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# From 3D-Scan to numerical model – a practical workflow for welded details

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A B S T R A C T

With 3D-Scanning devices becoming more popular in research and industry, increasingly more 3D surface scans of welded details are recorded. Still, these scans are mostly used to check manufacturing deviations or guideline requirements. The same data can be used to calculate notch stresses, identify locations for future crack initiation and predict load cycles until failure when transferred into a numerical model.

The objective of this study is to quantify the influence of scanning parameters, preprocessing and modelling parameters on the accuracy of fatigue-relevant stress calculations derived from 3D surface scans. A systematic parameter study demonstrates that a pointcloud resolution of at least 0.1 mm is necessary to obtain stress results within a ±5% deviation from reference solutions. The findings provide experimentally supported recommendations for reliable scan-based numerical modelling of welded details. Last, a reference specimen with corresponding stress values is presented, allowing each applicant to verify their individual process from the first scanning settings to the final numerical model.

## 1. Introduction and background

Even though welded details are usually the critical locations regarding fatigue resistance, they are usually numerically modelled completely idealized without considering the actual weld seam geometry. Typically, weld seams are modelled as triangle shaped prisms, often leading to significant inaccurate notch stress calculations even when using local notch stress concepts [1–3]. Modelling a more accurate weld seam geometry, e.g. by implementing higher degree polynomial spline functions, can only be done with complicated and time-consuming algorithms combined with local notch stress concepts which often still result in inaccurate notch stresses. With 3D-scanning devices becoming more popular and widely used in research and industry, actual weld seam geometries can be used for numerical modelling [4–7]. This allows to include all geometric fatigue affecting factors and therefore more accurate notch stress calculations [8,9]. Transferring a 3D-pointcloud into a functioning numerical model requires suitable parameter settings and procedures, otherwise it affects the final notch stress calculation [10,11]. Several scan systems, varying scanning technologies and hardware possibilities, different lighting conditions, user defined scan parameters and surface properties lead to an extremely high number of possible outcomes. While some parameters are uncritical and can be tolerated in wider ranges, others need to be precisely matched [12–14]. A scientific investigation to make 3D-scans applicable for research and industry applications is necessary. Within this study, a workflow on how to transfer 3D scan data into numerical models to perform fatigue-inducing stress calculations (notch

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shape factors) is proposed. Previous research on 3D scanning and numerical modelling solely focused on single aspects affecting the scanning accuracy, evaluation of few individual weld imperfections based on 3D-scanning or the numerical modelling of one specific case in steel construction [15–20]. For the first time, this manuscript provides a complete workflow which is practical applicable, while addressing the most common difficulties when it comes to creating a fully working numerical model from a 3D pointcloud.

The following nomenclature is used hereafter.

| | |
|---|---|
| C | Curvature |
| $d_r$ | Pointcloud resolution |
| E | Element size |
| r | Notch radius |
| $\Delta d$ | Point deviation |
| $\Delta_{pp}$ | Deviation preprocessed to CAD |
| $\Delta_{raw}$ | Deviation raw to CAD |
| $\sigma_1$ | First principal stress |
| $\sigma_v$ | Von Mises equivalent stress |
| $\omega$ | Notch opening angle |

## 2. Experimental data basis

### 2.1. Scanning systems

To evaluate scanning parameters and requirements for numerical modelling, a series of several different test specimens was recorded to create a wide data basis of scan data. Two different scanning systems were used, which scanning techniques stand representative for other market wide commonly used 3D-scan systems. First, a stationary system, the Zeiss Atos Q with two different measurement volumes (MV100 and MV500) resulting in a fixed pointcloud resolution of 0.04 mm and 0.15 mm. Second, a mobile handheld system, the Zeiss T-Scan-Hawk-2, with a fixed lens setup and a variable pointcloud resolution ranging from 0.15 mm to 0.5 mm. While the Zeiss Atos Q uses phase-shift fringe projection, the Zeiss T-Scan-Hawk-2 uses laser triangulation to produce 3D pointclouds. Both scanning systems require a reference point layout on or around the scanned object to determine their own position. Fig. 11 shows the setup of both 3D scan-systems, the mobile handheld one while scanning a weld detail of a bridge hanger and the stationary one while recording a ground notch specimen.

### 2.2. Specimens

Three different kinds of test specimens were used: Ground notch radii, laboratory made weld seams and bridge hanger weld seams. For the ground notch radii, seven radii ranging from 0.3 mm to 3 mm were ground into a blank steel surface with three different depths each. The varying depths create three notch opening angles for each radius (60°, 90° and 120°), resulting in a total of 21 individual

