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An evaluation of multiaxial fatigue criteria for welded joints under proportional load based on the notch stress, structural stress and nominal stress approach

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Abstract

Currently, there exists a relatively large number of guidelines and recommendations which deal with the fatigue assessment of welded structures. In these guidelines, different approaches are proposed to assess the service life of welded structures under multi-axial loading conditions. Aim of this paper is the evaluation of the quality of these approaches. Experimental fatigue data using multiaxial loading conditions from the literature were collected establishing a target data set. An evaluation of the data was performed using three guidelines (IIW-recommendations, FKM guideline and Eurocode 3) as well as a critical plane approach. All evaluations have been performed for the nominal, the structural and the effective notch stress approach.

Keywords

multiaxial fatigue, welding, steel, fatigue criteria, validation

1. Introduction

In reality, multi-axial stress states frequently occur locally in structural components. Compared to uniaxial stresses of the same magnitude, these may lead to a significant reduction in fatigue life. Therefore, neglecting this multiaxial stress requires rather high safety factors to ensure the fatigue strength of a component. To avoid this, a large number of multiaxial hypotheses exist, which can be used to calculate multiaxiality influence on the service life. On the basis of these hypotheses, recommendations for the implementation of a fatigue strength verification for multiaxial loading conditions are given in various sets of regulations, some of which differ considerably.

The aim of this work is therefore to investigate the assessment reliability of four different multiaxial fatigue criteria, which are proposed in guidelines and regulations currently applied in different industrial fields. For this purpose, a number of fatigue test results for different steel specimen gathered from the literature are examined and a suitable target data set is obtained. The evaluation of the quality of the different multiaxial fatigue criteria is done for the nominal stress, the structural stress and the notch stress approach respectively. The results are evaluated from the point of view of conservatism with respect to experimental targets and of the dispersion of the assessment results.

2. Theoretical background

2.1. Stress approaches

For the assessment of acting stress components, the following three approaches were considered [Hob16]:

For the **Nominal stress approach**, only the stress raising effects of the macro-geometric shape of the component in the area around the joint are taken into account, while the local stress increase induced by the weld seam is neglected. The nominal stress is normally calculated by simple formulas of elastic theory, so stress calculation is based on basic cross-section properties, such as area (*A)*, section modulus (*W)* or inertia moment (*I)*.

Structural stress is a linear stress distribution in the cross section of the plate; it includes all stress raising effects of a structural detail excluding that due to the local weld profile itself. Structural stress takes into consideration the linear effects related to the macro-geometry and the consequent increase in tension due to the structural configuration of the detail at the point of potential crack start, however it excludes the local nonlinear stress peak caused by the notch at the toe of the welding. The structural stress in this work is calculated following the IIW recommendations for fine mesh [Hob16].

Effective notch stress is the total stress assuming linear-elastic material behavior. The method is restricted to the assessment of welded joints with respect to potential fatigue failures from the weld toe or weld root. The notch stress is calculated in this work following the IIW guideline by Fricke [FWJ06], [Fri08]. **Fig. 2** summarizes the well-known stress evaluation approaches.

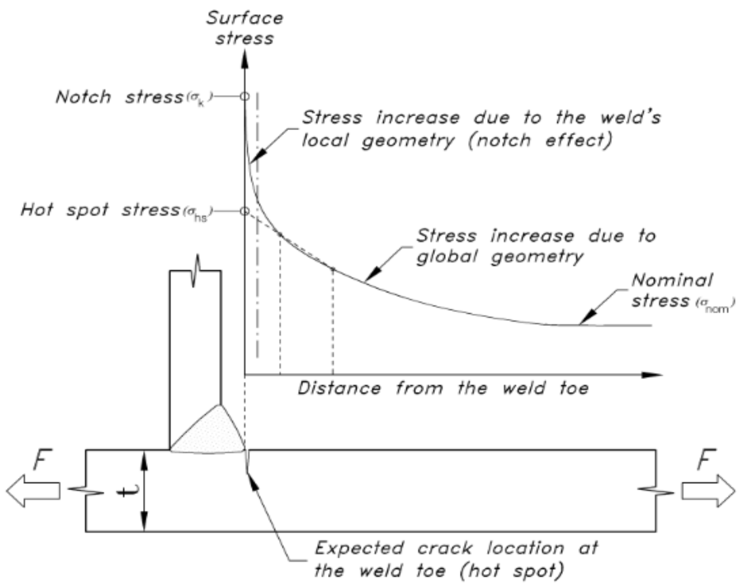

Fig. 1: Comparison of the three different stress approaches [Hob16]

2.2 Multiaxial fatigue criteria

This paper examines four different multi-axial hypotheses which are briefly presented below.

