1. Project objectives and goals

Many steel structures, including some parts of critical infrastructure such as bridges or wind turbines are mainly subjected to non-static loads. The alternating stresses lead to a decreasing load capacity of the structure with an increasing number of loading cycles. The fatigue strength can be far below the load-bearing capacity due to static loads. For this reason, the fatigue verifications according to DIN EN 1993-1-9 [1] are often decisive for the dimensioning of these construction details.

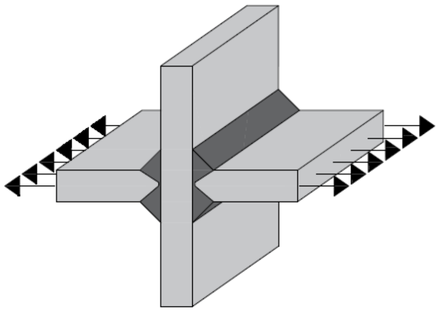

Figure 1: Load-carrying cruciform joint

The detail classification in DIN EN 1993-1-9 [1] is based on a test database that is several decades old. According to resent researches a correlation between the test results and the detail classification could not be recognized [4]. Many classifications are too conservative. Also DIN EN 1993-1-9 [1] does not contain any information on the linkage of weld imperfections with the detail classification of various design details. However, recent research has established a relationship between weld quality and fatigue resistance for many structural details. Especially for load-carrying cruciform joints (Figure 1) a certain lack of penetration could be tolerated if these could be quantified by non-destructive testing (NDT). Considered weld imperfections in the detail classification would allow more economical design and counteract unnecessary additional consumption of resources. In order to gain more information about the influence of a gap on the fatigue resistance of load-carrying cruciform joints a numerical investigation was performed. The aim was to determine the influence of the gap width and thickness on the fatigue resistance to later design specimens for fatigue tests.

2. Description of method and results

The Cruciform joint is regulated in the fatigue standard DIN 1993-1-9 tab. 8 [1]. The detail is classified with respect to the potential failure location. Cruciform joints under fatigue loads can either fail at the weld toe DIN 1993-1-9 table 8 detail 1 or at the weld root DIN 1993-1-9 table 8 detail 3 [1]. The potential failure location is decisive for the fatigue class and considered in the numerical investigations.

The numerical investigation were performed using the effective notch stress concept (ENSC) [5] to take into account nonlinear stress increases at the weld toe and weld root. With the help of the notch factor k_f the relationship between effective notch stress σ_{ENS} and nominal stress σ_{nom} could be descripted (Eq. 1).

$$\sigma_{ENS} = k_f \cdot \sigma_{nom} \tag{1}$$

For the simulations a parametric numerical model was established using Abaqus 6.14. In order to speed up computing time the symmetry was exploited and the submodel technique was used. A global model with a sufficient discretization to accurately represent the outcome variable is created first. Afterwards a submodel is generated which takes into account the guidelines of the effective notch stress concept. The accurate stress/strain rate of the global model is applied to the submodel via boundary conditions. The effective notch stress is evaluated at the weld root and weld toe. In a first step the model is verified by comparing the results of different settings. The boundary conditions and load case of the global model and the discretization of the submodel are shown in Figure 2.

