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Recent Progress on Geometrical and Stress Concentration Characterization of Welded Joints

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Abstract. Stress concentrations arise at welded joints due to local notches at weld transitions and determine fatigue life under cyclic loading. In order to accurately determine the severity of these stress concentrations from local weld geometry parameters advanced measurement technologies are required; however, the characterization of welded joints is traditionally based on manual measurements. In recent years, several techniques have been developed to characterize geometrical and stress concentration features of welded joints. This study briefly reviews a number of studies on weld geometry measurements, stress concentration characterization, and the determination of their influence on fatigue life estimation. Finally, an outlook on machine learning-based determination of fatigue life is given.

1. INTRODUCTION

In defect-free welded joints, fatigue strength is directly linked to areas of high stress concentrations along weld seams. Thus, the detection of such areas becomes an important task to ensure high weld quality and structural integrity of welded structures. Available measurement methods for weld geometries are either manually or computer-aided. The latter are typically based on the digitized surface geometry. The main problem of manual procedures is that the result is highly affected by the person performing the measurement [1]. Furthermore, to achieve comparability of weld qualities, large number of time-consuming measurements are required. In contrast, recent advances in automated measurement techniques allow virtually unrestricted numbers of inspections by digital measurements of weld profiles. In order to use these methods for improved fatigue assessment of welded joints a number of tasks have to be fulfilled. Among others, these include:

- The development of tools to determine weld geometries reliably and fast digitalized weld surfaces; and
- Methods to transfer weld geometries into indicators that describe the fatigue performance of welded joints.

Furthermore, the relation between these quantities and actual fatigue strength has to be established and the developed tools have to be tested and verified. Finally, a deeper understanding of statistical distributions of stress concentrations along weld seams is required to compare weld qualities of different welding processes and manufacturers. This is exacerbated by the fact that weld quality of different workshops varies significantly even if based on the same preliminary welding procedure specification [2].

In summary, reliable measurement methods for the weld geometries and stress concentrations at seam welds are required. In this context, this study presents a review of the current state-of-the-art on geometrical and stress concentration characterization of welded joints. The main objective is to provide an overview of recent developments and future steps towards in-production weld quality assessments.

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2. TRADITIONAL GEOMETRICAL AND STRESS CONCENTRATION CHARACTERIZATION OF WELDED JOINTS

To this day, non-destructive testing of engineering structures is largely built upon visual inspections, magnetic particle testing, and dye penetrant testing [3]. The main focus is to detect possible defects after production. To a limited extend visual inspections are performed to determine weld quality in accordance with standards like ISO 5817:2014. So obtained weld quality levels for geometrical feature and defect numbers could then be used to decide on possible reductions of fatigue strength, see [5, 6]. Recent developments both on geometrical and stress concentration characterization of welded joints offer possibilities to perform automatic inline quality inspections and fatigue strength assessment of welded joints, see Fig. 1. These developments are subsequently presented.

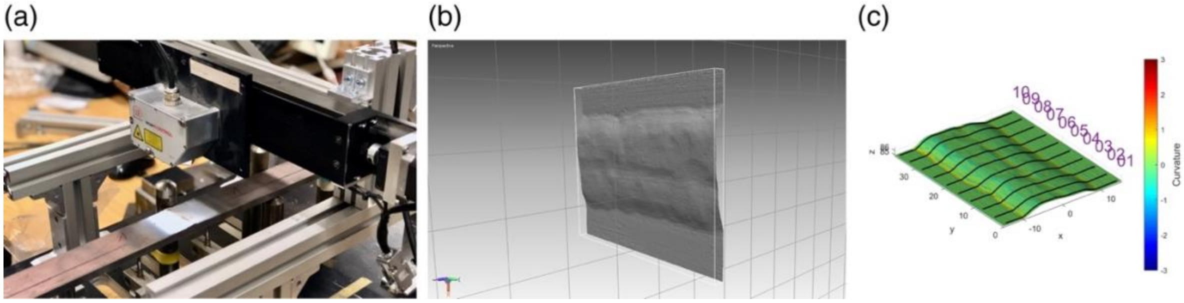

FIGURE 1. (a) Laser scanning of a butt joint; (b) visualization to check scan quality; (c) assessment of geometry with 2D weld slices [7].