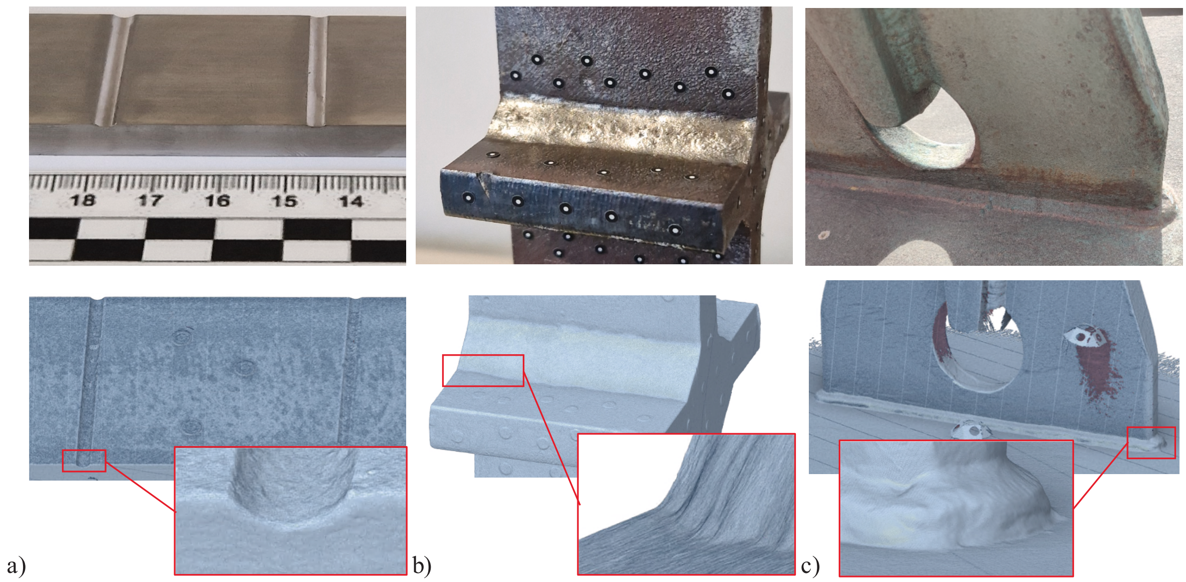


**Fig. 1.** Exemplary 3D-scan data of test specimens: (a) ground notch radii with 2.5 mm radius and different notch opening angles, (b) transverse stiffener with fillet welds, (c) weld detail of a bridge hanger welded to the longitudinal girder.

circular notches. As the notches are precisely CNC– ground inside a manufacturing tolerance of ±1 μm, their geometry is considered to be the same as their CAD geometry. Even though deviations from the manufacturing process to the absolute accurate CAD geometry are possible, they are considered negligible tolerances compared to other deviations caused by the 3D scanning and numerical modelling process. A 3D surface comparison was performed to ensure the exactly manufactured geometry of all 21 notches. The ground notches serve as an artificial, but therefore precisely known geometry to compare scanning results to CAD-geometries. Therefore, all effects having an impact on the final numerical results through the entire process can be detected and evaluated. While all ground notches were scanned having typical steel surface conditions (as- ground), three notches were polished later and three notches were sprayed with a thin coating (2–6 μm). The as- ground notches show a typical steel surface similar to welded surfaces, while the polished notches show a metallic blanc, reflective surface and the coated notches show a matt, light absorbing surface. Hereby, the effect of different surface conditions on the scanning results can be captured.

The second category of test specimens are weld seams manufactured under laboratory conditions. Eight fillet welds and two butt welds from three types of test specimens, two transverse stiffeners and one butt weld, were scanned. One transverse stiffener (IIW-A) has 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. While these specimens were produced under controlled workshop conditions compared to other welded civil engineering structures, they don't show any surface imperfections or welding flaws. As these three specimens were part of an IIW round-robin study [10,21], the scan results can be compared to the scan results of other research institutions. These scan data serve to ensure that the findings of the ground notches scan data can be transferred directly to scan data of actual butt and fillet welds.

Additionally, the weld seams of 16 connecting hangers as well as the longitudinal beam of a tied arch bridge were scanned. These weld seams were welded below workshop conditions on a constructions site and show a high number of surface imperfections as well as numerous corroded areas. In this study, they are used to evaluate the effects of construction site scanning conditions and to ensure that the developed procedures can be transferred to actual steel structures. Fig. 1 shows exemplary pictures and the belonging 3D surface scan data for one of each test specimen types.

### 2.3. Test matrix

To capture the effect of surrounding conditions, different lighting setups were considered. The majority of the scan data was recorded under laboratory conditions with dim lighting, which represents usual office or manufacturing surrounding under artificial lighting. Additionally, some scans were made under bright lighting to imitate the effect of sunlight or strong direct inside lighting. Naturally, the bridge hangers were scanned under outside lighting conditions with some scanned in direct sunlight and some scanned in the shadow. The illuminance ranges were measured in several locations for each surrounding category using a lux meter (Wilnos Mavolux 5032C). They represent typical lighting conditions, while the outside lighting conditions significantly vary depending on the current weather situation. Table 1 shows the entire matrix of collected scan data and the related parameters.

For both scanning systems other scanning resolutions are possible, while market wide other systems offer a large range of different scanning resolutions. The chosen scanning resolutions for the upcoming investigations resemble a limited choice of coarse and fine resolution for handheld and stationary systems.

## 3. Scan parameter requirements

### 3.1. Pointcloud resolution

The pointcloud resolution is the decisive factor for the overall outcome, as it directly affects the geometry and the preprocessing and therefore the final geometry for the numerical model. Additionally, the pointcloud resolution is bound to the scanning system and therefore the key parameter when choosing the correct hardware settings. In order to quantify the effect of the pointcloud resolution on the final geometry, the scan data of the ground notches are compared to their ideal CAD-geometry. Fig. 2 shows typical results of a 3D surface comparison for different pointcloud resolutions.

**Table 1**
Overview of scanned test specimens, scan systems and pointcloud resolutions.

| Type of specimen | Quantity | Scan Systems | Resolution [mm] | Illuminance [lx] | Surrounding |
|---|---|---|---|---|---|
| Ground notch | 21 | Atos Q MV100 | 0.04 | 200–400 | Laboratory dim |
| | 21 | Atos Q MV500 | 0.15 | 200–400 | Laboratory dim |
| | 21 | T-Scan-Hawk | 0.30 | 200–400 | Laboratory dim |
| | 21 | 2T-Scan-Hawk 2 | 0.15 | 200–400 | Laboratory dim |
| Ground notch polished | 3 | Atos Q MV100 | 0.04 | 200–400 | Laboratory dim |
| | 3 | Atos Q MV100 | 0.04 | 1000–2500 | Laboratory bright |
| Ground notch matt | 3 | Atos Q MV100 | 0.04 | 200–400 | Laboratory dim |
| | 3 | Atos Q MV100 | 0.04 | 1000–2500 | Laboratory bright |
| Butt/fillet weld | 10 | Atos Q MV100 | 0.04 | 200–400 | Laboratory dim |
| | 10 | Atos Q MV500 | 0.15 | 200–400 | Laboratory dim |
| | 10 | T-Scan-Hawk 2 | 0.25 | 200–400 | Laboratory dim |
| Bridge hanger | 8 | T-Scan-Hawk | 0.25 | 50,000–110,000 | Sunlight outdoor |
| | 8 | 2T-Scan-Hawk 2 | 0.25 | 800–10000 | Shadow outdoor |