IIW-recommendation

The recommendation given by the International Institute of Welding [Hob16] is based on the Gough-Pollard theory [GP39] which states that, under combined bending and torsion loading, ductile materials show an ellipse shape of the fatigue limits in the normal/shear stress diagram. The criteria of this theory consider a dimensionless damage parameter for normal and shear stress. Their sum is compared to a limit value, typically 1.0. If the sum of the left side of the equation is lower than the limit value, the specimen is expected to withstand the cyclic loading.

In the IIW approach the comparison value CV is introduced. Its value differs depending on the load type and the phase of stresses components. For constant amplitude load and proportional loads (no phase shift) CV = 1.0 applies.

$$\left(\frac{\Delta\sigma_x}{\Delta\sigma_R}\right)^2 + \left(\frac{\Delta\tau_{xy}}{\Delta\tau_R}\right)^2 \leq CV \qquad (1)$$

Eurocode 3 recommendation

The Eurocode 3 (EC3) recommendation is also based on the Gough-Pollard theory. However, in this case a modified version of the Gough-Pollard criterion with changed exponents is recommended, see equation (2).

$$\left(\frac{\Delta\sigma_x}{\Delta\sigma_R}\right)^3 + \left(\frac{\Delta\tau_{xy}}{\Delta\tau_R}\right)^5 \leq 1 \qquad (2)$$

FKM recommendation

The hypothesis given by the FKM (Forschungskuratorium Maschinenbau, German Research Association of Mechanical Engineering) recommendation for welded structures is the principal normal stress hypothesis [FKM12]. A safety factor should is not considered in the evaluation, therefore the limit value was set to 1.

$$\frac{1}{2}\left(\left|\frac{\Delta\sigma_x}{\Delta\sigma_{xR}} + \frac{\Delta\sigma_Y}{\Delta\sigma_{YR}}\right| + \sqrt{\left(\frac{\Delta\sigma_x}{\Delta\sigma_{xR}} + \frac{\Delta\sigma_Y}{\Delta\sigma_{YR}}\right)^2 + 4\left(\frac{\Delta\tau_{xy}}{\Delta\tau_R}\right)^2}\right) \leq 1 \qquad (3)$$

Critical Plane Normal Stress Hypothesis

The critical plane approach is based on the assumption that failure is caused by a crack initiating in a plane that depends on the local stress field. Planes that experience the highest normal stresses and strains are usually chosen as a critical plane. In critical plane approaches, a number of search plane intersecting the surface either orthogonally and/or at some inclination are searched for the maximum value of a damage parameter: the plane that maximizes the damage parameter is called the critical plane. Here, the principal stress is chosen as the damage parameter as it is recommended by the DNV GL rules [DNV16]:

$$\sigma_1 = \left(\sigma_X + \sigma_Y + \sqrt{(\sigma_X - \sigma_Y)^2 + 4{\tau_{XY}}^2}\right)/2 \qquad (4)$$

For all the stress components described in this paragraph, σ_X corresponds to the stress normal to the weld seam and σ_Y to the stress parallel to the weld seam.

3. Approach

3.1 Experimental Data

Relatively few experimental investigations have been carried out on multiaxial fatigue in welded joints and even less are available in open literature. The series of experiments considered largely match with those already investigated by [Ped16]. The tests carried out on specimens shown in **Tab. 1** have been considered in this work. All specimens are characterized by a combination of bending and torsion applied loads. While some tests were carried out also on out-of-phase load application, as mentioned, the present study focuses on tests carried out with proportional bending and torsion loads in order to keep its complexity within certain limits.