3. RECENT DEVELOPMENTS FOR GEOMETRICAL AND STRESS CONCENTRATION CHARACTERIZATION OF WELDED JOINTS

3.1 Developments related to geometry measurement systems

Typical computer-aided measurement methods for welded joints are usually based on 2D profiles of the weld. This is related to the fact that weld toe geometries vary significantly along weld seams [8]. Therefore, a common approach is to analyze the weld toe on a prescribed number of 2D profiles (slices) along the weld. A small number of slices typically leads to a large scatter of the weld toe parameters. This is particularly true for uneven manual weld seams with a high risk of missing critical areas, see [9]. On the other hand, a large number of slices increases processing times, which should preferably be limited. In two recent studies, Renken et al. [10] and Hultgren et al. [11] investigated the effect of sampling rates on measured weld geometries.

Renken et al. [10] observed convergence of modal values of geometrical parameter distributions. For a slice density of 1.25 S/mm, the modal values weld toe radii, local weld toe angle, and stress concentration factor varied less than ±1% of the assumed converged value. Similar results were obtained by Hultgren et al. [11]. They observed that there is an increasing probability to miss critical fatigue locations for sampling rates higher than 200 µm. Recently, Schubnell et al. [12] compared different weld geometry measurement systems and post-processing algorithms based on eight different welded joints. Interestingly, larger relative deviations in measured weld toe radii were observed than for weld flank angles. Their work is currently continued in a large international Round Robin study of more than 10 participants.

3.2 Developments for weld geometry and quality characterization based on measurements

Apart from advances on geometry measurement systems, weld geometry and quality characterization has recently seen a number of interesting developments. Renken et al. [10] developed an algorithm to determine weld geometry parameters, weld quality, and stress concentration factors along seam welds. They also performed a comparison of a long seam weld with fictious small-scale specimens taken from the same weld. Interestingly, with increasing sampling rate the measured weld quality is steadily decreasing. This seems to be related to a higher probability of observing a single scan with low quality. Such information can for example be used as a feedback for automated welding process control as Stenberg et al. [13] and Penttilä et al. [14] showed; however, this leads to questions regarding the applicability of current weld quality standards. These standards were developed based on the idea of a few manual gauge measurements. Linking the weld quality level to the lowest observed weld quality is not reasonable if measurements are performed every with micrometer spacing. Hence, weld quality assessments need to be supported by probabilistic methods.

3.3 Developments for stress concentration characterization of welded joints

With the development of weld geometry measurement systems, the characterization of stress concentrations at welded joints has seen significant progress. Recently, Ottersböck et al. [15] presented an improved characterization of undercuts by means of 3D surface scans. Undercuts can significantly reduce fatigue strength of welded joints, but are typically hard to assess due to their complex three-dimensional shape. Hence, Ottersböck et al. [15] showed that parametric stress concentration factor (SCF) equations may result in wrong estimates for deep undercuts. Similar results were obtained by Schubnell et al. [16], who used a parametric SCF formula derived by Anthes et al. [17] for fillet welded joints under tension and bending loading to compare SCFs at as-welded and repaired joints. Alternatively, they used 2D modelling of digitalized weld profiles, which they also applied in [12, 18]. Their comparisons showed a large discrepancy between actual stress concentrations and estimates based on parametric SCF formulas. This discrepancy is thought to be related to the idealization of weld profiles. This was also realized by Pachoud et al. [19] and Wang et al. [20], who both proposed descriptions of weld profiles based on parametric splines.

More advanced methods include polynomial regression with coupling terms (PRC) and artificial neural networks (ANN) to determine stress concentrations based on weld geometry measurements, see [21-24]. By performing several thousand parametric FE simulations, Oswald and co-workers showed that parametric SCF formulas sometimes lead to high errors. Additionally, parametric SCF formulas are typically limited to certain parameter combinations. Once these models (PRC and ANN) are set up, no additional time-consuming FE simulations are required. A similar approach based on ANN was also presented for butt-welded joints by Dabiri et al. [25]. They also included axial misalignment in their model.

In principle, ANNs consist of a number of inputs (typically geometrical parameters, e.g. weld toe radius, flank angle, plate thickness etc.), one or two hidden layers, and one or two outputs of stress concentration factors (i.e. for tension and bending loading). An example of an ANN is presented in Fig. 2.