Combining inaccuracies during the grinding process of the notch with not ideal flat surface geometries and non-perfect matching of the scan data with the CAD-geometry are causing deviations in a range of 0.01 mm. Deviation inside an uncertainty band of 0.01 mm, as plotted in Fig. 2a), are therefore considered an exact representation of the CAD-geometry. While flat surfaces are captured evenly accurate with coarser pointcloud resolution, finer scanning resolutions create more accurate surface geometries on deformed surfaces. Especially sharp edges and deep pockets show significant deviations when generated with coarse pointcloud resolutions. This is a severe issue when notch stresses are evaluated, as it causes a smoothing effect on notch geometries. This smoothing effect can especially be observed on sharp edges and deep pockets which are usually the most critical regarding notch stresses. In Fig. 3, a critical example between the finest pointcloud resolution and the coarsest pointcloud resolution in this study is shown. While the coarse resolution theoretically still shows a sufficient number of points to recreate the notch shape, the pointcloud deviation increases towards the edges and the bottom of the notch. Often, the sharp edges of the notch or the lowest located bottom points of the notch are not exactly matched because they fall through the pointcloud resolution grid. If they are closely matched, false noise filtering causes a smoothing of notch edge and bottom. Small numbers of points, which are correctly matching the notch edge, deviate from the large mass of points in flat areas and are therefore considered noise. Noise points, which create a smoother transition, are incorrectly considered actual surface. Similar but less critical effects are observed for other pointcloud resolutions and scans of weld seams. In general, the sufficient recording of edges and pockets is bound to the pointcloud resolution.

The edges and the bottoms of the ground notches are the critical locations for the notch stress evaluation and the most difficult locations to capture by the scanning systems. Therefore, these locations will be used to evaluate the deviation of the pointcloud to the CAD-geometry for different pointcloud resolutions. Fig. 4 shows the pointcloud deviation related to the notch radii, the notch opening angle and the pointcloud resolution. All ground notches are circular, while the notch opening angle changes as a function of the notch radius depth.

For both scanning systems (handheld and stationary) the notch edges are more difficult to capture than the bottom of the notch. This effect increases with smaller notch opening angles and smaller notch radii, resembling higher flank angles and deeper pockets. Unrelated to the scanning resolution, the handheld system shows higher deviations at the notch edges. With finer scanning resolution of the handheld system, the deviation at the bottom of the notch decreases. Still, the stationary system delivers significantly more accurate results than the handheld system when using the same scanning resolution. The stationary system shows increasing deviation results with decreasing notch radii for coarse scanning resolution, while the fine scanning resolution shows constant accurate results with little deviation. With increasing notch opening angles and therefore more blunt notches, the deviation results begin to scatter. As the notch opening angle is created by varying notch depths of the same radius, these notch bottoms are closer to surface level, impairing the ratio of scanning inaccuracies to notch depth. A notch with a radius of 0.3 mm and a notch opening angle of 120° has a maximum depth of 0.04 mm, matching the finest pointcloud resolution and resulting in more randomly distributed deviation results. Additionally, the stationary systems tend to cluster a denser pointcloud around geometric jumps, benefiting the accuracy for sharper notches. At the same time, with increasing notch opening angle the edges do not have to be matched as precisely anymore to create the same accuracy. This effect benefits the handheld systems since similar inaccuracies lead to smaller deviations.

Regarding the deviation results in Fig. 4, the pointcloud data recorded with a scanning resolution of 0.04 mm are considered a nearly exact representation inside a small uncertainty band of the surface geometry and will in the following be used as a baseline for the welded specimens without available CAD geometries. The measured deviations are negligible small and were often caused by the manufacturing process or a non-perfect alignment of the scan data and the CAD-geometry. The scattering results for a notch opening angle $\omega = 120^{\circ}$ are of less importance, because blunt notches are in general less critical with regard to fatigue inducing stresses.

Similar results as plotted in Fig. 4 were received when comparing different pointcloud resolutions on actual weld seams, see Fig. 6. While the handheld system showed similar deviation results on the weld seams as on the ground notches, the deviation results of the

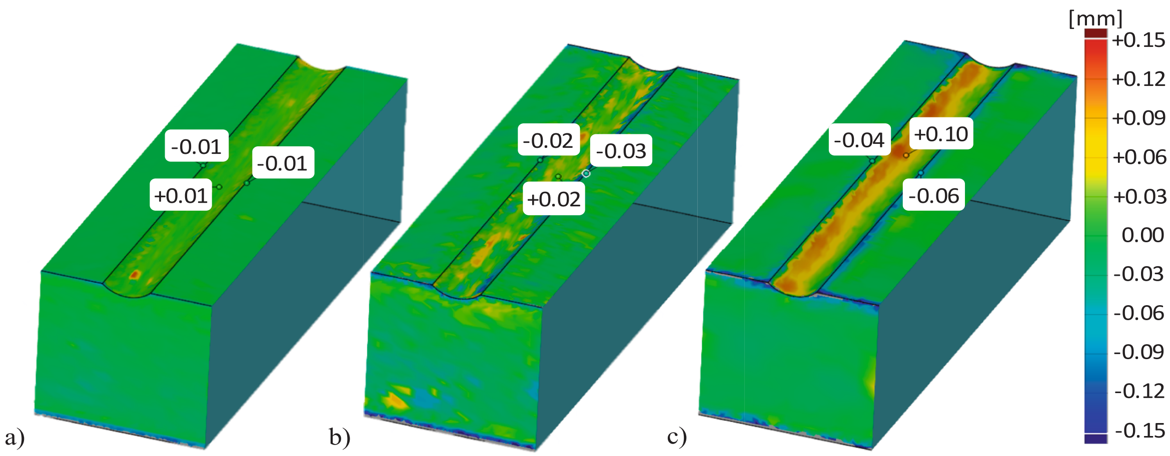


**Fig. 2.** 3D-surface comparison of a ground notch with a radius of 2.0 mm and a depth of 0.59 mm: (a) pointcloud resolution 0.04 mm, (b) pointcloud resolution 0.15 mm, (c) pointcloud resolution 0.3 mm.

