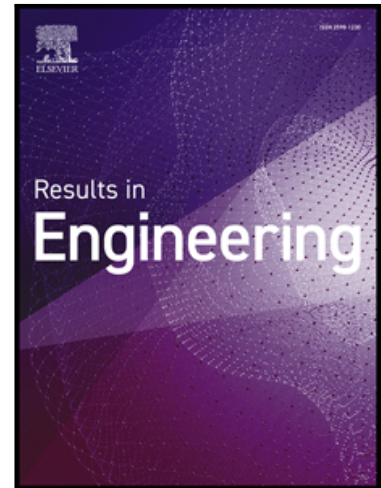


A fully 3D-based algorithm to determine fatigue critical notches of welded joints

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Highlights

- Fully 3D-based algorithm to determine fatigue critical notches on 3D surface scans
- Automatic determination of fatigue critical geometrical parameters
- Highly accurate results for artificial datasets, milled notches, welded specimens
- Determination of possible fatigue crack initiation locations

A fully 3D-based algorithm to determine fatigue critical notches of welded joints

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Abstract

While the local weld seam geometry in general has a high impact on the fatigue resistance of welded joints, the weld toe radius (r) and weld toe angle (α) are the two decisive critical geometry parameters. With 3D scanning of weld seams becoming more popular in manufacturing industry and research, a small number of manual, semi-automatic and automatic evaluation methods have been developed. Despite the benefit of 3D surface scans, all currently existing methods are only evaluating 2D cut sections to determine in plane weld toe radii and angles. In this research work, a newly developed 3D evaluation method is presented, using the full potential of 3D scan data. Due to this 3D approach, critical surface areas are detected automatically, lower pointcloud resolutions are required, notch critical aspects regarding the loading direction can be considered and the entire 3D surface is evaluated. After describing the algorithm workflow, the method is tested and evaluated on numerous datasets. First, on artificial scan data with varying weld toe radii, weld toe angles and pointcloud resolutions. Second, on a machine milled notch specimen and third on as welded, repaired and HFMI-treated fillet- and butt welds provided by an IIW round-robin study. The results show an accurate alignment with the artificial scan data and the notch specimen for both parameters (r , α). For the weld specimens, similar results as the global median of the round-robin study are achieved, while results show a significantly smaller scatter.

Keywords: Local weld geometry; 3D surface scans; weld evaluation; weld quality inspection, fatigue of welded joints

1. Introduction

When it comes to fatigue resistance of steel structures, welded joints are usually the fatigue critical details [1–6]. Besides residual tensile stresses which reduce the fatigue resistance of welded joints the local weld seam geometry itself has the biggest impact on the fatigue resistance [3, 5, 7, 8]. While the weld seam height and width have little impact on the fatigue resistance, the weld toe radius (r) and weld toe angle (α) have a high impact on the fatigue resistance of the weld seam [2, 9–11]. This effect can be explained due to stress concentrations created by the notch at the weld toe which naturally forms along the weld bead [3, 4, 8]. The decrease in fatigue resistance due to lower weld toe radii and angles is also established in multiple guidelines regulating weld seam manufacturing qualities and weld seam surface imperfections (EN ISO 5817 [12], EN ISO 6520-1 [13], VOLVO STD 181-0004 [14]). Additionally, the microstructural support effect in the notch itself, which is increasing the fatigue resistance, is closely related to the notch radius and notch opening angle [7, 15–17].

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While these geometrical parameters are monitored by manufacturers of steel constructions to ensure quality regulations, e.g. quality class B of EN ISO 5817 [12] for fatigue-loaded steel structures, it is mostly done with simplified circular shaped gauges and angle gauges manually. Due to a difficult and inaccurate placement regarding the handling of these gauges, the results vary widely and are of strong subjective nature. Additionally, manual quality control is time consuming and expensive for steel construction manufacturers. With 3D scanning systems becoming more popular in research and industry, increasing amounts of 3D scan data are recorded during or after the welding process and evaluated for quality insurance issues. After automatic welding and automatic recording of scan data, the automatic evaluation and following quality control of the critical geometrical parameters r and α is the next logical step to make quality control significantly more efficient. Currently this is done either manually, semi-manually or with one of few automatic algorithms which use 2D cut sections created from 3D scan data [18–23]. Using only 2D cut sections leaves a big research gap when it comes to accurately evaluating 3D scan data, as results solely depend on the positioning of the 2D cut sections while additionally not considering any sensitivity to load directions. Additionally, the existing 2D evaluation methods only evaluate the weld toe radius and opening angle at two sides of the weld seam and therefore ignore possible critical notches on multi-layer weld seams. In order to improve the performance, to reduce varying results and to enable the full potential of a 3D surface scans, a newly developed automatic algorithm is presented in this paper to close this research gap. This algorithm is actually using entire 3D scan data to evaluate fatigue critical weld toe radii and angles, making use of the full 3D scan data potential.

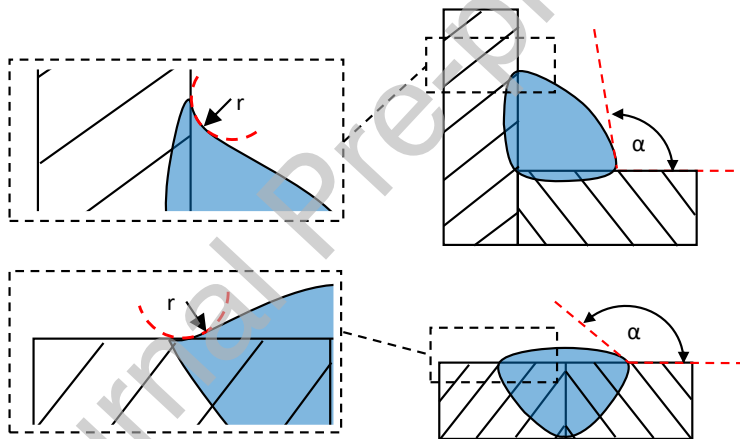


Figure 1: Geometrical parameters: Weld toe radius r and weld toe angle α for fillet- and butt welds

Nomenclature

$\hat{a}$	Unit vector	p_i	pointcloud point
c	Initial center	q_i	Projection of p_i to cylinder axis
d_r	Pointcloud resolution	RMSE	Root Mean Square Error
e	Residual	r	2D circle radius
F_{neg}	Force input in neg. direction	r_c	Detected cylinder

F_{pos}	Force input in pos. direction	r_{max}	Maximum radius
k	Number of NHR	r_{min}	Minimum radius
LS	Least Square	SVD	Singular Value Decomposition
NHR	Neighbourhoodring	α	Weld toe angle
n_z	Vertex normal	ω	Notch opening angle
p	Initial Parameters		

2. General idea and existing evaluation methods

2.1. Other existing evaluation methods

Evaluating notch radii of weld toes automatically to determine fatigue critical weld seam geometries is generally not a new idea. Schubnell [18, 19], Stenberg [24, 25] and Dänekas [26, 27] already addressed this idea and developed automatic algorithms to determine weld toe radii and weld toe angles. All previously developed methods create 2D cut sections perpendicular to the weld seam out of the 3D pointcloud and calculate the radii and angles for the two weld toes of butt welds and fillet welds. A brief explanation of the three existing 2D methods is given in the following:

Curvature method: The curvature method (CM), determines the weld toe radius by calculating the curvature of a 2D weld profile based on the idea that the curvature of a circle can be derived by $\kappa = 1/r$. Using partially derivatives of 2D pointclouds, the location of maximum curvature identifies the weld toe, and its inverse value gives the weld toe radius [18, 19].

Least square method: Inside the least square method (LSM), a least square fit is applied to the circle definition in cartesian coordinates to determine the weld toe radius. Similar to the curvature method, the weld toe location is identified using the curvature, derived by $\kappa = 1/r$ with the weld toe region being defined by a curvature exceeding 30 % of the maximum value [24, 25].

Iteration method: The iteration method (IM) uses potential start points, end points and radii to estimate the weld toe by a circular segment. For each start point around the weld toe area, circle segments with varying radii are iteratively compared against several geometric criteria, while the combination with the smallest evaluation quotient determines the weld toe radius. Equally to the other methods, the weld toe location is identified using the curvature [26, 27].

Additionally to these three methods many methods exist in commercial 3D scanning software, all working with a similar principle in order to evaluate 2D cut sections [19–21].

2.2. Approach of a new 3D based evaluation method

While 2D evaluation methods deliver good results, especially on grinded notches or artificial scan data [20, 28], there are multiple areas which can be improved by a 3D approach. Results of 2D evaluation methods are severely depending on the number and position of the cut sections. This effect can be seen in a IIW round-robin study on fillet and butt weld specimens, comparing the widely spreading results of 19 participants [21]. As the 2D cut sections are only evaluated in one specified orientation (usually perpendicular to the weld seam direction), notch radii are also only valid for one loading direction. While this is sufficient for laboratory weld specimens which are usually uniaxially loaded tensile specimens, weld seams in real steel structures are often subjected to inclined load directions to the weld seam. Additionally, 2D evaluation methods need high pointcloud resolutions to achieve a sufficient amount of points which can be matched by the cut section to ensure reliable results [21, 28]. The idea of a 3D based evaluation method solves these issues. Instead of 2D cut sections, the entire pointcloud is evaluated as a triangulated surface (STL). Critical surface areas are automatically selected to prevent fatigue critical notch radii falling through the 2D cut section grid. Hereby, notches in the weld bead created by multi-layer weld seams are additionally detected and evaluated. By evaluating notch radii in a three-dimensional space, either the most critical notch radii overall or the most critical notch radii for a specified load direction can be determined. Taking the vertices of a circular 3D surface area to determine the notch radii increases the relevant number of points to define fatigue critical radii. Therefore, lower pointcloud resolutions can be used or a higher accuracy with consistent pointcloud resolution can be achieved. Additionally, a 3D-based evaluation method will detect notches in unexpected locations outside the weld toes as well e.g. surface pores or regions with corrosion damage. Figure 2 gives an impression on the working principal of the 3D evaluation method for calculation of weld toe radii and weld toe angles.

