed to the volume constancy and the material behaviour. During the forming process, the thread flank is held laterally by contact with the thread-die. Only the first thread is not held laterally. To prevent breakage, the starting area of the raw workpiece is sloped [2].

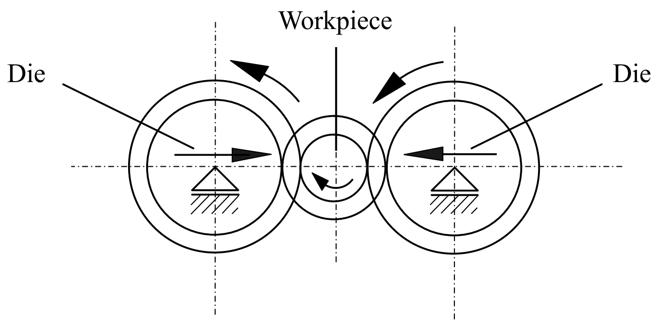


Figure 3: Principle sketch of piercing process for threads [2]

2.1 Review

Fares [4] simulates with a three-dimensional model the forming process of SG M 10 bolt, for which an elastic-plastic material model is used, without hardening and softening effects. Essential parameters such as element type and time step are not specified. Thus, the quality of the simulation cannot be assessed. The axial residual stresses are validated by comparing the calculated stress with a measured residual stress curve. The stresses

are reproduced well in the near-surface area of the thread root, Figure 8.
Furukawa et al. [5] investigate the influence of residual stresses on the fatigue strength of bolts. A two-dimensional FE model (plane strain state) is used to analyse the origin of the residual stresses. In order to reduce the calculation time, only three threads are simulated. The movement of the die is applied by 11 steps of loading and unloading. The elastic springback in the unloading phase and the subsequent loading lead to cyclic loading of the material. However, the used material model only considers isotropic hardening behaviour. The results of the simulation are compared with residual stress measurements. A two-dimensional simulation model can reproduce the residual stresses in an acceptable range. The authors note that a three-dimensional model could reproduce a better stress state. They assume that friction influences the material flow when the die comes into contact with the Workpiece.
Present research mainly focuses on the development of suitable rolling tools and the determination of parameters for bolt manufacturing machines. The correct reproduction of the residual stress state is not the focus of research. Predominantly axial symmetric models with elastic-plastic material behaviour are used in the simulation. Hardening and softening of the material are usually not considered [2].

3 Modeling

3.1 Material Model

In order to describe the material state of SG HT-bolts, it is necessary to describe the Bauschinger effect, cyclic hardening and softening as well as creep and stress-relaxation. A widely used material model that combines these properties is the *Chaboche* material model [1]. The material model implemented in `Abaqus` according to *Chaboche* requires 7 to 25 parameters to describe the material behaviour. The number depends essentially on the number of back stresses (γ_i, C_i), which indicates the nonlinear kinematic hardening. For each occuring back stress, the number of parameters has to be increased by two. A maximum of 10 back stresses can be used. The nonlinear isotropic hardening is determined by three parameters ($\sigma|_0$, Q, b), the elastic by two (E, ν).The used parameters are listed in table 1.

Table 1: Material Parameters [2]

E	ν	$\sigma\|_0$	C_1	γ_1	C_2	γ_2	C_3	γ_3	Q	b
[MPa]	[-]	[MPa]	[MPa]	[-]	[MPa]	[-]	[MPa]	[-]	[MPa]	[-]
192263	0.28	871.69	42796	120.37	187524	1257.5	1759340	31770	-450.85	24.87

The parameters are determined with a incremental step test on un-notched specimens. The evaluation methodology is explained in [2]. A complete adaptation of the material model to the test data is not possible for two reasons: If the parameters are selected in such a way that the cyclic material behaviour is described exactly, the initial load path cannot be represented correctly. If an adjustment is made to the initial load, the cyclic material behaviour is underestimated. This general problem has been recognized several times [6]. Chaboche et al. [1] publish an extended elastic-plastic material model with a memory surface. However, this improvement is not yet implemented in commercial FE programs such as `Abaqus`. The chosen parameter set represents an acceptable compromise between monotonous and cyclic material behaviour. Since especially the cyclic behaviour is of importance, an overestimation of the monotonous behaviour is accepted[2].

3.2 Modeling Parameters

An implicit simulation of the forming process is carried out using `Abaqus` with the elastic-plastic material model according to *Chaboche*. An axial symmetric model is used according to Furukawa et al.[5]. Since large deformations in relation to the element size occur during the forming process, the model is re-meshed in specified time steps, cf. Figure 5. With Mesh-to-Mesh Solution-Mapping (MTMSM) the solution is transferred to the new mesh. The developed `Python` script for the simulation control is based on the concept of Abbas [3].