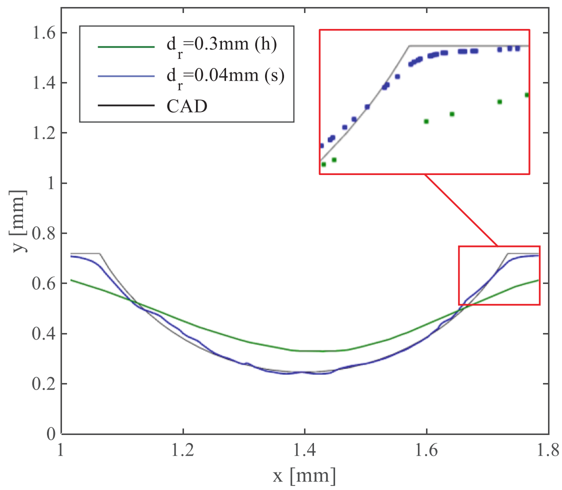


**Fig. 3.** Scan results for a high pointcloud resolution of a stationary system ($d_r$ = 0.04 mm) and for a coarse pointcloud resolution of a handheld system ($d_r$ = 0.3 mm) compared to the CAD-geometry of a 1 mm ground notch cut section.

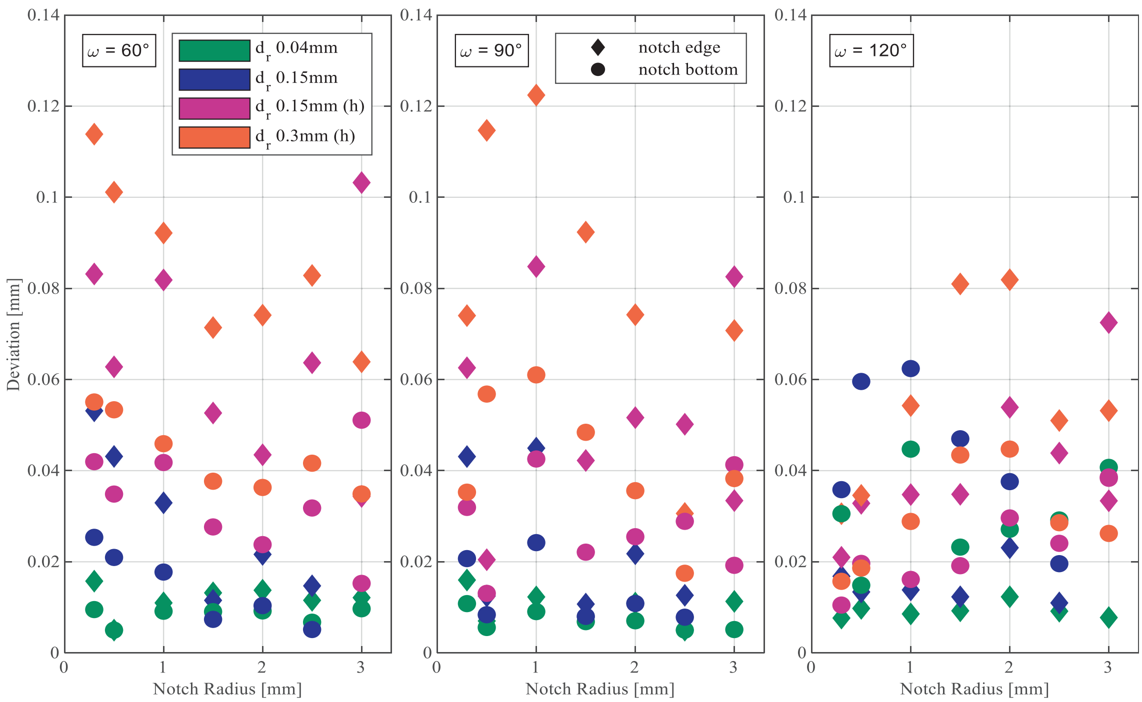


**Fig. 4.** Deviation of 3D surface scans with different scanning resolutions and scanning techniques (s = stationary, h = handheld) to the ideal CAD-geometry of ground notches with different radii and notch opening angles.

stationary system improved significantly. Once, because the weld seam surface is less reflective. Second, because weld seams generally have more continuous curved geometries which are easier to match with coarse pointcloud resolutions than hard geometric jumps which have to be exactly matched. The deviation was evaluated at both weld toes of cut sections at equal distances of 10 mm, as pictured in Fig. 5. The scan data recorded with the handheld system and a pointcloud resolution of 0.3 mm were not further considered due to the severe deviation results on the ground notches.

To quantify the impact of the pointcloud resolution and the resulting deviation on the subsequent stress calculation, the scan data of the grind notches were modeled in Ansys Mechanical 2025.R1. Following scientific best practice, the numerical modelling process would usually be explained before the numerical results are presented. This study uses the numerical results before to verify findings while explaining the numerical modelling process in the later chapters. Therefore, the workflow itself, starting with scanning and ending with numerical results, is presented in comprehensible order. No preprocessing of the pointcloud was done except a facet