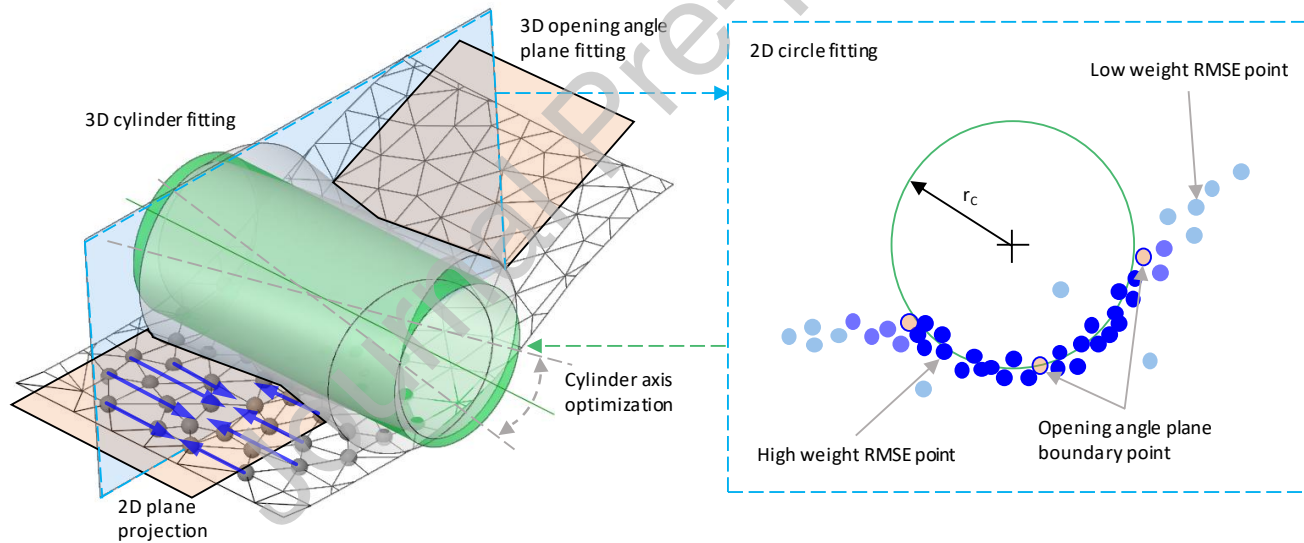


Figure 2: Basic working principal of the 3D evaluation method for weld toe radius and weld toe angle calculations

3. Algorithm workflow

3.1. Determination of critical locations

After triangulating the pointcloud to create a closed surface, the geometry is imported as an STL file. As a first step, a normal vector is created on each vertex of the triangulated surface. Each vertex normal vector is defined by averaging the normal vectors of all facets sharing this vertex. Averaging over the facet normal vectors aligns the vertex normal vectors in areas with noise and gives smoother results for curved areas. By comparing the vertex normal vector angles to a vertical threshold, vertexes which are located in flat areas are discarded. The curvature itself is then checked individually for small areas called curvature neighbourhoods (NHR). Each curvature NHR consists of one central vertex and a ring of surrounding facets with a radius of three edge traversals ($k = 3$). Three edge traversals create a patch with sufficient size to identify curved areas while keeping the calculation effort low. If the normal variation of the vertex normal vectors inside one curvature NHR is larger than the defined flatness threshold, the facets inside this curvature NHR are considered highly curved and therefore as a critical surface. For each considered curvature NHR, a concavity check is performed to discard convex areas. Curvature NHRs which are highly curved but convex shaped will not create fatigue critical notches and are therefore not further considered. The remaining curvature NHRs form the vertex candidate list which defines the final critical surface area. Each vertex found in the vertex candidate list creates an own candidate NHR defined by a radius ($k(d_r)$) based on the pointcloud resolution and the size of the critical surface patch around it. Using the size of continues critical surface patches, the geometry of the weld toe is accounted for in the candidate NHR radius. Irregular weld seam geometries show smaller continues patches of critical (curved) surface than regular weld seams. As the candidate NHR radius is a function of the pointcloud resolution and the size of continues patches of critical surface area, the absolute size of the candidate NHR stays consistent with varying pointcloud resolutions and only varies depending on the weld toe shape. Otherwise, a finer pointcloud resolution created from the same geometry would result in a smaller absolute size of the candidate NHR compared to a coarser pointcloud resolution. Still, the radius can only be increased or decreased by at least one edge traversal, creating slightly varying absolute candidate NHR sizes with varying pointcloud resolutions. Inside each candidate NHR, the notch detection is performed.

3.2. Notch detection

For each previously defined NHR, the main notch detection algorithm will compute one possible cylinder, see chapter 3.3. Afterwards, the opening angle (ω) for each cylinder is determined, see chapter 3.4. After the 3D fitting function determined a critical cylinder and its corresponding opening angle, the radius of the cylinder is checked for the upper and lower radius limits. While very large radii (≥ 3 mm) are uncritical regarding notch stress evaluation, very small radii (< 0.3 mm) are rather considered a crack or scanning inaccuracy [7, 17, 29]. Last, the detected cylinder has to touch a minimum of surface points inside a 0.5 % cylinder radius tolerance. Due to the naturally regular longitudinal shape of weld seams, a cylinder proved to deliver more accurate results than a sphere while significantly reducing calculation effort.

3.3. 3D cylinder fitting

In order to iterate the best fitting cylinder, an initial cylinder axis is computed first by performing singular value decomposition (SVD). The singular values define the variance of the pointcloud along each axis. Due to the naturally regular longitudinal shape of weld seams, the variance in longitudinal weld direction is the smallest. Therefore, the direction of the smallest variance defines the cylinder unit vector ($\hat{a}$) which automatically aligns with the longitudinal weld direction. Perpendicular to the cylinder unit vector, a 2D plane is created on which all points inside the NHR are projected in cylinder unit vector direction. Projecting the 3D pointcloud of a NHR

on to a 2D plane transfers a 3D optimization problem into a 2D optimization problem. For the 2D pointcloud, circle fitting using the Kasa circle fitting method [30] is performed. Compared to geometric circle fitting methods, implementing the Kasa method significantly increases calculation time. The Kasa method roughly estimates best-fit circles on pointclouds by minimizing the squared algebraic residuals of a linear transformation of the circle equation [31]. Afterwards, the weighted root mean square error (RMSE) of the fitted circle is calculated. By implementing a weighing function to the RMSE, points which are close the previously fitted circle are weighted stronger while points further away are weighted lower. This reduces the impact of noise on the circle fitting, as single points far away from the fitted circle are neglected. In the iteration loop the cylinder unit vector is changed until the delta of the unit axis vector is below the tolerance value of 0.0001 rad and the delta of the RMSE for the circle fitting is below 0.0001 mm. Lower tolerances would result in possible non-detection of critical radii due to noise and scanning imperfections, larger tolerances would allow for the overestimation of radii. By iterating over several cylinder unit vectors for each NHR, a high amount of cylinder radii in different orientations run through the Kasa circle fitting method subsequently. Last, the final cylinder unit vector, cylinder center and radius are saved. Figure 3 shows a graphical explanation of the 3D cylinder fitting. For the formula used in the 3D cylinder fitting, please refer to Appendix 1.

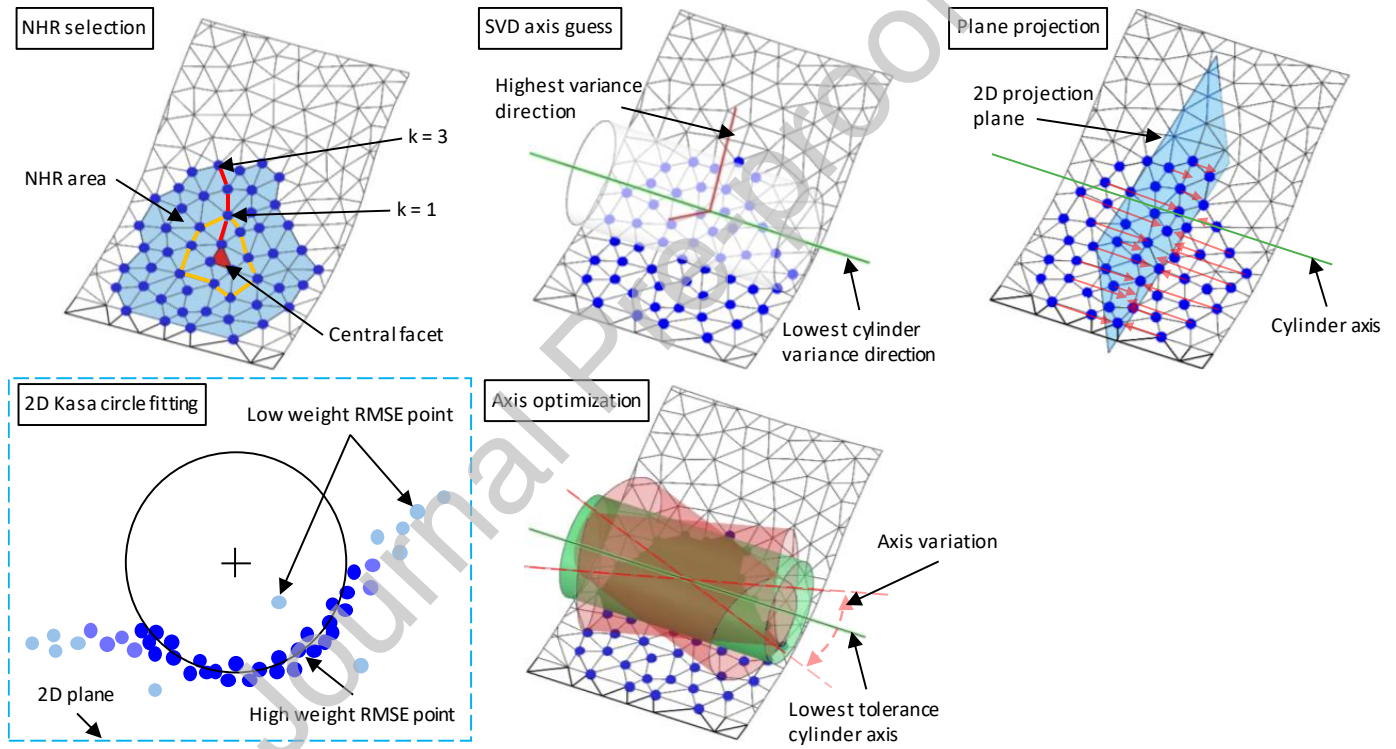


Figure 3: Graphical explanation of the neighbourhoodring (NHR) logic and the 3D cylinder fitting workflow

3.4. Opening angle

Besides the notch radius, the notch opening angle is responsible for the criticality of a notch [5, 15, 17]. For the notch opening angle, the boundary points are determined by projecting the points which previously defined the cylinder to a 2D plane. Similar to the cylinder-axis estimation, SVD is used to fit a plane to the points on each

flank of the notch. The flanks are identified by separating the points between the boundary points at the highest angular discontinuity between consecutive meshed vertices. Equally, the mid-point where both planes intersect is estimated, see Figure 2. The notch opening angle is then calculated from the scalar product of the plane normal vectors.