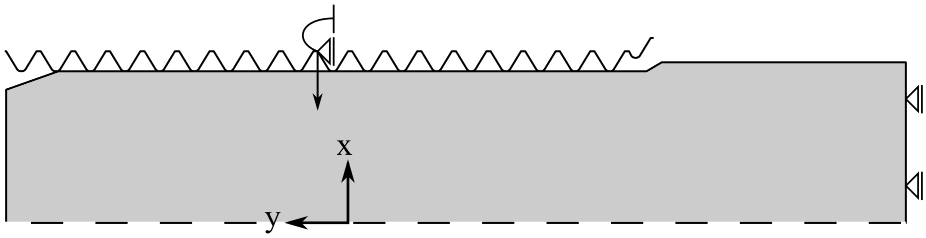


Figure 4: Geometry and boundary condition of the axial-symmetrical model [2]

In the real production process, the thread is rolled via two die rollers using the piercing process. In order to limit the size of calculation, a simplified process model of the forming process is selected for the simulation, cf. Figure 4. The complete thread and the transition area to the shank are taken into account. The die is modeled via a rigid line object. Provided that the deformation of the die is small in relation to the deformation of the Workpiece.

By the use of `General Contact` a new definition of the contact is not necessary. Since the die is modeled as a line object with two surfaces, the contact can be detected incorrectly if it overlaps with the Workpiece. Therefore, the automatic elimination of contact overlaps is omitted. The `Penalty` method is used for the contact kinematics problems.
The displacement in horizontal direction is constrained in the bolt center axis, as is the vertical displacement at the bolt shank. The rigid line object is constrained at the reference point against rotation and horizontal displacement.
The parameters of the thread forming simulations are summarized in Table 2.

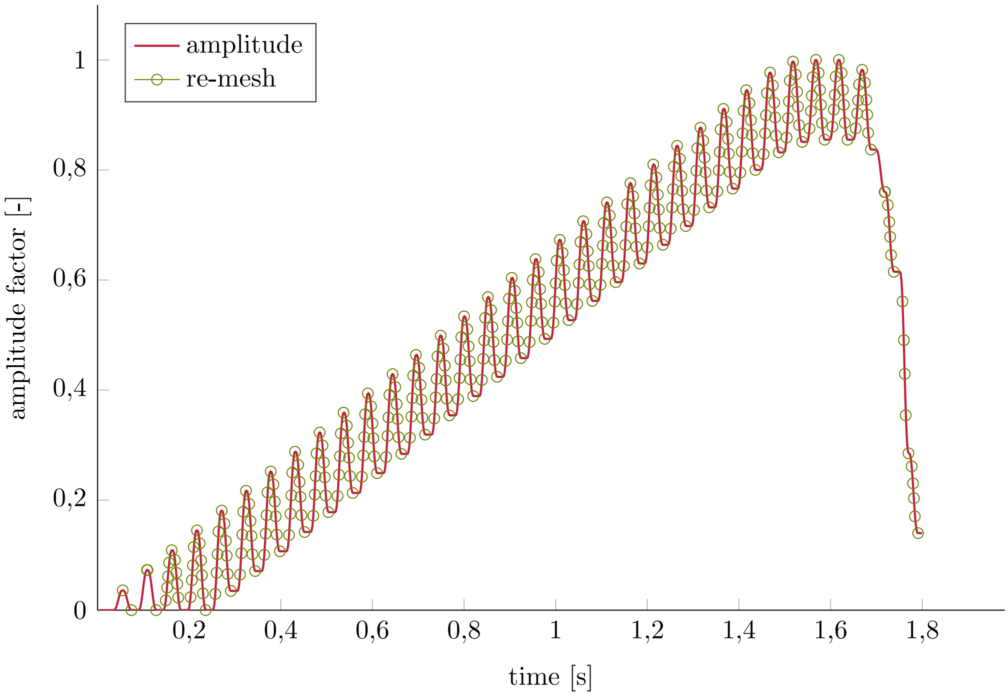


Figure 5: Displacement of the die over time [2]

Table 2: Simulation Parameters [2]

Model	implicit
Workpiece radius	22,5 mm
Contact	General Contact
Friction coefficient	0.015
No. of elements	79,060 - 254,694
No. of nodes	86,734 - 264,740
Edge length smallest element	0.1 - 0.07 mm
Edge length largest element	1 - 0.7 mm
Element type	CAX3 and CAX4

4 Results

In order to reproduce the formed geometry and residual stresses from the forming process for a M 48 HT thread, extensive parameter studies are carried out. Essential parameters are the radius of initial bar, the deformation path of the line object and the friction between the thread-die and the workwpeace.