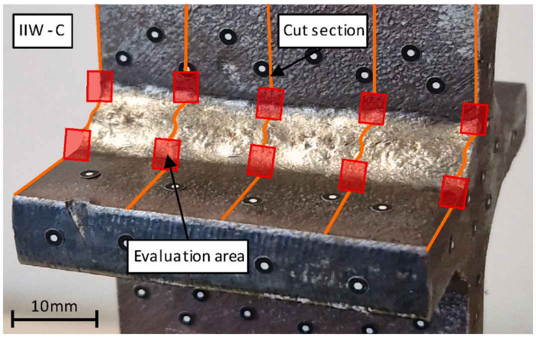


**Fig. 5.** Cut sections and evaluation areas for one exemplary weld seam – IIW weld specimen C.

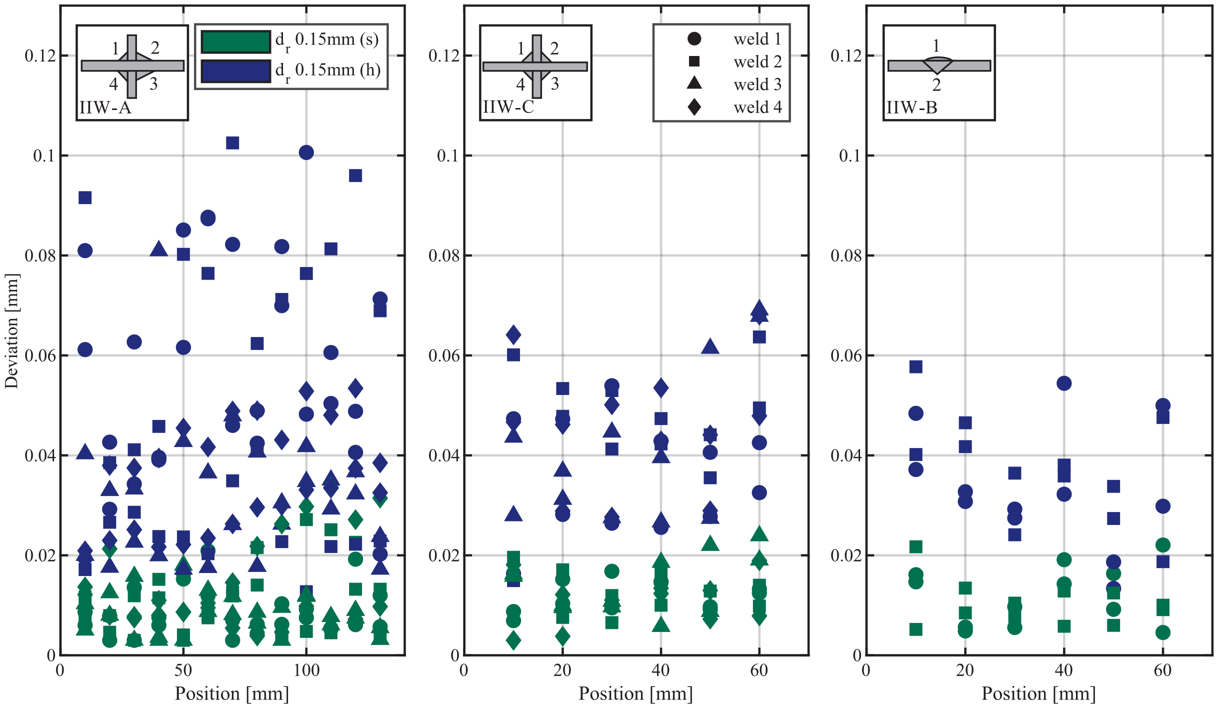


**Fig. 6.** Deviation of 3D surface scans with different scanning resolutions and scanning techniques (s = stationary, h = handheld) compared to the highest scan resolution ($d_r$ = 0.04 mm) for three weld specimens (results of both weld toes of one weld seam combined).

normalization which is necessary to create a functional numerical mesh, see chapter 4. A numerical element size equal to the facet size was used, see also chapter 4. All models were rigidly fixed at one end and subjected to a tensile uniform stress of 1 MPa on the other end, automatically resulting in the notch shape factor based on the first principal stress results. A sensivity study was performed to ensure that no singularities caused by boundary effects affected the stress distribution in the area of interest.

Fig. 7 shows the first principal stress results for the ground notches compared to the ones of the CAD-geometry. While the 0.04 mm pointcloud resolution data shows results close to the CAD reference results, evenly deviating unrelated to notch radius and notch opening angle, the 0.15 mm point cloud resolution results are more scattered. While the results are still considerable for larger radii, they significantly fall below the CAD reference results for radii smaller than 1 mm. With lower pointcloud resolution and smaller radii, the notch bottom is less likely to be matched exactly by one scan point. As the scan points are more likely to be found slightly left and right apart from the notch bottom with a decreasing pointcloud resolution, notch depths are decreased respectively in the meshed surface. Even though recorded with an equal pointcloud resolution of 0.15 mm, the handheld recorded scan data results in significantly lower stresses than the scan data recorded by the stationary system. The handheld system records more noise due to the constant movement of the device during the scanning process. When the noise gets filtered, single scan points in sharp notches get mistakenly deleted as noise, while noise points creating a smoother surface are considered actual surface data. This effect mostly effects notch bottoms and notch edges. It increases significantly with a decreasing pointcloud resolution and creates flatter notches with increased radii. Therefore, the 0.3 mm pointcloud resolution data is also not considered within the numerical stress calculations, showing even