By considering only the points defining the cylinder rather than including surrounding points of the notch, more accurate results can be obtained for imperfect or post-treated weld seams. For example, notch created by HFMI treatment exhibit sharp edge transitions to the weld seam, which would lead to inaccurate notch opening angles if surrounding points were included. Similar inaccuracies may arise from weld imperfections like undercuts.

3.5. Grouping

The notch detection and 3D cylinder fitting procedures described in chapters 3.2 and 3.3 result in a very large number of cylinders. This output is difficult to evaluate for several reasons. First, the overlap of NHRs creates a very dense distribution of cylinders along critical areas. Second, the applied tolerances may allow the detection of a small number of invalid cylinders. Third, scanning inaccuracies can lead to isolated false cylinder detections. In order to make the results more interpretable and reliable, the cylinders are grouped. Therefore, all detected cylinders inside a cluster radius of 1 mm are assigned to one group. Next, within each group, cylinders with similar radii and orientation are counted. If fewer than five cylinders with similar properties are found in a group, they are excluded from further analysis. Finally, a filtering based on the critical axis direction is performed. Therefore, a mean axis direction based on the cylinder axis of all cylinders is calculated. Cylinders whose axes deviate by more than 30° from this main direction are not further considered. Due to the regular longitudinal shape of weld seams, such large directional variations are unlikely. The excluded cylinders are therefore most likely caused by scanning noise or rare point cloud configurations that enable false-positive cylinder fits within the given tolerances.

3.6. Notch evaluation

The notch evaluation relates the previously found cylinders to the load direction. First, the user has to define two force vectors (X, Y, Z – component) in positive and negative directions. Based on the user-defined forces, a main load direction is calculated and compared with the longitudinal axis of each cylinder. A main load direction that is perpendicular to the cylinder longitudinal axis results in the highest criticality score, while alignment between the cylinder axis and the main load direction results in the lowest criticality score. This approach enables the user to discard smaller notches in non-critical load directions or to reassess larger notches in critical load directions. Additionally, critical load directions can be identified based on the spatial distribution of cylinders with small radii. It is planned to validate the notch evaluation using numerical models based on 3D scan data.

3.7. Report

The final output contains once a graphic visualization and second a data array. In the graphic visualization, the original pointcloud, the pointcloud with all areas marked which were considered for evaluation as critical locations, the original pointcloud including all final cylinders including their axis and centers and a criticality colormap for all cylinders depending on the users force input is plotted. The data array contains all cylinder center coordinates, axis directions, radii and opening angles, before and after the grouping workflow.

3.8. Overview flowchart

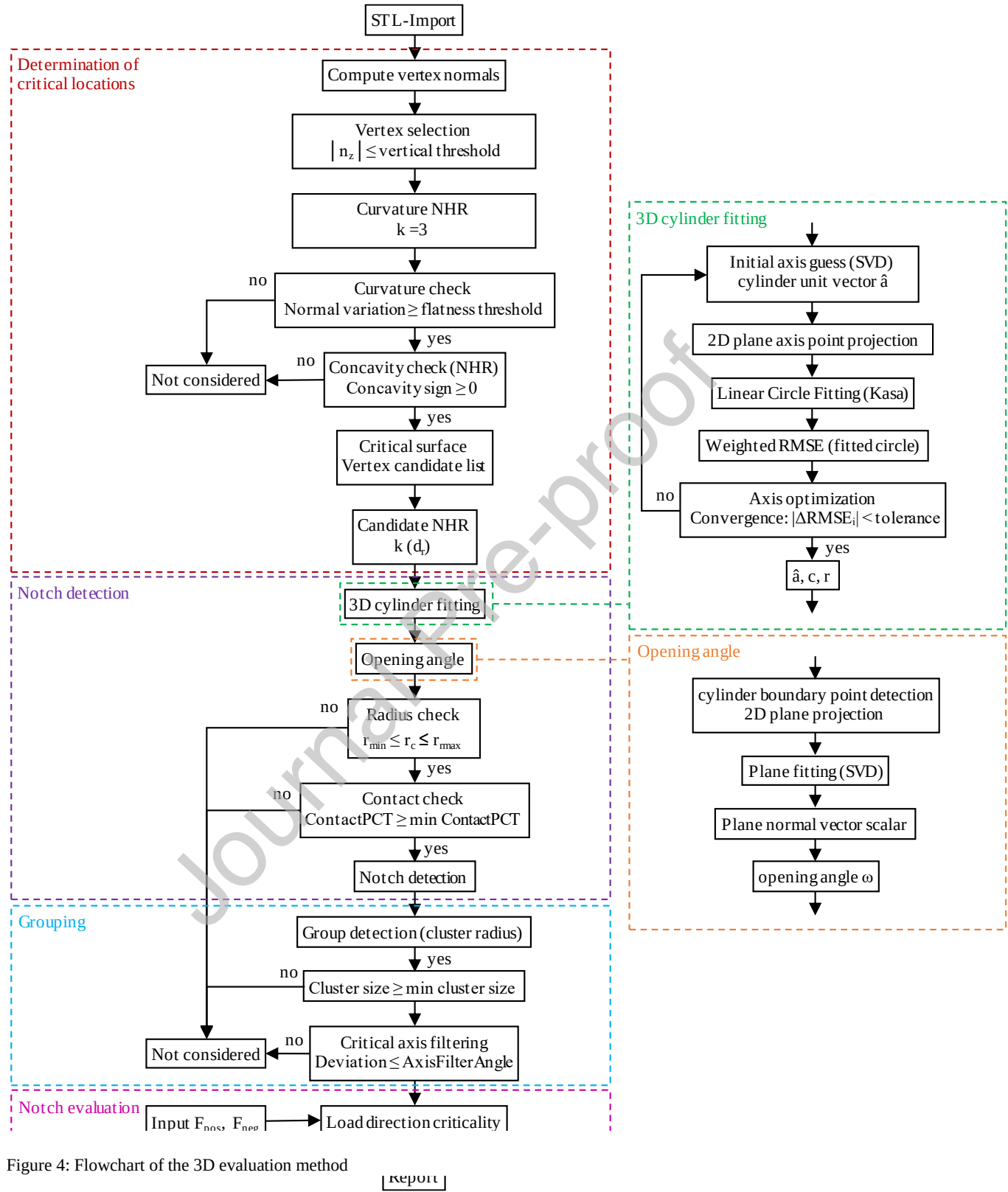


Figure 4: Flowchart of the 3D evaluation method

4. Data Evaluation

4.1. Artificial scan data

As a first dataset to test this 3D evaluation method, artificial scan data resembling an idealized weld toe is created. By varying the pointcloud resolution of the weld toe angle and the weld toe radius, a wide range of artificial weld toe profiles is created, see Figure 5. Each weld toe profile is evaluated using a pointcloud resolution of 0.03 mm, 0.07 mm and 0.15 mm. The 0.15 mm pointcloud resolution serves as an application boundary, because small radii are most likely not be defined with sufficient amounts of points [32]. The width of each weld toe profile allows for multiple radii and angle evaluations for each individual geometry, leading to a total of more than 1000 weld toe radii and angle checks.

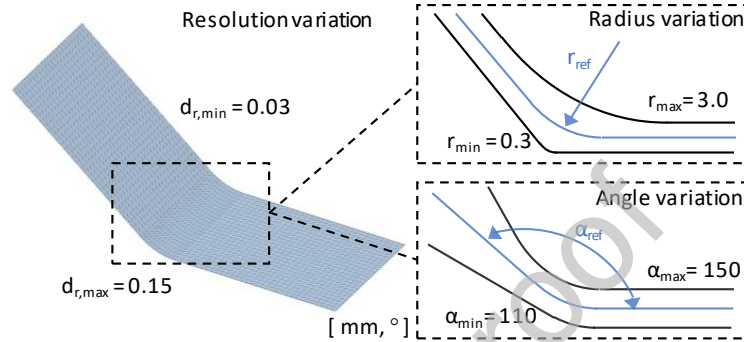


Figure 5: Artificial scan data - idealized weld toe with varying point cloud resolution, weld toe radius and weld toe angle

In contrast to the evaluated scan data in Chapter 4.2 and 0, the artificial scan data is generated based on CAD data. As a result, the point cloud is uniformly distributed in all directions and surface deviations arise solely from variations in pointcloud resolution. Additionally, the scan data doesn't include noise or other scanning inaccuracies. Figure 6 shows the results of the 3D evaluation method compared to the reference radii and angles and Figure 7 the relative error for the determined radii and opening angles.