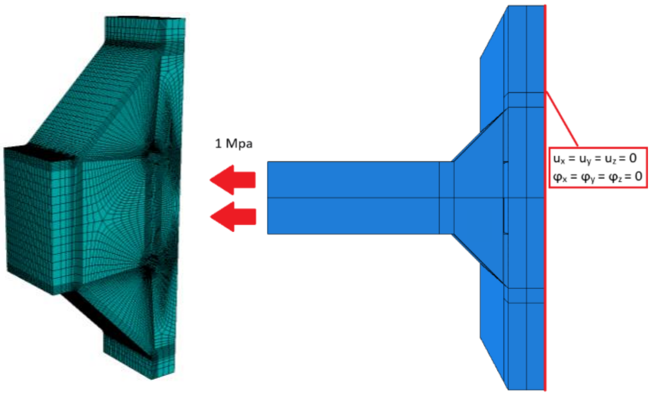

Figure 2: Global model of cruciform joint and discretization of submodel

In a second step a simulation program is performed to compare the fatigue resistance of already performed fatigue tests to the numerical investigated fatigue resistance calculated with the previously introduced model. The results of the fatigue tests are accurately represented in the numerical simulations as shown in figure 2. On the bases of the experimental results using the average fatigue class $\Delta\sigma_c$ and the simulation results in terms of average effective notch stress $k_f$an average reference effective notch stress could be calculated based on Eq (1). The calculated value of 222 MPa is very close to the proposed value of 225 MPa [5]. Also considering the evaluation of the test date fatigue class 36* seems to low for load-carrying cruciform joints with potential root failure.

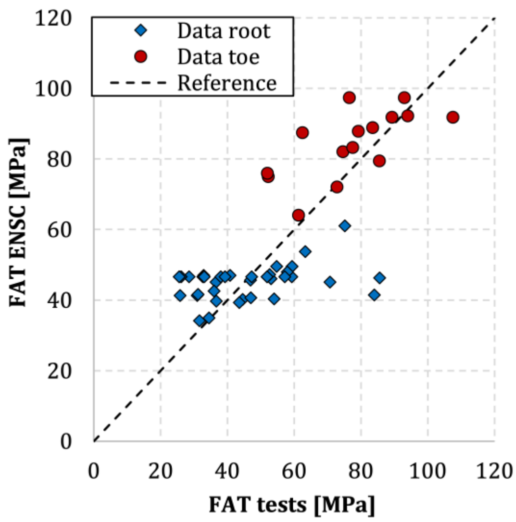

Figure 3: comparison of fatigue class of database evaluation and numerical simulations with ENSC

Due to the sufficed results explained earlier the numerical model is used to perform an extensive simulation program to determine the influence of the gap. The key part of the numerical investigation is the influence of the gap width and weld thickness on the fatigue resistance of load-carrying cruciform joints and to later design series for fatigue tests. All other geometric parameters are fixed chosen based on fatigue tests performed in the past. For the simulation program the load-carrying cruciform joint were classified into three types. Type A are fully penetrated butt-welded joints with no gap where toe failure has to be assumed. On the opposite Type C are cruciform joints with a pure fillet weld and the gap width equals the width of the tension plate and the weld root as the potential failure location. For specimens type A and C only the size of the weld was investigated. On the one hand the influence of the weld thickness to the fatigue resistance could be neglected for specimens that are fully penetrated. On the other hand the fatigue resistance of specimens with a pure fillet weld is highly influenced by the thickness of the fillet weld. The third type (type B) invested are partly penetrated cruciform joints with an additional fillet weld. For those type of specimens 56 different combinations of additional fillet welds and gap width are investigated. Considering the results of those investigations a connection between the additional weld size, the gap width and the potential failure location can be assumed. The potential failure location shifts from the weld toe to the weld root with increasing gap width and decreasing additional weld thickness. The intersection area where the potential failure location shifts is shown in Figure 4. The effect is accompanied with smaller notch factors, meaning higher FAT classes and toe failure can be inspected visual. Based on Figure 4 borderline curves for the failure location are created. With the evaluated borderline function a necessary weld size depending on the gap width can be calculated to archive toe failure.