Although the dimensions of the Workpiece are known, the final geometry cannot be adequately reproduced with this simulation model. Either the thread flank is too short in the final state or the core diameter is too small. This phenomenon indicates an insufficient

reproduction of the material flow due to friction between the workpiece and the die. In reality, friction is negligible due to the continuous lubrication. In simulation, a frictionless contact leads to instability of the model: a chink forms on the thread flank, creating a strong local distortion. In reality, the chink is also present [2]. In order to ensure the stability of the simulation, it is necessary to consider a very small friction. This means that the initial diameter must be increased in order to provide sufficient material for the flank. This phenomena is also observed by Furukawa et al. [5].
A good combination of the initial parameters is given in Figure 7. The simulation result of the stress in bolt longitudinal axis σ_{22}, as well as the final geometry of the HT-bolt are given in Figure 7a. The stress in the thread root is given in Figure 7b. The thread geometry is well reproduced both in the thread root and flank, cf. Figure 6. The transition area from the thread to the shank is described sufficiently.

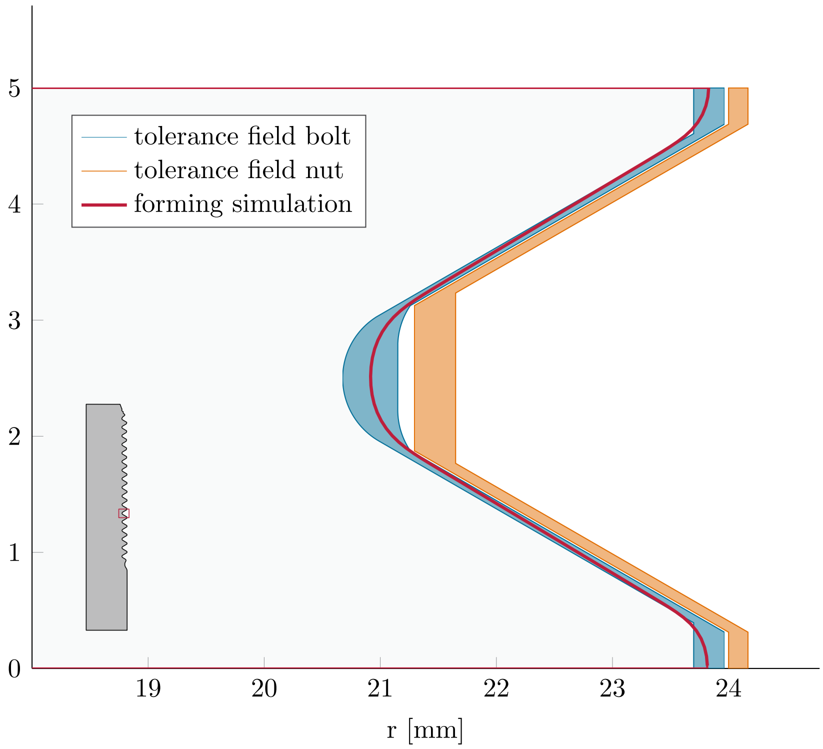
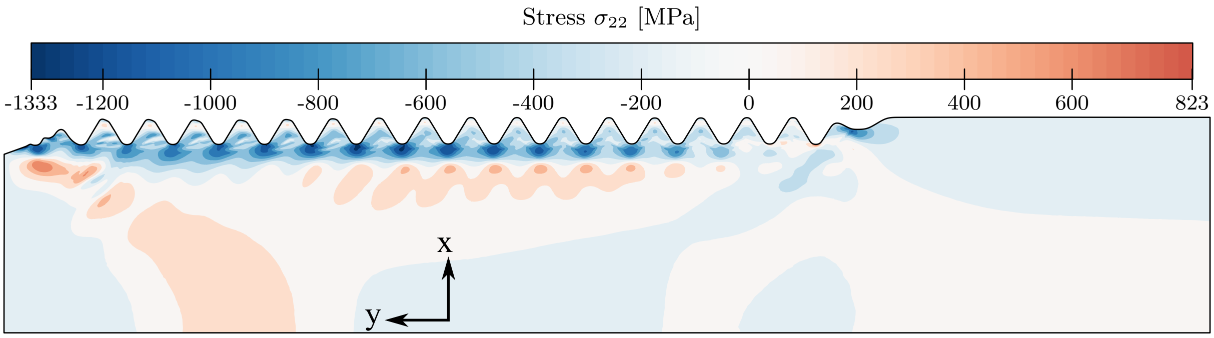