Table 1: Overview of the examined test results from the literature

Author	**t (mm)**	**Expected failure location**	**Loading**	
Sonsino TT [Son97]	6	Weld toe	Bending	Torsion
Witt [Wit97]	8	Weld root	Bending	Torsion
Yousefi [You01]	8	Weld root	Bending	Torsion
Amstutz [Ams01]	10	Weld toe	Bending	Torsion
Siljander [Sil91]	9.5	Weld root	Bending	Torsion
Young [You89]	8	Weld root	Bending	Torsion
Razmjoo [Raz00]	3.2	Weld root	Tension	Torsion
Sonsino TP [Son97]	10	Weld toe	Bending	Torsion
Bäckström [Bst03]	5	Weld toe	Bending	Torsion
Dale [Dah97]	10	Weld toe	Bending	Torsion

3.2 FEM analysis

For each of the literature sources given in **Table 1** a finite element model was created. In the subsequent calculations, the stress components were determined according to the structural stress approach and the effective notch stress approach at the critical locations of the respective component. These critical locations are shown in **Fig. 2** on the specimen geometries. In the critical location all nodes were examined while only the one for which the minimum number of cycles is obtained was used for the later evaluation. The stress components for the nominal stress approach were determined analytically using the cross-sectional area and the moment of inertia of the area. The numerical analysis was carried out considering linear elastic material behavior, without considering any plasticity.

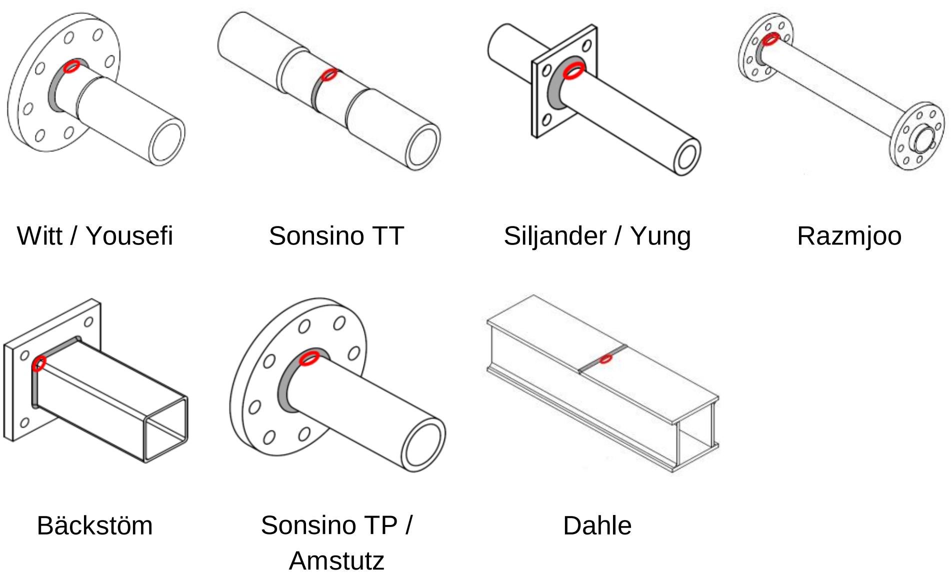

Fig. 2: Fatigue tests specimens with critical locations in red [Ped16].

3.2 *Determination of the fatigue strength*

In the first step, an equivalent stress was determined for which the inequalities of the respective multiaxial criterion are satisfied at their respective limits, i.e. CV or 1. In the next step, a number of cycles for this equivalent stress was determined using the appropriate design-S-N-curve of each fatigue assessment approach. The parameters of the design-S-N-curve were taken from the respective recommendations. Hence, in accordance with the recommendations, the FAT classes specified in the IIW guideline were used for IIW and FKM, which represent the stress that results in a survival probability of 97.5% at 10^6 cycles. In EC3, on the other hand, separate FAT classes are given. In the case of the critical plane approach the S-N curve parameters from the IIW recommendation were used. An overview of the different design-S-N-curve used in this work is given in **Table 2** for the values according to IIW and in **Table 3** according to EC3.