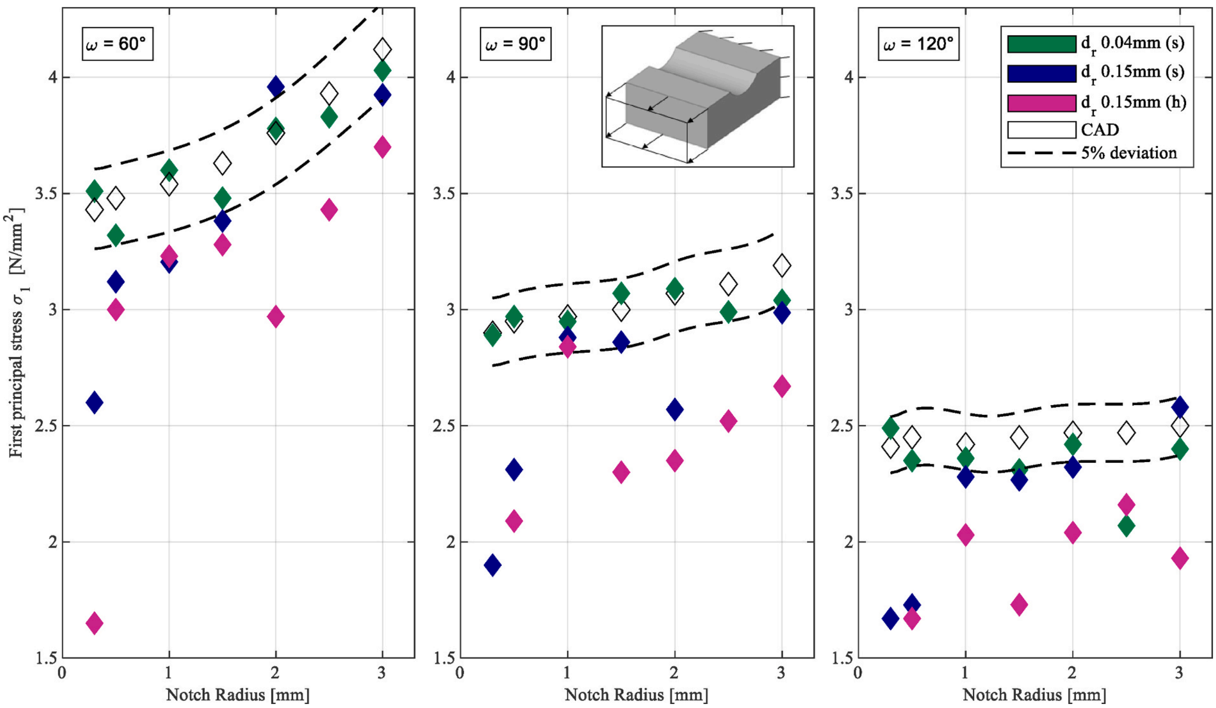


**Fig. 7.** Numerical first principal stress calculations based on scan data of ground notches (s = stationary, h = handheld) with different radii and notch opening angles and corresponding CAD-geometry results.

lower stress results than the 0.15 mm pointcloud resolution.

Similar to the 3D surface scan data of the ground notches, the scan data of the weld seams with different pointcloud resolution were used to create numerical models. All models were also rigid fixed at one end and subjected to tensile uniform stress of 1 MPa on the

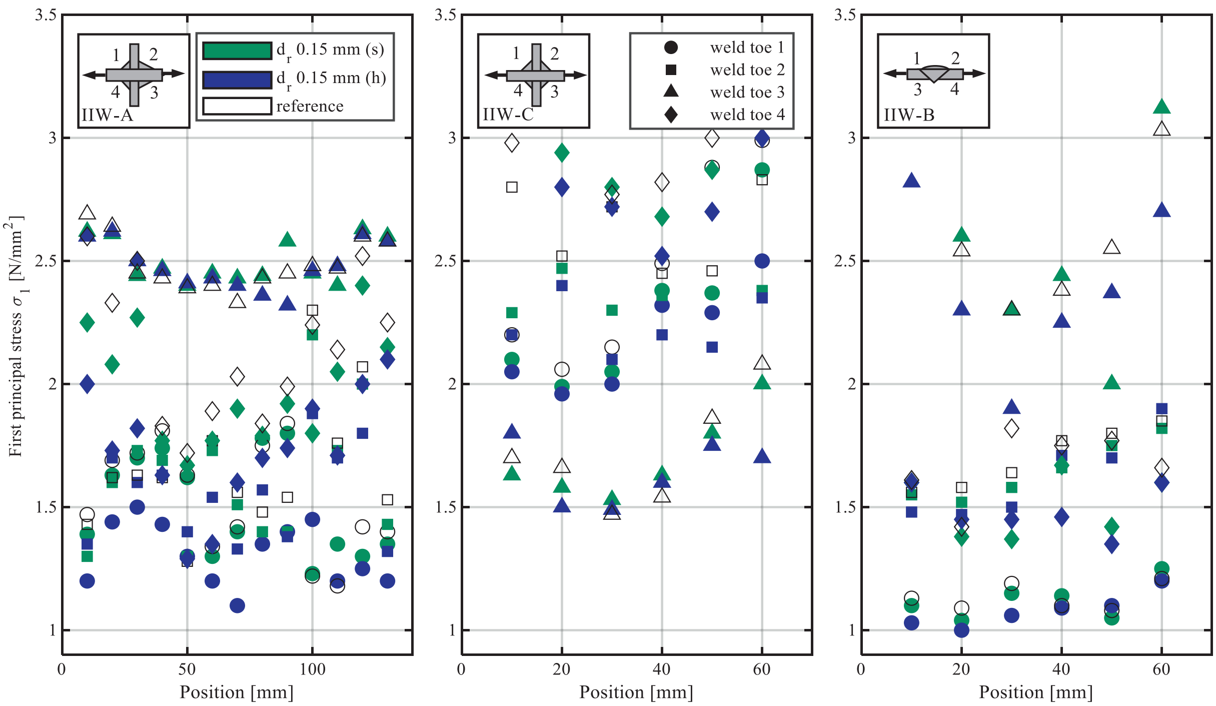


**Fig. 8.** Numerical first principal stress calculations based on scan data of IIW weld specimens (s = stationary, h = handheld) compared to numerical results of reference scans (dr = 0.04 mm, stationary).

other end. The stress results calculated using the 0.04 mm pointcloud resolution serve as the baseline (reference), equally to the procedure of evaluating the surface deviation. Compared were the 0.15 mm pointcloud resolution for both, the stationary and the handheld system to the 0.04 mm pointcloud resolution (reference). Fig. 8 shows the first principal stress for the weld specimens, evaluated at the same weld toe areas at equal distances of 10 mm. In Fig. 9 all stress results deviating more than 5% from the reference results are marked grey.

A pointcloud resolution of 0.15 mm and therefore a minimum element size of 0.15 mm would align with the IIW meshing recommendations of the notch stress concept for a weld toe radius of 1 mm [22]. For larger weld toe radii and high scan quality of the stationary system, the reference results are therefore well inside the 5% deviation. Higher stress deviations for large weld toe radii are caused by scanning inaccuracies (see chapter 3.2) which are smoothing the notch. Even for high scan quality, the notch bottom of smaller weld toe radii is often not matched by a pointcloud resolution of 0.15 mm, leading to lower values of resulting stresses. Both effects significantly increase when using the handheld system. Additionally, the higher inaccuracies of the handheld system combined with the coarse pointcloud resolution can severely overestimate (creating a sharp triangle) or underestimate (completely smooth a notch) the resulting notch stresses. The impact of these inaccuracies is clearly visible in Fig. 9, where most stress results of the handheld system do not match the 5% criterion, while the majority of the stress results of the stationary system still do with an equal pointcloud resolution. In general, stress results get more reliable with finer pointcloud resolution. The absolute size of inaccuracies decreases and small notches are modelled more accurately. Still, fine pointcloud resolutions result in extremely high numbers of numerical elements and therefore high preprocessing efforts and calculation times. If radii are large and evenly curved, they can still be accurately modelled with coarse scanning resolutions. Weld toe No. 3 on specimen IIW-A was HFMI treated with a 2.0 mm pin radius and shows nearly identical results for all scanning resolutions.