The comparison of the evaluated weld toe radii to the reference radii shows accurate results for the point cloud resolution 0.03 and 0.07 mm unrelated to the weld toe angle. For the pointcloud resolution of 0.15 mm, an overestimation of the reference radii appears in the small and medium radius range, increasing with rising opening angles. For coarse pointcloud resolutions (0.15 mm) smaller radii with large opening angles lack a sufficient amount of points defining the notch to retrieve reliable results. For larger radii, sufficient number of points define the notch, leading to accurate results even for coarse pointcloud resolutions (0.15 mm). Additionally, due to tolerances which are set to eliminate noise effects of real scan data, slightly larger radii can be detected within these radius ranges. For the small (0.03 mm) and medium (0.07 mm) pointcloud resolution, single results significantly overestimating the reference radii are found. As these results constitute just a small percentage of the overall results, they are considered outliers. The weld toe angle results are slightly overestimated for larger radii with decreasing weld toe angles, but all well below a relative error of 0.1. Besides the larger radii, the weld toe angles for all weld toe radii and angles are precisely matched to the reference values. In previous studies, coarse pointcloud resolutions such as 0.15 mm were not considered and excluded in advance, often working with a pointcloud resolution of 0.025 mm to achieve sufficient amounts of points inside the notch [19–22, 28]. In a recent study comparing the three state of the art automatic 2D algorithms (see chapter 2.1), Dänekas et al. even consider a relative error of less than 0.2 a perfect match, as a relative error of

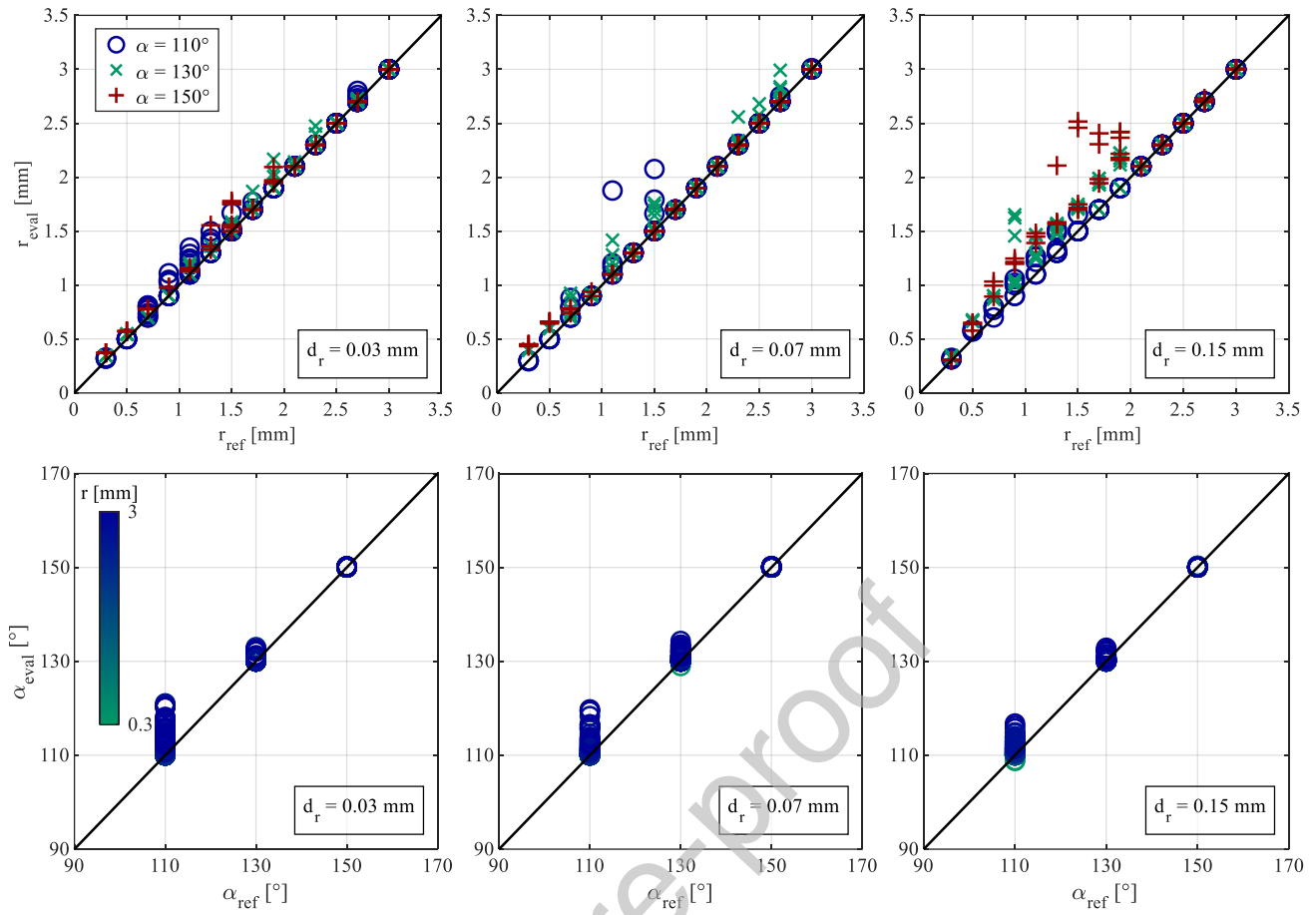


Figure 6: Evaluation of the artificial scan data

0.2 corresponds to a relative error on the stress concentration factor of maximum 5 % [28]. Under these premises and compared to the evaluation of artificial notches using the curvature method, least square method and iteration method by Dănekas [28], the 3D evaluation method performs equally well for small and medium pointcloud resolutions, while showing the potential to work on significantly coarser pointcloud resolutions. As small and medium radii in combination with a coarse pointcloud resolution result in an overestimation of weld toe radii, non-conservative fatigue resistance estimations of welded details are possible. Here, an additional evaluation using a finer pointcloud resolution is recommended.

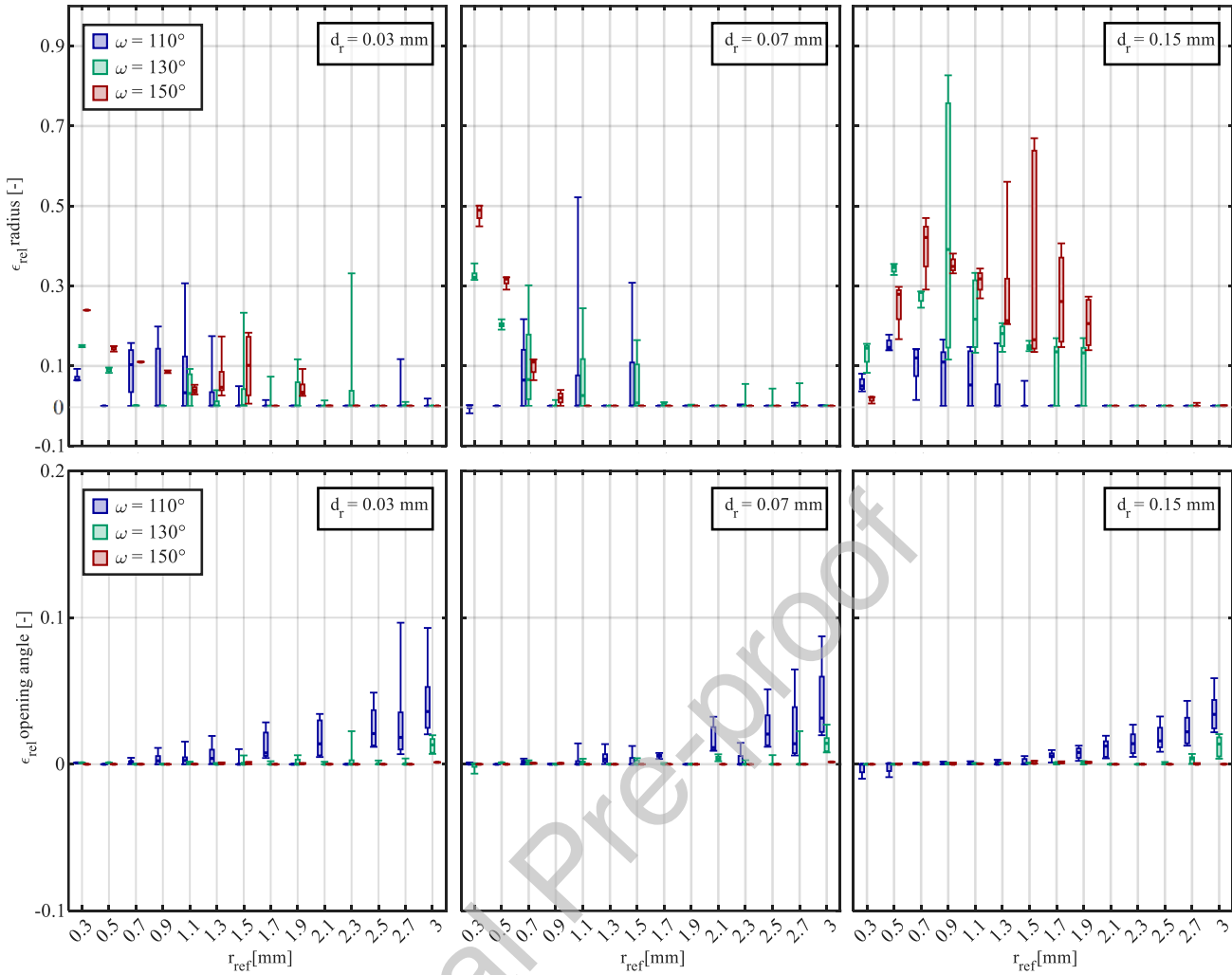


Figure 7: Relative error for radius and opening angle of the artificial scan data

4.2. Notch specimen

During part A of the IIW round-robin study, a machined specimen with eight different notch radii was created to evaluate different measurement systems and techniques for 3D scanning of weld seams [20], see Figure 4. In this section, the notch specimen is used to validate the 3D evaluation method with actual scan data of known reference radii. Unlike the artificial scan data of the idealized weld toes presented in chapter 4.1, the scan data of the notch specimen contains scanning inaccuracies like noise or small surface artefacts. Additionally, the pointcloud resolution is not exactly consistent over the entire surface, but varies up to 0.01 mm inside the notches due to the scanning technique. The specimen was scanned using the Zeiss Atos Q with a pointcloud resolution of $d_r = 0.04$ mm. Figure 9 shows the results of the 3D evaluation method compared to the designated reference radii and Figure 10 the corresponding relative error.



Figure 8: IIW round-robin part A notch specimen, a) dimensions, b) matt surface conditions, c) cut scan data for evaluation [23]

For the radii B, E, and H, nearly perfect results were achieved while the radii F and G were slightly overestimated. Manual inspection of the scan data showed an increased radius in the scan data of 0.58 mm for radius F and of 0.76 mm for radius G. 3D scanning systems tend to smooth small radii, because the notch bottom and the notch edges must be exactly captured to recreate an unsmoothed notch shape. Additionally, single scan points matching the notch bottom and notch edges are often falsely considered noise and erased by the scanning system. The IIW round-robin study part A showed similar deviations for both notches and other 3D scanning systems [20]. Giving the increased radii of F and G, the smaller radii up to a size of 1.9 mm can be considered an accurate match to the reference radii. For the larger radii A, C and D the results begin to scatter. The large majority of the results are close to the reference radii and just single results deviate up to 0.8 mm from the reference radii. With increasing radii but same pointcloud resolution, the absolute amount of vertices which later define the 3D-fitted cylinder remain consistent due to the NHR logic. Therefore, a smaller percentage of the entire notch is used to define the cylinder radius, making the 3D evaluation method more sensitive to noise and other scanning inaccuracies for large radii. As varying larger radii are in general less critical with regard to fatigue inducing stresses and uncommonly found in these dimensions on actual weld seams, the results are considered uncritical for further evaluation of weld seams. The weld toe angle results show a very small deviation of maximum three degrees over the reference angle for all radii exceeding a value of 0.5 mm. For radii F and G, the weld toe angle of a few results is slightly overestimated, but the majority of detected weld toe angles for these two radii accurately matches the reference angle of 135° . The noise of the notch specimen scan data ranges between 5 and $10\ \mu\text{m}$. Compared to the artificial scan data, no significant effect regarding the radii or opening angle results shows. Still, smoothing large noise and reducing scanning inaccuracies without changing the geometry of fatigue critical notches generally improves the accuracy of the results.