Table 2: Parameters of the design-S-N-curve according to IIW

<table>
<tr><th rowspan="2">Specimen</th><th colspan="4">Notch stress in MPa</th><th colspan="4">Structural-stress</th><th colspan="4">Nominal stress</th></tr>
<tr><th>σ_{FAT} in MPa</th><th>k_σ</th><th>τ_{FAT} in MPa</th><th>k_τ</th><th>σ_{FAT} in MPa</th><th>k_σ</th><th>τ_{FAT} in MPa</th><th>k_τ</th><th>σ_{FAT} in MPa</th><th>k_σ</th><th>τ_{FAT} in MPa</th><th>k_τ</th></tr>
<tr><td>SonsinoTT</td><td rowspan="8">225</td><td rowspan="8">3</td><td rowspan="8">225</td><td rowspan="8">5</td><td>100</td><td>3</td><td>100</td><td>5</td><td>71</td><td>3</td><td>100</td><td>5</td></tr>
<tr><td>Witt, Youseffi</td><td>90</td><td>3</td><td>90</td><td>5</td><td>45</td><td>3</td><td>80</td><td>5</td></tr>
<tr><td>Amstutz</td><td>100</td><td>3</td><td>100</td><td>5</td><td>50</td><td>3</td><td>100</td><td>5</td></tr>
<tr><td>Siljander, Young</td><td>90</td><td>3</td><td>90</td><td>5</td><td>45</td><td>3</td><td>80</td><td>5</td></tr>
<tr><td>Razmjoo</td><td>90</td><td>3</td><td>90</td><td>5</td><td>50</td><td>3</td><td>80</td><td>5</td></tr>
<tr><td>SonsinoTP</td><td>100</td><td>3</td><td>100</td><td>5</td><td>56</td><td>3</td><td>100</td><td>5</td></tr>
<tr><td>Bäckström</td><td>100</td><td>3</td><td>100</td><td>5</td><td>45</td><td>3</td><td>100</td><td>5</td></tr>
<tr><td>Dahle</td><td>100</td><td>3</td><td>100</td><td>5</td><td>71</td><td>3</td><td>100</td><td>5</td></tr>
</table>

Tab 3: Parameters of the design-S-N-curve according to EC3

<table>
<tr><th rowspan="2">Specimen</th><th colspan="4">Notch stress in MPa</th><th colspan="4">Structural-stress</th><th colspan="4">Nominal stress</th></tr>
<tr><th>σ_{FAT} in MPa</th><th>k_σ</th><th>τ_{FAT} in MPa</th><th>k_τ</th><th>σ_{FAT} in MPa</th><th>k_σ</th><th>τ_{FAT} in MPa</th><th>k_τ</th><th>σ_{FAT} in MPa</th><th>k_σ</th><th>τ_{FAT} in MPa</th><th>k_τ</th></tr>
<tr><td>SonsinoTT</td><td rowspan="8">-</td><td rowspan="8">-</td><td rowspan="8">-</td><td rowspan="8">-</td><td>100</td><td>3</td><td>100</td><td>5</td><td>71</td><td>3</td><td>100</td><td>5</td></tr>
<tr><td>Witt, Youseffi</td><td>90</td><td>3</td><td>90</td><td>5</td><td>40</td><td>3</td><td>100</td><td>5</td></tr>
<tr><td>Amstutz</td><td>100</td><td>3</td><td>100</td><td>5</td><td>50</td><td>3</td><td>100</td><td>5</td></tr>
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</table>

Since the IIW Recommendation does not specify S-N-curve parameters for the structural stress approach, the same parameters were used as in the case of pure normal stress load. An evaluation according to the notch stress approach could not be performed in the case of the EC3 recommendation, since no parameters are given for this case.

4. Evaluation

In order to evaluate the quality of the different recommendations, the ratio of the calculated fatigue life to the experimental target fatigue life is shown in **Fig. 3** for the three fatigue assessment stress approaches. The black marked diagonal describes the range in which the calculated and the experimental number of cycles match. Points above this line are a consequence of a non-conservative estimation, points below represent conservative results. Conservative estimations could be expected in all cases, as the calculated number of cycles was determined for a survival probability of 97.5% while the experimental results correspond to a survival probability of 50%. Contrary to this assumption, it can be seen that the calculated number of cycles exceeds the service life determined in the experiments in a considerable number of cases. This is particularly noticeable in the Amstutz, Dahle and Razmijo test series.