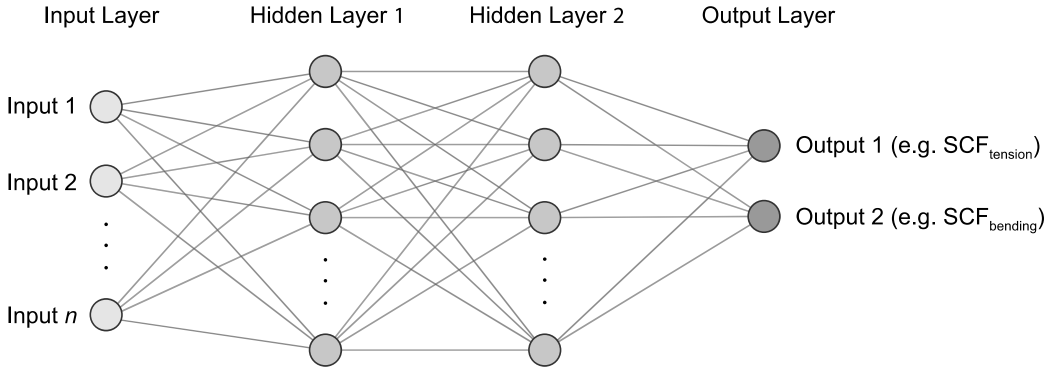

FIGURE 2. Principle of artificial neural networks to determine stress concentration factors used by Dabiri et al. [25], and Oswald and co-workers [21-24]

Renken et al. [10] also showed that the weld toe radius and local weld angle have a high impact on the variation of stress concentration factors along a seam weld. This could lead to significant progress in upcoming years in combination with assessment methods based on highly stressed regions along weld seams, see Deinböck et al. [26]. To achieve this goal, a better understanding of statistical distributions of weld geometry parameters and stress concentrations is needed. Thus, Braun et al. [27] recently determined statistical variations of stress concentrations along seam welds using ANNs based on the work by Oswald et al. [23].

4. PROGRESS ON FATIGUE LIFE ESTIMATION BASED ON WELD GEOMETRY AND STRESS CONCENTRATION CHARACTERIZATION

Typically, in-production assessment of fatigue life of welded joints is linked to macro-geometric weld quality and reference geometry measurements of easy to obtain geometrical features determined by gauges, e.g. flank angle, weld thickness, weld asymmetry. This approach is also reflected in the new guidelines on weld quality in relationship to fatigue strength ISO/TS 20273:2017-08; however, there has recently also been notable progress on fatigue life estimations of welded joints based on weld geometry and stress concentration characterization.

In general, it is highly recommended to report measured weld geometries (among other properties) to enable future usage of test data and to avoid repeated testing of similar specimens. This could either be mean or modal values in connection with standard deviations (see e.g. [18, 28, 29]), or histograms or similar plots of measured quantities (cf. [30-33]).

4.1 Progress on finite element modelling of weld geometries

Local fatigue assessment based on finite element (FE) models is traditionally based either on using reference radii methods (see Baumgartner [35]) or approximation of weld toes as sharp V-type notches as for example in the SED [36] or peak stress method [37]. For accurate FE modelling, it is recommended to base FE models on measured weld geometry, see Braun et al. [38]. This is also true for post-weld treated joints, as Ahola et al. [39] and Shiozaki et al. [40] have shown. Similarly, advanced effective stress methods such as those summarized within the Theory of Critical Distances are sometimes also based on actual measurements of weld geometry and weld toe radii, see [41-44].

For large scale structures, an accurate representation of the actual weld geometry can be very challenging, see Larsen et al. [45] and Schürmann et al. [46]. Both case studies are good examples of how complex it is to transfer measured geometries of large-scale structures into FE models. Alternatively, a coupled subelement approach can incorporate local weld geometries into complex 3D models without high computational effort, see Heyraud et al. [47].

Recently, Niederwanger et al. [48] presented a comparison of the impact of actual measured and idealized weld geometries on fatigue life assessment and Liinalampi et al. [49] analyzed the difference between 2D and 3D modelling of undercuts. In general, 3D FE modelling based on weld scans remains rare due to the large preparation effort. For some problems like weld ends they have, however, proven to allow very precise assessment, see [50, 51]. In another recent study, [11] showed that 3D FE modelling based on weld scans can also be applied to seam welds.

Besides stress-based fatigue assessment, also fracture mechanics models can benefit from detailed weld geometry modelling. Two advanced methodologies for such assessments are the IBESS procedure [32, 52], which is based on linear elastic fracture mechanics, and the strain-based fracture mechanics approach developed by Remes [53]; however, judging by the number of publications, they seem to be less frequently applied as stress-based fatigue assessment methods.