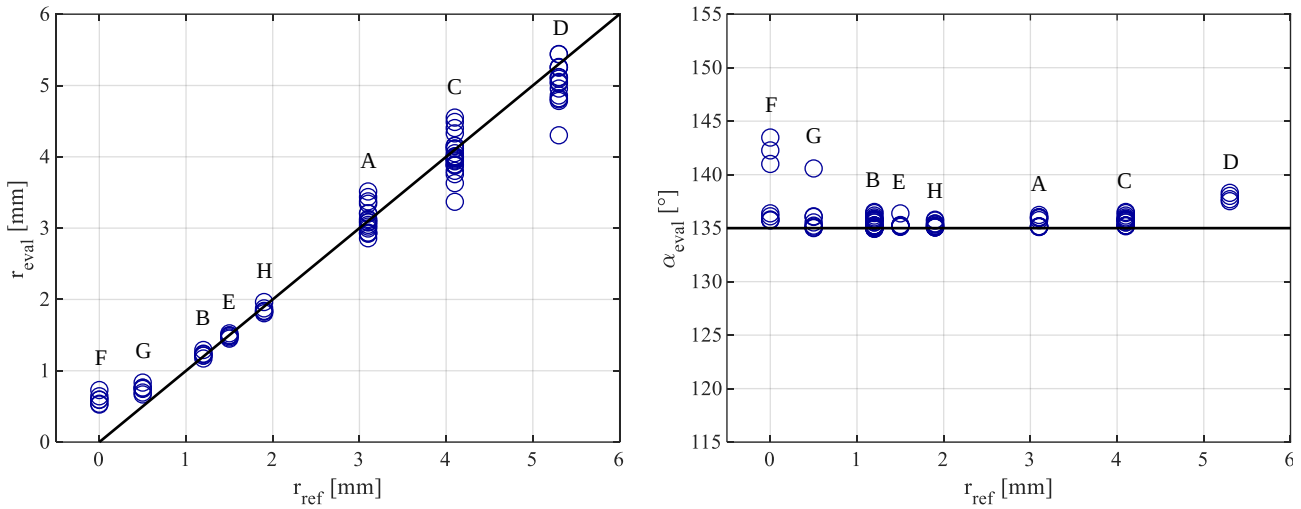


Figure 9: Evaluation of the IIW notch specimen

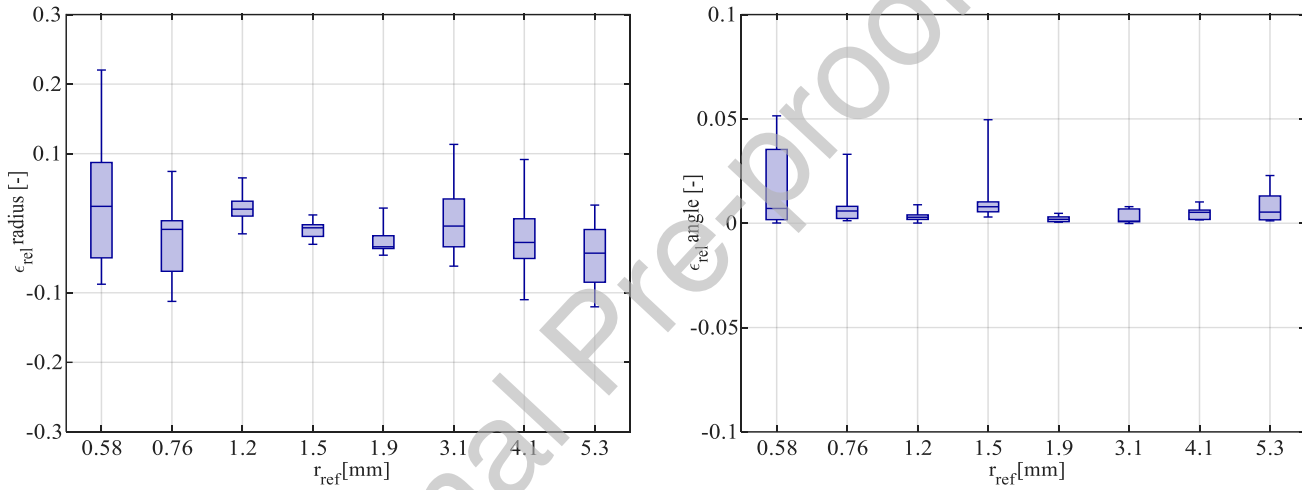


Figure 10: Relative error for radius and opening angle of the IIW notch specimen

4.3. Weld seams

To test the 3D evaluation method on scan data of actual weld seams, the welded specimens of the IIW round-robin study part B were scanned. Eight fillet welds and two butt welds from three types of test specimens, two transverse stiffeners and one butt welded joint were scanned, see Figure 11. One transverse stiffener (IIW-A) contains one HFMI-treated weld seam and two repaired weld seams. The two other test specimens (IIW-B and IIW-C) were scanned in as welded condition. As with the scan data of the notch specimen, the average point cloud resolution is 0.04 mm, with variations of up to ± 0.01 mm. The noise of the weld specimens 3D scan data ranges between 10 and 15 μm .

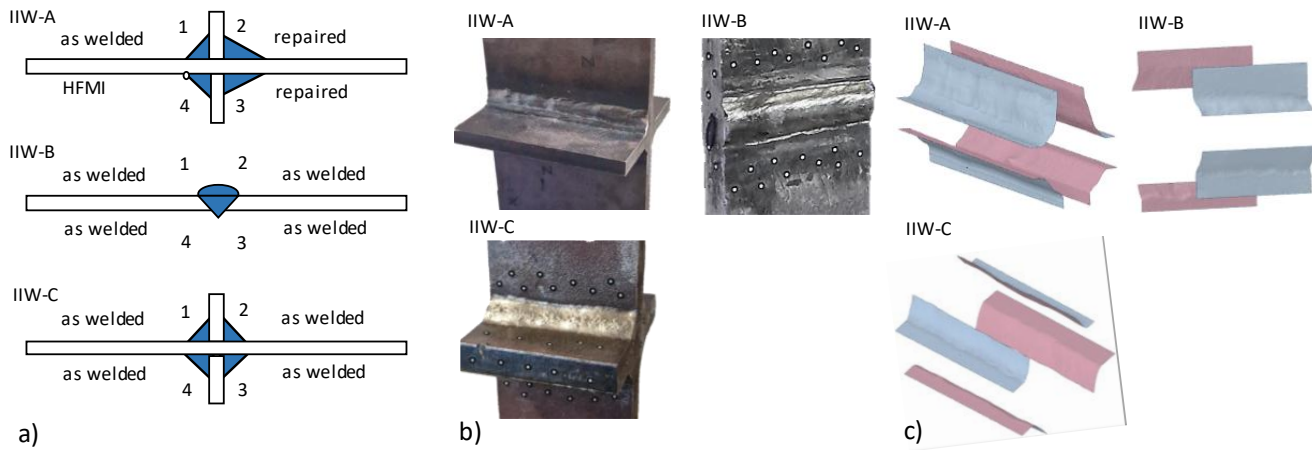


Figure 11: IIW weld specimens, a) design, b) welded specimens, c) evaluated scan data

During the IIW round-robin study part B, 19 participants evaluated the three provided welded specimens regarding the weld toe angle and the weld toe radius [21]. Figure 12 shows the results of the 3D evaluation method for the 12 analyzed weld seams compared to the average results of the IIW round-robin study and the median of the curvature method, least-square method and iteration method. The three external 2D evaluation methods were applied to the same 3D scan data, placing the 2D cut sections in 1 mm distance. All three 2D algorithms were provided by the WeldAnalysis software package [33].

Equally to the IIW round-robin study, only the weld toes at the junction with the base plate were evaluated. The box of the boxplots spans from the first quartile to the third quartile and represents the middle of the results. The blue line marks the median, while the green line marks the global median of all results of all participants of the round-robin study. With the upper and lower whiskers indicate the 5th and 95th percentiles, values outside of these whiskers are plotted as individual points and considered outliers.

In general, the results of the 3D evaluation method show good agreement for weld toe radii and angles within typical ranges for this weld quality with low scatter along the weld seams. Manually fitted radii and angles align with the results of the 3D evaluation method. The manually fitted radii and opening angles were determined by placing cut sections in randomly selected locations aligning with locations in which the 3D evaluation method detected radii. Ansys Spaceclaim was used to create the cut sections and manually fit circles and angles. As the real geometry of the welded specimens is unknown, the global median of the results from all participants of the IIW round-robin study as well as the median of the CM, LSM and IM for each weld seam serves as an indicator for verification.