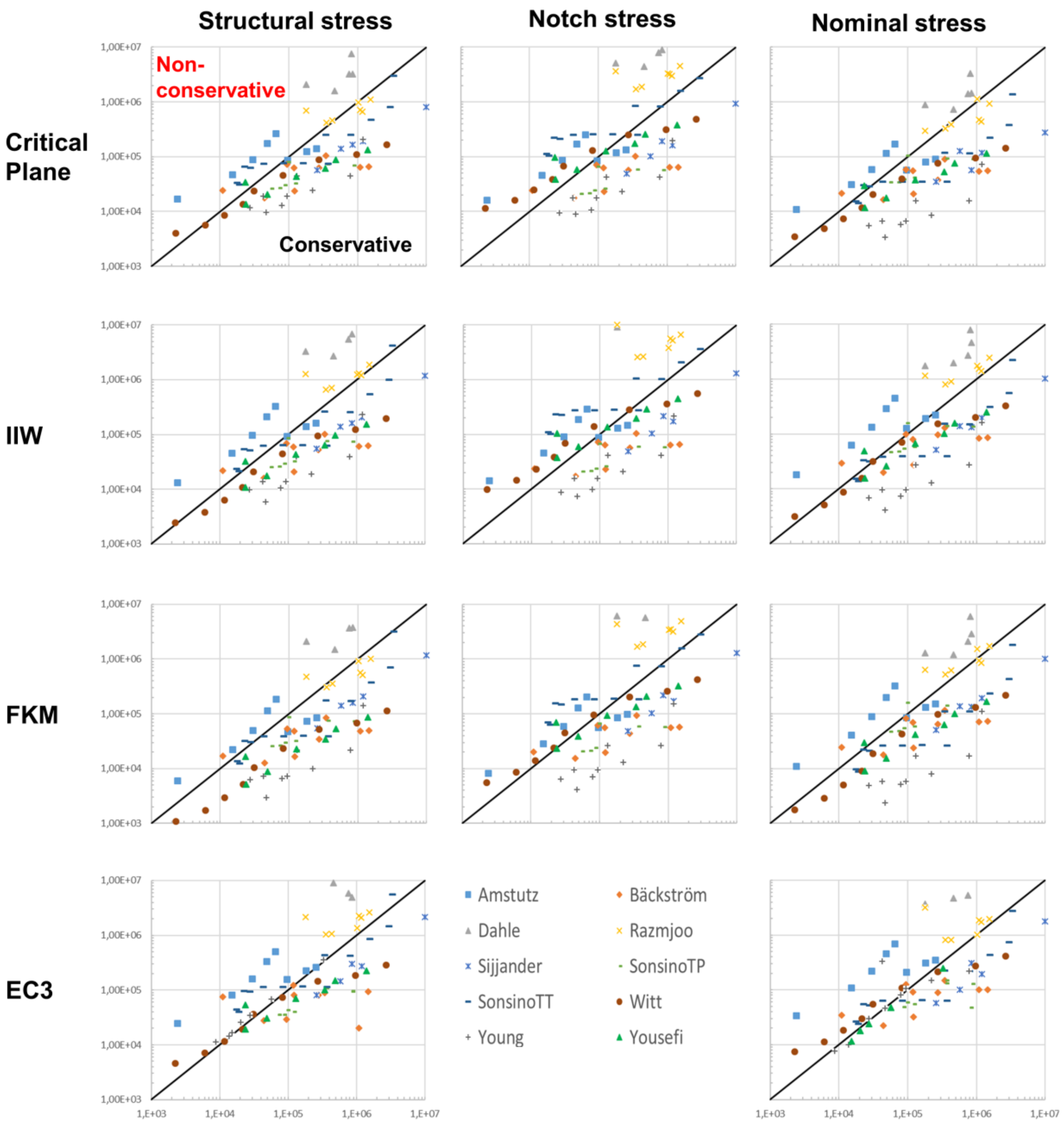

Fig. 3: Evaluation of the four examined multiaxial hypothesizes in regard of the different stress approaches

5. Conclusion

The most conservative results are obtained for the FKM Recommendation using the nominal stress approach and the structural stress, as well as for the critical plane normal stress hypothesis using the nominal stress approach, see **Fig 4**. In contrast, the results according to EC3 and the notch stress approach show a particularly high number of non-conservative values. In many of these cases the mean value of the results is also in the non-conservative range.