4.2 Recent developments on machine learning-based determination of fatigue life of welded joints

Braun et al. [54] recently estimated fatigue failure location and fatigue life of small-scale butt-welded joints based on weld geometry measurements and load-related features (stress and force amplitude, and corresponding maximum values etc.). To this goal, explainable machine learning algorithm and the SHapley Additive exPlanations (SHAP) framework was applied to assess the mutual influence of the various influencing factors and to rank them by impact. As machine learning models, gradient boosted trees [55, 56] and the XGBoost implementation [57] were used due to the tabular nature of the data and good performance in preliminary analyzes [54].

Fig. 3 presents the average impact of features on fracture locations and lifetime of the assessed butt-welded joints. Misalignment features (angular and axial) have by far the highest impact on fracture location. In contrast, stress amplitudes had the highest impact on lifetime (number of cycles to failure). Both results are not surprising, but these results present quantitative measures of the impact of certain features for fatigue strength of welded joints for the first time. So far, similar attempts only existed for plain and notched base material specimens, see [58, 59]; however, welded joints are much more complex to assess due to the variation of geometrical parameters along the weld seam.

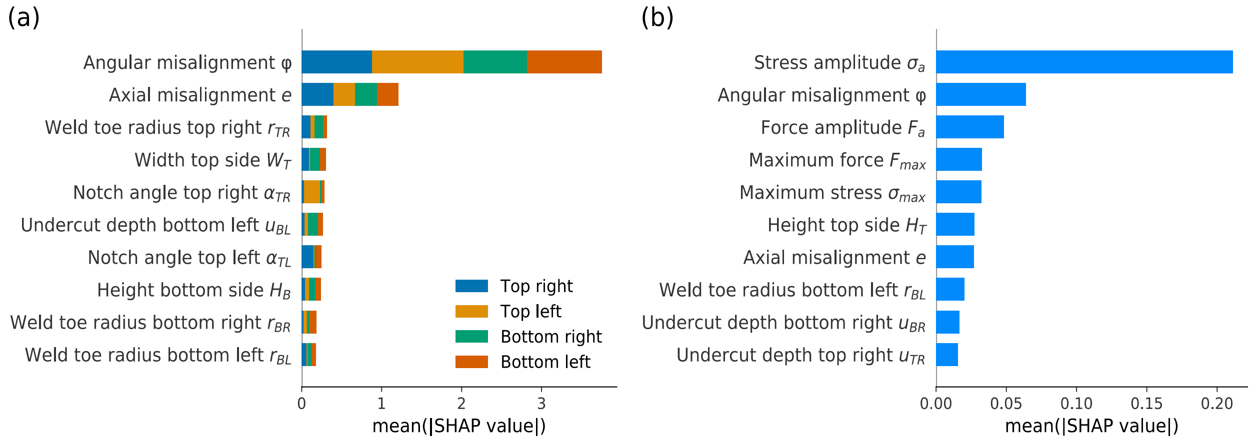

FIGURE 3. (a) Average impact of features on fracture location (the four weld toes) for different possibly locations and; (b) average impact of features on lifetime of small-scale butt-welded joints, adopted from Braun et al. [54]

5. CONCLUDING REMARKS

In defect-free welded joints, fatigue strength is directly linked to areas of high stress concentrations along weld seams. Thus, the detection of such areas becomes an important task to ensure high weld quality and structural integrity of welded structures. With recent developments made on automated digital measurement techniques, virtually unrestricted numbers of weld inspections are possible; however, there is still a number of tasks to be fulfilled before these technologies can be used for in-production weld screening. Hence, this study reviewed recent progress made on geometrical and stress concentration characterization of welded joints. The following conclusions are drawn from the review:

- Determined weld geometry parameters, stress concentration factors and weld quality levels are highly dependent on sampling rate, i.e. number of measurements along a weld seam, and geometry measurement systems. Thus, an on-going Round Robin study aims at determining measurement deviations.
- Currently, weld geometries are typically idealized for finite element-based fatigue assessment. Recent progress on polynomial regression with coupling terms and artificial neural networks enables a direct determination of stress concentrations based on measured weld geometry parameters.
- In order to assess complex geometries like tubular joints and undercuts, 3D finite element models are still required. These types of assessment are, however, very time-consuming.
- Finally, explainable machine learning algorithm offer a fast way of estimating fatigue failure location and fatigue life of welded joints; however, more research is required to adopt them for large-scale engineering structures.

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