For most of the weld seams, the results of the 3D evaluation method are close to the average round-robin results, while the round-robin results over all participants scatter significantly more. Inside the round-robin study, different scanning systems, point cloud resolutions, digitizers, evaluation methods and 2D cut sections were used, resulting in a wide range of scattering results. Out of the three weld specimens, IIW-A is the most comparable dataset. WT4 was HFMI-treated with a 2 mm radius pin and shows therefore a similar estimated weld toe radius. Both, the 3D evaluation method and the average round-robin study show that the majority of

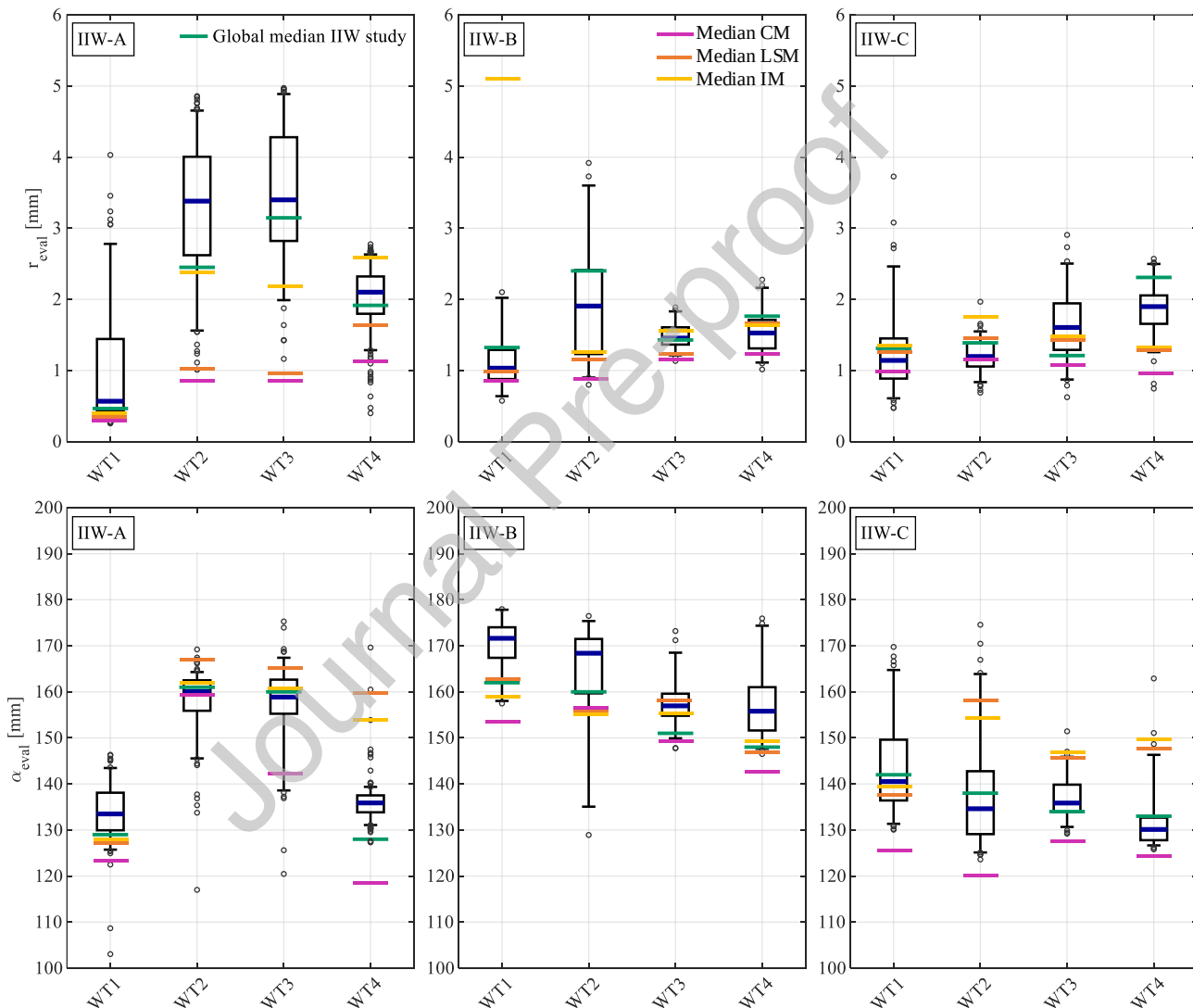


Figure 12: Weld toe radius (top) and weld toe angle (bottom) evaluation of the IIW weld specimens compared to the global median of all participants of the IIW round-robin study and the median of CM, LSM and IM

the radii lie within a narrow range around 2 mm. The smaller and larger radii detected by the 3D evaluation method lay outside the HFMI-treated notch. Due to the HFMI treatment, material gets partially moved outside of the notch and forms small ridges at the base plate side of the HFMI notch. In this case, results outside the first and third quartile were detected at these ridges. WT2 and WT3, which were repair-welded, therefore exhibit significantly higher and more uniform weld toe angles, as well as larger weld toe radii. For both specimens, the weld toe angle results lay inside a small range and exactly match the global median of the round-robin results. The detected weld toe radii are significantly larger than for other weld seams and more widely spread. Among all weld specimens in the round-robin study, these weld seams exhibit the largest variation in radii, with most values reaching up to 5 mm within the middle 50 %. For WT1 of IIW-A nearly all participants of the round-robin study achieved the same weld toe radii results with small variation. The results of the 3D notch evaluation are consistent with these findings, except for a small number of larger radii. These larger radii were detected not parallel to the weld direction but rotated to the weld direction. Due to the 3D cylinder fitting and the iterative axis rotation (see chapter 3.3), radii not positioned in a 2D cut section perpendicular to the weld direction are also detected. In the later criticality evaluation (see chapter 3.6), these radii can be excluded or further considered depending on the load direction. For the remaining weld specimens IIW-B and IIW-C, good agreement with the global median of the round-robin results is observed, as well as with visual inspection of the weld specimens. Furthermore, the results for both parameters exhibit less scatter than those reported by most participants.

While the results of CM, LSM and IM are also included in the global median of the IIW round-robin study, a separate comparison shows areas of good alignment as well as areas of deviation. For small radii, the 3D evaluation method shows similar results inside a small corridor, while significant larger radii are detected for large weld toe radii (IIW-A, WT2 and WT3). For the HFMI treated weld toe (IIW-A, WT4), the 3D evaluation method delivers radii closest to the HFMI 2 mm radius pin, while the CM significantly underestimates the 2 mm radius. In general, the CM delivers lower weld toe radii and weld toe angles in all cases, also compared to LSM and IM. For steep weld toe angles (IIW-C, WT1-4 and IIW-A, WT1 and WT4) the 3D evaluation method shows results in between the LSM, IM and the CM, while overestimating flat weld toe angles (IIW-A, WT2,3 and IIW-B, WT1,2,4). It should be mentioned, that the results from CM, LSM and IM might vary depending on the number and positioning of the 2D cut sections. For a more detailed comparison, Figure 13 shows the

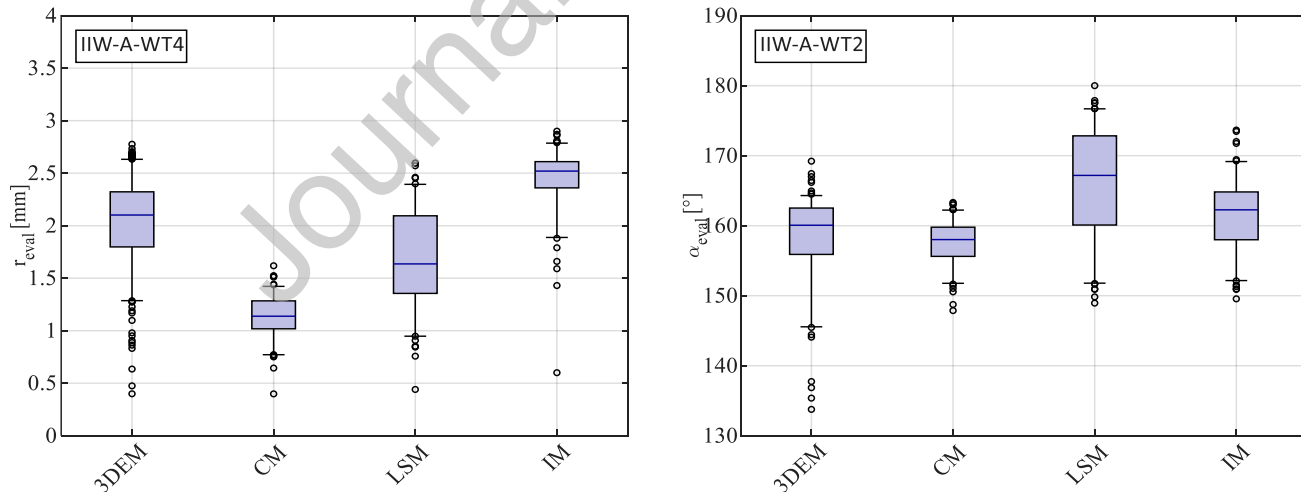


Figure 13: Weld toe radius (left) and weld toe angle (right) evaluation of the IIW weld specimen IIW-A WT4 (radius) and WT2 (angle) using the 3DEM, CM, LSM and IM

results of the four evaluation methods for weld specimen IIW-A (WT2 and WT4). For WT2 the weld toe angel is displayed and for WT4 the weld toe radius is plotted. WT4 is the HFMI-treated weld seam and WT2 one of the repair-welded weld seams. For both parameters, these two weld toes showed the smallest deviation in the IIW round-robin study.

As the exact result for the welded specimens is unknown, it is impossible to determine which evaluation method delivers the smallest error. Therefore, a more detailed comparison of all four methods is suggested in future research, making results more comparable.

5. Correlation of detected radii to fatigue tests

Since the notch with the smallest radius and the smallest opening angle (highest notch sharpness) generates the highest notch stress, the highest notch strains and consequently crack initiation should occur at the location of the sharpest notch along the weld seam. Accordingly, the 3D Evaluation Method can be used to predict the location of crack initiation at weld seams during fatigue testing. To validate this, measurements were performed using a Digital Image Correlation (DIC) system on butt welds during running fatigue tests. The specimens are single-sided welded butt welds with remaining weld pool, welded using a robotic process (GMAW-135) with weld pool backing. Specimens from two test series are used, both made of S355J2C+N, having a plate thickness of either 3 or 4 mm depending on the series. The load is applied in the tension-tension fatigue range ($R = 0.1$) centrally on the weld specimen and orthogonally to the weld seam. To measure the occurring notch strains, the DIC system (Limess Q400-3D in a 2D measurement configuration) is positioned centrally close above the weld seam. Figure 14 shows the experimental setup and the specimen dimensions.