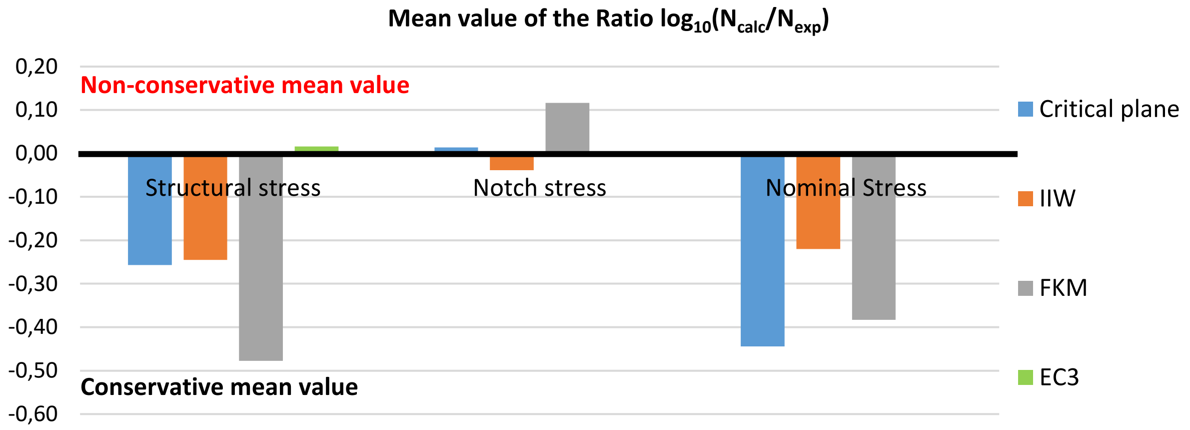

Fig. 4: Visualization of the mean value of results given in Fig. 3

Further statements about the quality of the results can be made by determining the standard deviation for the graphs, see **Fig. 5.** It turns out that of the three stress approaches considered, the nominal stress approach leads to the lowest scatter. Of the four methods considered, the smallest scatter results for the critical plane nominal stress hypothesis. Of the three sets of rules, the FKM guideline leads to the lowest scatter and the Eurocode 3 recommendation to the highest scatter.

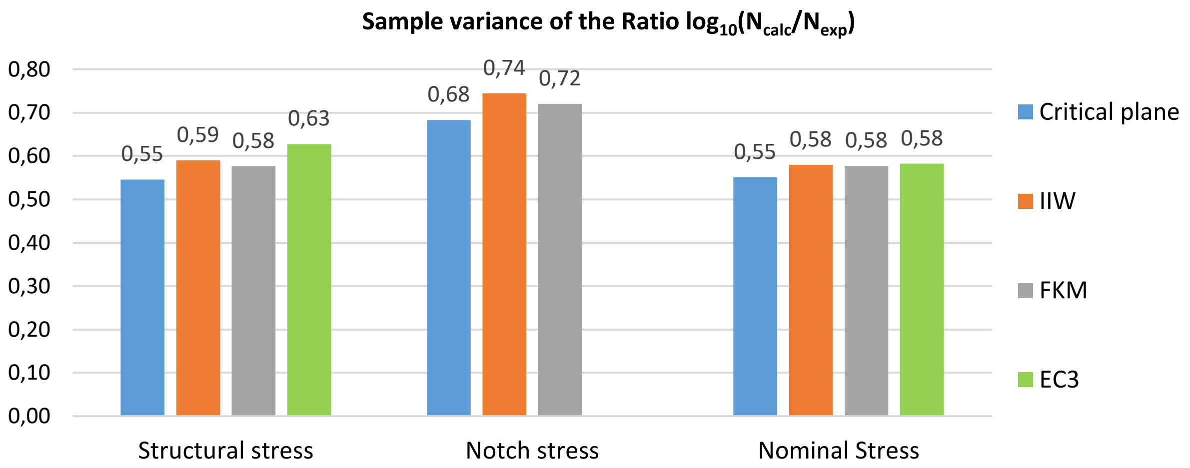

Fig. 5: Visualization of the standard deviation of results given in Fig. 3

For future work, a more detailed investigation of the experimental results obtained by Amstutz, Dahle and Razmijo would be particularly useful, as these are responsible for the majority of all non-conservative results obtained in the evaluation.

6. Acknowledgement

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