Based on the numerical results of the ground notches and weld seams, a pointcloud resolution of at least 0.1 mm (stationary scanning system) is recommended for reliable stress calculations, implying a good scan quality. The numerical results based on the 0.04 mm pointcloud resolution show accurate results throughout the entire test matrix, but create a large amount of data as well as high modelling and calculation effort. The numerical results based on the 0.15 mm stationary scan system pointcloud resolution still show accurate numerical results in most cases, but do not match the 5% criterion in every case. These findings suggest, that a 0.1 mm pointcloud resolution will show a sufficient accuracy regarding numerical stress calculations, while making the workflow more practical and suitable for a wider range of scan systems. Finer pointcloud resolutions might be necessary for small notches ($\leq$ 0.5 mm) or deep pockets, which might appear on weld seams with small weld toe radii and small weld toe angles. Coarser pointcloud resolutions can be sufficient for evenly curved surfaces or larger radii. The necessary pointcloud resolution is highly depending on the scan quality. Pointclouds recorded with handheld systems are not recommended for reliable stress calculation. Significantly higher deviations appeared under equivalent pointcloud resolution while strong smoothing effects were observed on sharp notches, resulting in inaccurate and often non-conservative stress results.

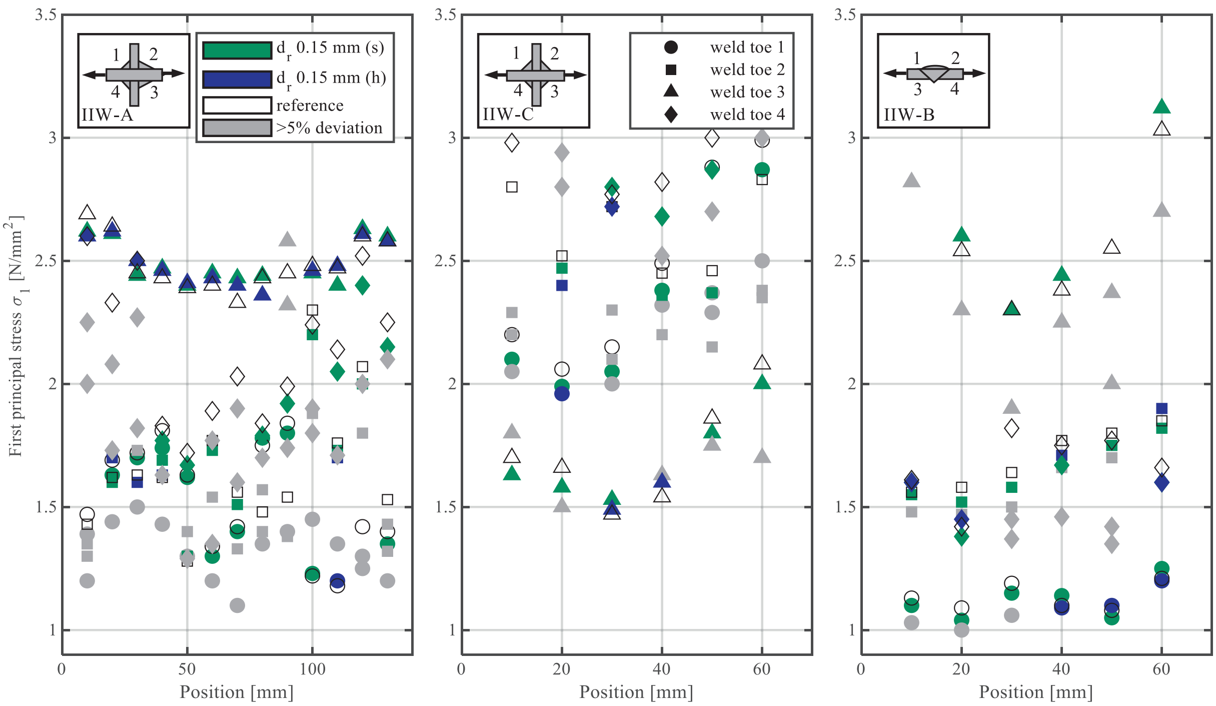


**Fig. 9.** Numerical first principal stress calculations based on scan data of IIW weld specimens (s = stationary, h = handheld) compared to numerical results of reference scans (dr = 0.04 mm, stationary) with results deviating more than 5% greyed out.

### 3.2. Scanning inaccuracies

Every pointcloud has scanning inaccuracies which cannot be avoided. While some types of scanning inaccuracies must only be corrected to create a closed solid for the numerical geometry input, others can also affect the results of the stress analysis. The following ones are most common:

**Missing points.** Too many missing points are causing incomplete surface data and therefore holes, which must be filled to create a closed solid body. These holes are caused by shadows of the weld seams own surface geometry and few camera angles insufficiently covering every aspect of the entire surface. Nearly every 3D modelling software provides filling algorithms to create new surface data based on the surrounding edge properties of each hole. If too many holes are located in the area of interest, the scan should be repeated to achieve better point cloud quality, as filling algorithms tend to smooth surfaces.

**Detached facets.** Small solids or small surface areas, which are unconnected to the main body are caused by reflections or by particles in the air. They can be easily deleted. Larger unconnected areas are caused by incorrect pointcloud registration. The pointcloud registration combines pointclouds from multiple camera angles into one pointcloud covering the entire surface. An inaccurate combination of theses pointclouds creates larger unconnected surface areas, often tilted or shifted to the correct surface. In this case, not only the unconnected facets, but the entire pointcloud created by this camera angle should be deleted. Connected facets of these incorrect registered pointclouds might be included in the final pointcloud. Incorrect pointcloud registration is also caused by changes inside the reference point layout during the scanning process.