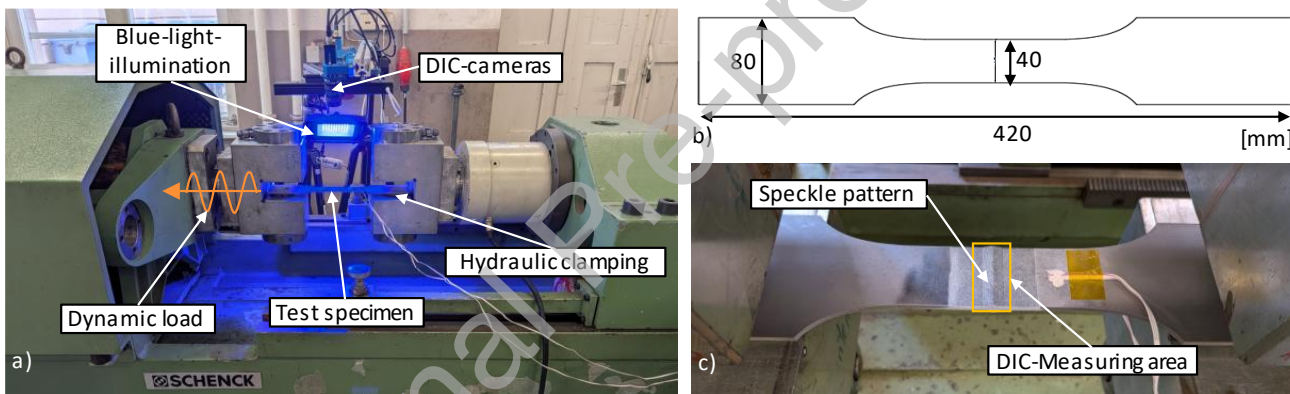


Figure 14: a) Fatigue test setup, b) dimensions of the test specimens, c) Test specimen with speckle pattern

Strain measurement at weld toes of weld seams using a DIC system during ongoing fatigue testing requires a high metrological effort. Since the loads in the fatigue tests are significantly lower than in a static tensile test, the strains at the weld toe are proportionally lower. To record these strains with the necessary accuracy, a correspondingly small measurement area (40 x 20 mm) with the highest possible resolution (12 MP) must be selected and a very fine speckle pattern must be sprayed. In addition, the camera system must be positioned and calibrated precisely, since even small displacements of the DIC system lead to high measurement errors. Even with an accurate measurement setup, the evaluation of the measured strains proved to be extremely difficult and resulted in a high rate of fatigue tests with no evaluable DIC-measurement data. Out of the two recorded fatigue test series, six specimens were evaluable. Figure 15 shows the fatigue tests of the two test series and the specimens which delivered evaluable strain distributions from the DIC-measurements.

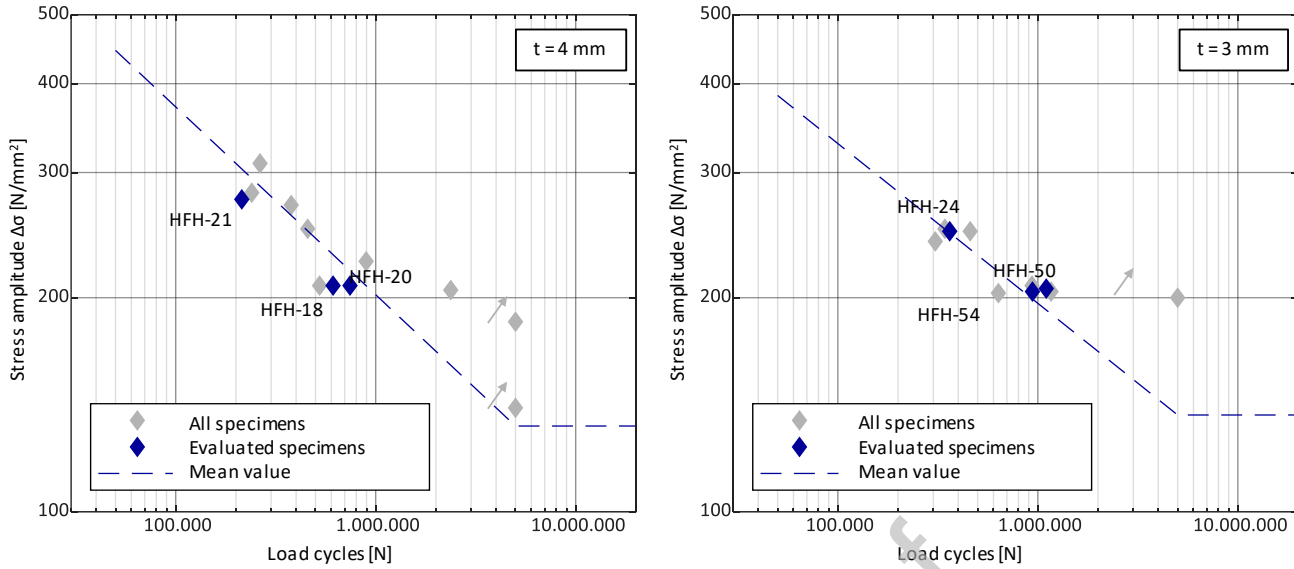


Figure 15: Evaluated fatigue test results

The specimens in the fatigue tests conducted here are welded from one side using a weld pool backing which was later removed. Therefore, the weld pool remains as the weld root on the underside of the specimen. Due to the shape of the weld pool backing, the underside of the weld exhibits a significantly sharper notch effect than the weld bead on the top side. At almost all test specimens, the crack therefore initiated from the underside of the weld and not from the top side which was recorded by the DIC-system. Additionally, the weld pool backing creates a uniform root geometry and an evaluation using the 3DEM would consistently deliver the same radii and opening angles. Consequently, only the notch strain on the top side of the weld at maximum load is evaluated and compared with the weld toe radii detected by the 3DEM. Of all specimens evaluated here, only specimen HFH-21 showed a crack initiation at the weld toe on the top side.

To validate the notch radii detected by the 3DEM, the first principal strain is evaluated in one image of the DIC measurement during maximum load. In order to make the locations of the maximum notch strain visible in each fatigue test, the value range and the smoothing of the DIC result are individually adjusted for the graphical representation. This allows for the assignment of the location of the maximum notch strain, but does not allow for an exact quantification of the first principal strain. In Figure 16, the DIC-measured first principal strain of the six evaluable fatigue tests is compared to the detected radii of the 3DEM. Individual detected large radii were partially removed from the plots because they obscured a large number of detected small radii in the visualization. These isolated large radii are outliers that are incorrectly detected in small numbers, see sections 4.1 to 4.3. The specimens were scanned with a point cloud resolution of 0.04 mm. Subsequently, the point cloud resolution was reduced to 0.1 mm by merging facets in the same plane, thereby creating 3D scan data which geometrically corresponds to the raw data but has a lower pointcloud resolution. No further preprocessing steps were performed. The exact positions of the minimum weld toe radii were determined based on the exact coordinates from the data array of the result output. The value range of the detected radii is limited to 3 mm in this evaluation and larger detected radii are no longer visualized.

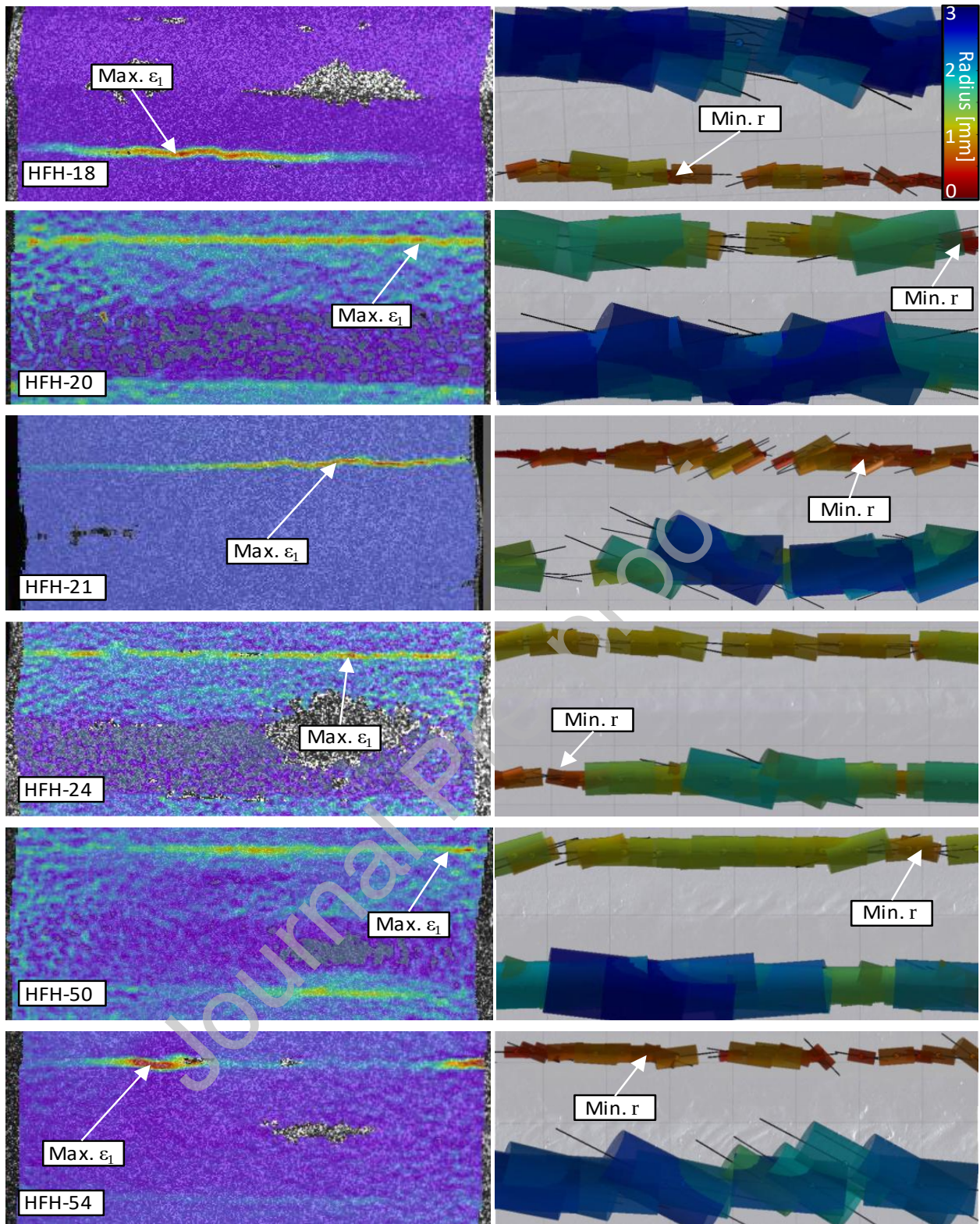


Figure 16: Comparison of maximum first principal strain measurements recorded with a DIC-System during fatigue tests to radii detected by the 3DEM

The comparison of the first principal strain and the detected weld toe radii generally shows a clear correlation. Consistently, small weld toe radii are detected at locations with high strain and large notch radii at locations with low strain. Particularly for the specimens where a clearly assignable maximum notch strain is identifiable (HFH-18, 21, 54), the minimum weld toe radius was detected at the same position. In addition to the low DIC-measurement noise in these three fatigue tests, these specimens each exhibit one sharp and one rather blunt weld toe. Here, the 3DEM not only detects the smallest weld toe radius at the appropriate location, but also consistently shows large weld toe radii (1.8 to 3 mm) at the weld toes that exhibit no visible notch strain in the DIC measurements. Regardless of the correlation between the smallest weld toe radius and the maximum strain, similarly small weld toe radii are detected at locations with comparably high strain.