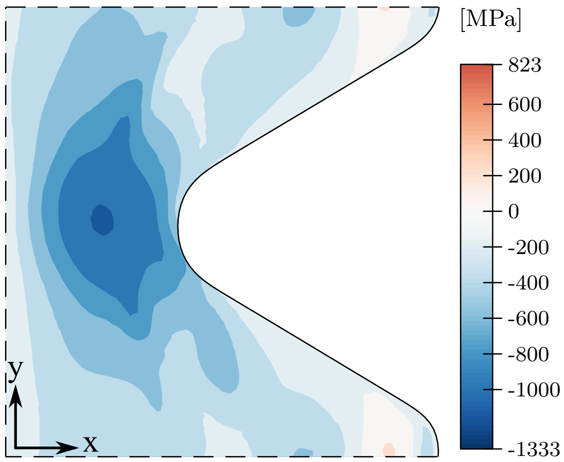
Figure 6: Comparison: Geometry from forming simulation with the permitted tolerance field for M 48 HT thread [2]

There are compressive stresses in the thread root which reach their maximum below the surface. Tensile stresses are present towards the thread core. Stresses tend to change in the direction towards the free bolt end. This is due to the axial symmetric modelling approach: When compression is applied by the die, the material flow can only shift in the direction of the free end. It can also be seen that the stresses vary slightly from thread root to thread root. This behaviour cannot be detected in residual stress measurements on M 48 HT bolts. Here, only slight fluctuations due to the measurement uncertainty

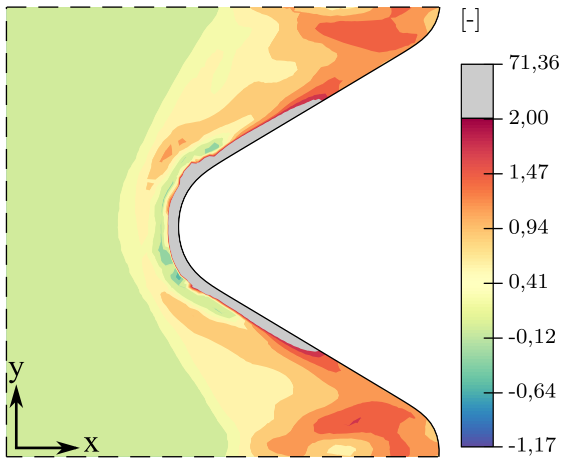
would occur [2].
In Figure 7c the plastic equivalent strain shows a strong increase form to the thread core to the surface. As a result of the lateral strain obstruction in the simulation, the plastic equivalent strain is noticeably overestimated. In reality, there is no lateral strain obstruction of the boundary condition, the material flow can also develop in the circumferential direction of the thread during compression. From hardness measurements it can be seen that there is a hardening of the material, but not as expected from the simulation. Similar observations are confirmed by Fares [4].



(a) Stress state after forming in the M 48 HT bolt



(b) Stress σ_{22}



(c) Strain $\epsilon_{pl,eq}$

Figure 7: Results: Simulation of forming prosess, stress in bolt longitudinal axis and plastic equivalent strain in the thread root [2] .

4.1 Residual Stresses

In Figure 8 a stress path in the thread root is compared with the measurements of Unglaub [2]and the measurement of Fares [4]. The path of the axial stress component is plotted. The horizontal axis refers to the nominal bolt diameter. It should be noted that size effects are included, especially when compared to the small M 10 bolt. In the simulation and measurement of the M 36 HT bolt, the maximum is located in the pressure area beneath the surface. This is due to the elastic springback of the surface when the dies are retracted. The strong decrease of stresses towards the thread core can be seen more clearly in the measurement data on the M 10 thread. Both the measurements and the simulation show moderate tensile stresses towards the thread core.