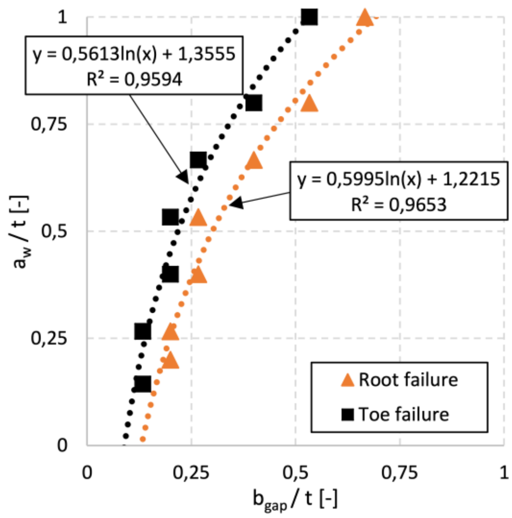

Figure 4: Borderline curves for toe and root failure

Based on the borderline function three specimens with different weld and gap size where chosen to study the influence of the gap thickness to the fatigue resistance numerically. Regardless of the gap thickness, width and weld size no switch of the potential failure location can be observed. Due to the guidelines of the effective notch stress concept even thicker gaps lead to smaller notch factors, saying higher FAT classes. It was not possible to gather satisfying results on the influence of the gap thickness.

The Information gathered in the investigation of the collected information of previously made fatigue tests on cruciform joints with gaps shows a clear correlation between the gap width and the fatigue resistance. Also fatigue class 36* seems too low for detail 3 in Table 8.1 of EN 1993-1-9 [1]. Those findings obtained are corroborated by the results of the numerical investigations.

Taking into account the previously presented results four test series are designed to investigate the failure mode of load-carrying cruciform joints. Series A is the reference series for potential toe failure. The specimens of the series are fully penetrated butt-welded joints. To study the influence of the gap size on the failure location Series B1 and B2 are designed with a gap in a way that toe failure is more likely. Series C is designed with pure fillet welds and a gap with the same size as the tension plate as a reference series for toe failure. All gaps are designed with a thickness of 2 mm which is the worst case occurred in the numerical investigations.

3. Potential for application of results

Considering all gathered information during this investigation and the advance in NDT, related to the opportunities to quantify inner weld imperfections like gaps sufficiently, the lowest possible fatigue class 36* due to EN 1993-1-9 [1] does not seem to be appropriate for load-carrying cruciform joints with gaps anymore. Based on the numerical investigations a clear relation between the width of the gap and potential failure location was occurred and the presence of a gap does not necessary mean that the weld root is the weakest part considering fatigue resistance. The borderline function evaluated earlier enables one to calculate the required weld size with respect to the gap width leading to toe failure, meaning much higher fatigue classes. In the long term, it should be possible to derive fatigue classes for cruciform joints with imperfections, such as a small gap, by performing experimental investigations and possible adaptations to the numerical simulations. In this context, the requirements for the design according to DIN EN 1993-1-9 [1] and the requirements for the design quality according to DIN EN 1090-2 [3] and DIN EN ISO 5817 [2] should be harmonized by possible new findings.

Another potential gathered during this master thesis is the fact, that experimental investigations with consume a lot of resources during a research project can be sufficiency prepared with numerical investigations.

4. References

[1] DIN Deutsches Institut für Normung e. V. Dezember, 2010. DIN EN 1993-1-9: Eurocode 3: "Stahlbauten – Teil 1-9: Ermüdung". Beuth Verlag GmbH, Berlin.

[2] DIN Deutsches Institut für Normung e. V. 2014. DIN EN ISO 5817: "Schweißen - Schweißverbindungen an Stahl, Nickel,Titan und deren Legierungen (ohne Strahlschweißen)".

[3] DIN Deutsches Institut für Normung e. V. 2018. DIN EN 1090-2: "Technische Regeln für die Ausführung von Stahltragwerken".

[4] Feldmann, M., Bartsch, H., Ummenhofer, T., Seyfried, B., Kuhlmann, U., and Drebenstedt, K. 2019. Neubewertung und Erweiterung des Kerbfallkatalogs nach Eurocode 3 für eine zukunftsfähige Auslegung hochbeanspruchter Stahlkonstruktionen.

[5] Jonsson, B., Dobmann, G., Hobbacher, A. F., Kassner, M., and Marquis, G. 2016. IIW Guidelines on Weld Quality in Relationship to Fatigue Strength. Springer International Publishing, Cham.