The specimens HFH-20, -24, and -50 show significantly higher levels of measurement noise combined with lower measured strains. Here, the location of the smallest detected weld toe radius only matches clearly for specimens HFH-20 while a close match is achieved for HFH-50. The notch radii in these three specimens are consistently larger and more evenly distributed. Additionally, the strain along the weld toes varies only within a narrow interval, meaning that the location of the maximum strain cannot be exactly identified. In combination with the strong measurement noise, a precise correlation of the maximum strain to the smallest weld toe radius is difficult for these specimens. However, even for these specimens, smaller weld toe radii are consistently detected in areas with high strains and larger weld toe radii in areas with low strains.

In contrast, a clear correlation between the detected weld toe radii and the fatigue strength of the specimens cannot be established. Although specimens HFH-18 and HFH-21 show a significantly lower fatigue strength than the mean S-N curve of all tests while very small weld toe radii were detected, specimen HFH-50 actually lies above the mean S-N curve despite having comparably small weld toe radii. Specimen HFH-20 exhibits some of the largest weld toe radii at both weld toes and falls below the mean S-N curve. This effect is primarily attributable to the weld root. Since these specimens were welded from one side with a weld pool backing, the weld root produces significantly higher notch stresses than the top side of the weld. Accordingly, crack initiation starts from the underside of the weld in five of the six specimens. Only for specimen HFH-21 the location of the smallest weld toe radius is also the location of crack initiation. In addition, the specimens exhibit extremely little angular distortion (between 0.4° and 1.2°), resulting only a slight increase in strain on the top side of the weld induced by the welding distortion. Irrespective of the geometric imperfections, the welding residual stresses are also unknown and can lead to crack initiation away from the location of the smallest weld toe radius. Nevertheless, a good correlation between notch strain and weld toe radius is consistently evident across all six fatigue tests.

In summary, locations along the weld toe that exhibit small weld toe radii and consequently increased notch strains can be reliably identified using the 3DEM. These locations show a significantly higher potential for reduced fatigue strength and potential crack initiation.

6. Discussion

The presented algorithm can clearly detect and quantify critical notches in 3D surface scans and therefore predict fatigue critical weld seam geometries as well as above average quality weld seam geometries. Besides the evaluated surface geometric criticality, a direct link to the fatigue resistance of welded structures and a holistic fatigue life prediction is hardly possible. This can be explained by the superposition of other fatigue-relevant factors, such as tensile welding residual stresses, angular distortion, axial misalignment or internal weld imperfections which can mask or override the influence of the weld toe geometry.

Tensile residual stresses which are thermally induced, resulting from melting and the subsequent restrained thermal shrinkage, occur most severely at the weld toe. They therefore directly superpose with the stress

concentration caused by the geometric notch effect of the weld toe radius and opening angle. As the tensile residual stresses are not uniformly distributed along the weld toe, the superposition of both stresses can lead to crack initiation not matching the location of the most critical weld toe detected. For the same reason, fatigue life might be overpredicted or underpredicted depending on the distribution of the residual stresses and the weld toe geometry.

Angular distortion and axial misalignment can mask or override the influence of the weld toe geometry as well if particularly pronounced and critical for the considered weld detail. Weld toe locations which are considered critical by the 3DEM can be loaded with additional compressive stresses due to angular distortion and therefore show higher fatigue life than expected from the weld toe geometry. In contrast, angular distortion can induce additional tensile stresses to weld toe locations which are considered rather uncritical by the 3DEM.

Additionally, 3D surface scans never detect internal weld imperfections such as root defects or internal lack of fusion. The internal weld imperfections result in a significant lower fatigue resistance and often have a stronger effect than the weld toe geometry, usually leading to internal crack initiation.

Considering these limitations, the 3DEM can serve as an applicable and useful method in manufacturing and structural integrity assessment. The local notch strain is directly correlated to the weld toe radius and opening angle, resulting in a high significance regarding weld seam quality assessment and fatigue life indication. While other factors might overpower stress concentrations caused by the weld toe geometry, a sharper weld toe will result in a higher stress concentration and consequently in a lower fatigue resistance at this location.

7. Conclusion

In this scientific study, a newly developed 3D evaluation method for detection and qualification of fatigue critical notches in welded joints based on the weld toe radius and angle is presented. The 3D evaluation method is the first fully 3D-based and completely automatic working algorithm which is closing significant fatigue relevant research gaps for 3D surface scan evaluation, while performing on a highly accurate level. A comprehensive description of the entire algorithm workflow is provided and a wide range of 3D scan data evaluated to test, assess, and compare the method. The following key findings were obtained:

- Accurate results were achieved for artificial scan data of idealized weld toes for fine and medium point cloud resolution. For small and medium radii in combination with a coarse pointcloud resolution, radii are overestimated due to an insufficient amount of points describing the notch. Weld toe radii are slightly overestimated for medium-sized radii due to cylinder fitting tolerances introduced to suppress noise in real scan data. Weld toe angles show excellent agreement across the entire data set, with only minor overestimations observed for radii larger than 2.7 mm in combination with small weld toe angles.
- The evaluation of a machined notch specimen demonstrated high accuracy for radii and angles for radii up to 2 mm. For radii larger than 2 mm, weld toe radii results exhibit increased scatter due to noise sensitivity in the cylinder fitting procedure. With the exception of a few outliers, weld toe angles results remain consistently accurate.
- Results obtained from IIW round-robin weld specimens show good alignment with manual inspections, expected parameter trends (HFMI notch, repair welded transitions) and the global median results of the round-robin study. The 3D evaluation method provides plausible results with significantly less scatter compared to most other round-robin evaluations. Compared to the CM, LSM and IM, the 3D evaluation method overestimates weld toe radii and angles for very large weld toe radii

and very low angles. Good alignment with the LSM and IM is provided in most cases, especially for small weld toe radii, while the CM constantly shows lower results.

- The first principal strain along the weld toe was measured during fatigue tests of butt welds using a DIC-system. Locations along the weld toe that exhibit small weld toe radii and consequently increased notch strains can be reliably identified using the 3DEM. For most specimens, the location of the highest strain matched the location of the smallest radius.

Overall, the data analysis demonstrates that the proposed 3D evaluation method enables accurate determination of weld toe radii and angles. In addition, critical surface regions are automatically detected, lower point cloud resolutions can be utilized, notch criticality with regard to load direction can be incorporated, and entire 3D surface evaluations are achieved. In future research projects regarding fatigue resistance of welded specimens, the hereby presented 3D evaluation method will be used to determine crack initiation locations, estimate micro-structural support effects in numerical analysis and comprehend outlier weld specimens in fatigue tests. It is planned to apply the 3D evaluation method on fatigue loaded steel structures in near future to make its benefits available for manufacturing of fatigue loaded welded joints and therefore increase manufacturing quality and detect weld seams with low fatigue life in advance.

While a direct correlation between fatigue life and weld toe geometry solely based on the radius and opening angle is not possible, future research should work on incorporating these parameters into the fatigue assessment. Guidelines for quality regulations of welded structures could implement the automatic determination of the weld toe geometry for the already existing reduced FAT-classes for surface imperfections [12]. In the long term, future studies could investigate the possibility of a reduction or amplification factor for existing FAT-classes based on detected radii and opening angles. Until then, the main use case of the 3DEM is the manufacturing quality control and the identification of fatigue critical details in existing welded structures.

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Appendix A.

A.1. Initial parameters unit vector

$$\hat{a} = \begin{bmatrix} \cos(el) \cos(az) \\ \cos(el) \sin(az) \\ \sin(el) \end{bmatrix}^T \quad (A1)$$

Where

$\hat{a}$ = initial unit vector of the cylinder axis

el = elevation

az = azimuth

A.2. Axis point projection to 2D plane

$$U_i = P_i \cdot \hat{u} \quad (A2)$$

$$V_i = P_i \cdot \hat{v} \quad (A3)$$

Where

$$\hat{u} \perp \hat{a}, \hat{v} = \hat{a} \times \hat{u}$$

P_i = points projected on the 2D plane

$\hat{u}, \hat{v}$ = orthogonal basis vectors to $\hat{a}$

U_i, V_i = 2D coordinates

A.3. Linear Circle Fitting

$$[2U_i \ 2V_i \ 1] [uc \ vc \ C]^T = [U_i^2 + V_i^2] \quad (A4)$$

Where

C is substituted for $r^2 - uc^2 - vc^2$

After solving for C , its value is returned to determine the radius r

$$r = \sqrt{C + uc^2 + vc^2} \quad (A5)$$

A.4. Weighted RMSE

$$RMSE = \sqrt{(\sum w_i (d_i - r)^2) / \sum w_i} \quad (A6)$$

$$w_i = e^{(-d_i^2 / 2\sigma^2)} \quad (A7)$$

Where

w_i = Guassian weight

d_i = radial distance from initial axis

σ = Guassian weight distribution factor

A.5. Cylinder boundary point detection

$$d_{\perp,i} = \| (P_i - C) - (P_i - C) \cdot a \| \quad (A8)$$

$$|d_{\perp,i} - r| < Tolerance \quad (A9)$$

Where

$d_{\perp,i}$ = perpendicular distance from point P_i to the cylinder axis

C = approximated center point on the cylinder axis

a = unit vector representing the orientation of the cylinder axis

A.6. Opening angle plane fitting

$$\bar{P} = U \Sigma V^T \quad (A10)$$

$$\hat{n} = V(:,3) \quad (A11)$$

$$\varphi = 180^\circ - \arccos(\hat{n}_1 \cdot \hat{n}_2) \quad (\text{A12})$$

Where

$\bar{P}$ = centered coordinate matrix of points

V = eigenvectors of the point cloud (direction)

$\hat{n}$ = normal vector of the fitted plane

φ = opening angle

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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