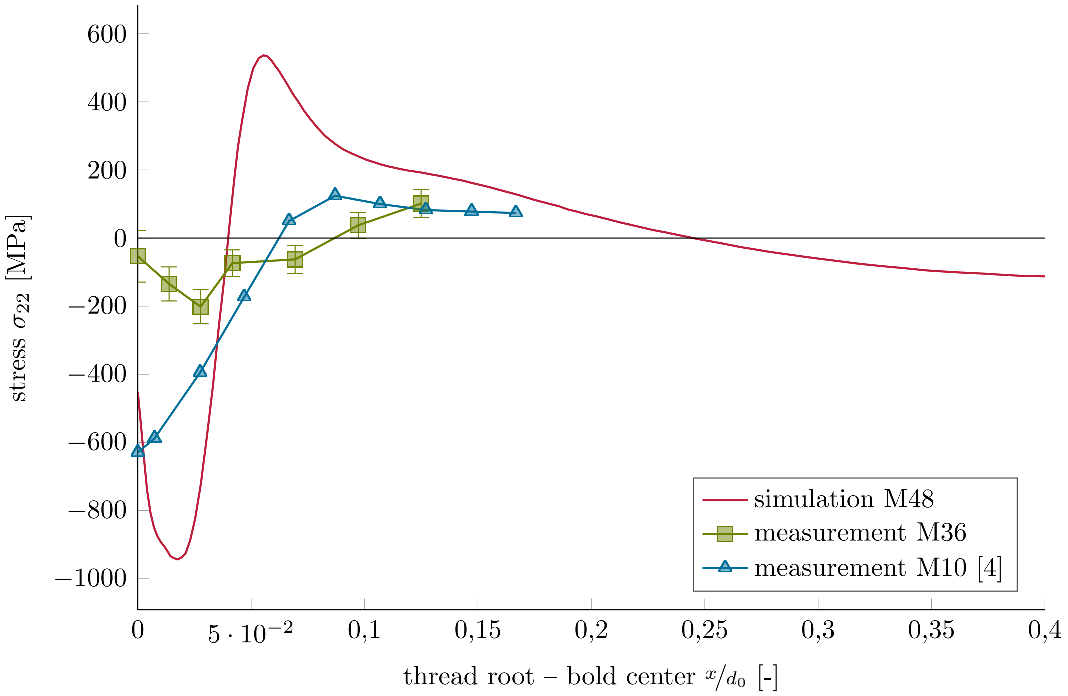


Figure 8: Comparison of the forming simulation with own residual stress measurements of Unglaub [2] and Fares [4]

5 CONCLUSIONS

The final geometry of the forming simulation fulfils an average tolerance field of HT-bolts. The residual stresses from the rolling process are reproduced qualitatively. In the thread root, there are residual compressive stresses, found with SG bolts. The plastic equivalent strain, especially in the area close to the surface, is clearly overestimated. This difference is caused by the drawbacks of the material model on the one hand and on the other hand by the obstruction of the lateral strain due to the axial symmetrical modelling. In summery:

- good achievement of the final thread geometry
- qualitative reproduction of the residual stress state in the thread root
- overestimation of the plastic equivalent strain in the thread root

6 OUTLOOK

In order to improve the results of the forming simulation, further investigations with an modified material model are required. The forming simulation with a three-dimensional model can provide information about the influence of the lateral strain obstruction. A validated simulation model can be used for investigations on fatigue strength with notch-strain-concepts. Further investigation on crack initiation as a result of hot-dip galvanizing and crack propagation in residual stress fields is needed.

REFERENCES

[1] Lemaitre J. and Chaboche, J.-L. *Mechanics of solid materials*, Cambridge, (1990).

[2] Unglaub, J. *Einfluss von Eigenspannungen auf die Ermüdungsfestigkeit von großen Schrauben*, Diss., TU Braunschweig (2019).

[3] Abbas, S. M. *Mesh-To-Mesh Solution Mapping in Abaqus to Simulate Sharp Indention Using Python Scripting and User Element Subroutine*, http://swym.3ds.com/#post:42016 (2016).

[4] Fares, Y. *Dimensionnement en fatigue des assemblages boulonnes a l'aide de criteres de fatigue multiaxiale*. Diss. (2006).

[5] Furukawa, A., Hagiwara, M.: Relationship Between Fatigue Strength of a Bolt and the Residual Stress at the Thread Root. (1st Report, Residual Stress on the Groove-Rolled Specimen). *The Japan Society of Mechanical Engineers* 75 (2009), p. 1049–1055.

[6] Scheibe, H.-J. *Zum zyklischen Materialverhalten von Baustahl und dessen Bercksichtigung in Konstruktionsberechnungen.* Diss., (1990).

[7] Olveda, D., Beyer, J., Panic, D., Beier, T. H. Gewindeverbindungen örtlich II. Vorhaben Nr. 297, *Örtliche Bewertung der Schwingfestigkeit von Gewindeverbindungen II* ; Abschlussbericht. Frankfurt, M (2014).

[8] *FKM-Richtlinie: Rechnerischer Festigkeitsnachweis fr Maschinenbauteile aus Stahl, Eisenguss- und Aluminiumwerkstoffen.* Frankfurt, M (2012).