**Noise.** Noise specifies points which are laying slightly over or under the actual surface. It can be caused by many factors, most commonly by surface reflections, bright lighting, vibrations and movement, varying temperatures and inaccurate calibration. The result is an uneven, wave-like surface. If strong noise occurs in the area of interest, it can significantly affect the stress results, see chapter 5.3. Noise can be corrected by the use of preprocessing algorithms, see chapter 4.

**Surface artefacts.** Similar to noise, surface artefacts are caused by reflections, vibrations and movement. Unlike noise, the points are significantly further away from the actual surface, but are still considered close enough to be part of the surface. This creates small irregular surface shapes and spikes, usually in areas with low pointcloud densities and reflections, e.g. on sharp edges. Surface artefacts should be smoothed or deleted, because even if they are not located in the area of interest, they usually cause meshing errors during the numerical modelling.

Fig. 10 shows examples for the four scanning inaccuracies on a triangulated pointcloud of the transverse stiffener IIW-C without any preprocessing. Unrelated to the type of scanning inaccuracy, a dependence between the pointcloud resolution and the number of inaccuracies was observed. A higher pointcloud resolution showed a higher number of inaccuracies, but the inaccuracies had smaller dimensions. Therefore, the preprocessing effort increases significantly with a higher pointcloud resolution, but the postprocessed surface will be more accurate.

### 3.3. Surrounding conditions

In order to evaluate the effect of the surrounding conditions and to give best practice scanning recommendations, scan data of ground notch radii as well as bridge hangers were evaluated. Resembling different laboratory or manufacturing hall conditions, the ground notch radii were scanned with different surface properties (ground, polished, matt) and lighting conditions (dim, bright) using the stationary system with a scanning resolution of 0.04 mm. Resembling outdoor manufacturing or building inspection conditions, scans of bridge hanger weld seams under different natural lighting conditions (sunlight, shadow) using the handheld system with a scanning resolution of 0.25 mm were recorded. The corrosion protection coating of the bridge hanger weld seams was removed shortly before the scanning, creating a ground, metallic surface. Fig. 11 gives an impression of the respective surrounding conditions.

Under laboratory conditions, the reflectiveness of the surface has the biggest impact on the scan quality, while the lighting conditions showed very little impact on the scan quality. Polished, highly reflective notch surfaces resulted in high numbers of scanning mistakes and significantly higher deviations than ground and matt notch surfaces. Due to the curved surface, as often found on weld seam geometries as well, areas are reflecting light directly into the camera, creating low quality pointclouds. The reflecting areas cause low pointcloud densities due to overexposure and low pointcloud quality due to falsely recorded points from reflection. This produces

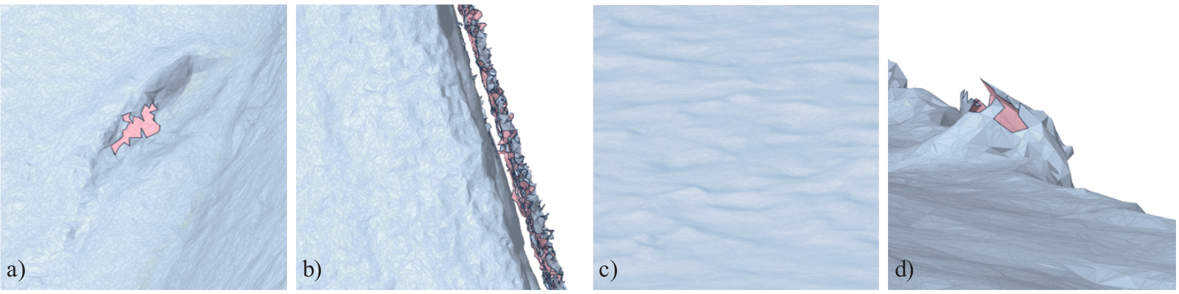


**Fig. 10.** Examples of scanning inaccuracies: (a) missing data due to shading of a ridge, (b) detached facets caused by incorrect pointcloud registration shifted to the correct surface, (c) noise on a flat surface, d) surface artefact on a sharp, reflective edge.

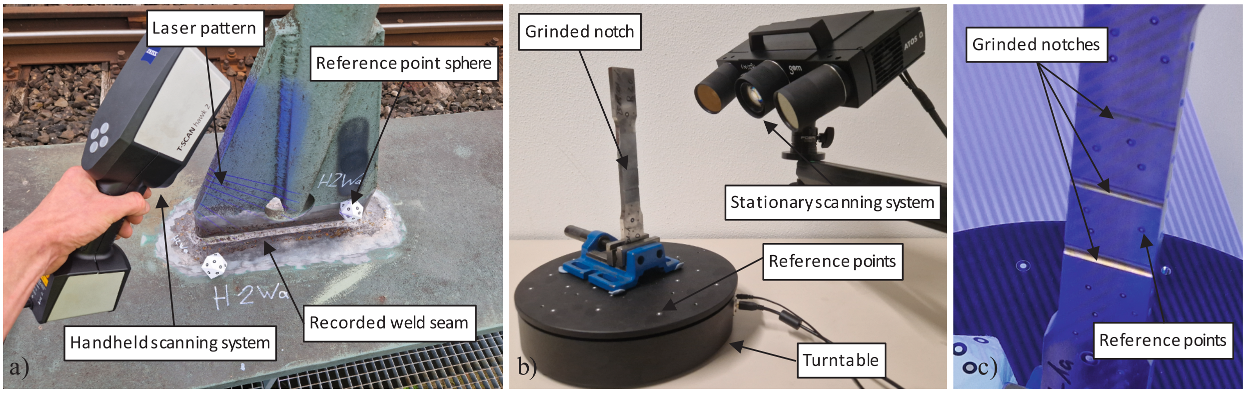


**Fig. 11.** (a) Scanning of the bridge hanger weld seams, (b) scanning setup of the stationary system, (c) scanning of the ground notches.

large numbers of scanning inaccuracies combined with inaccurate surface areas. Dim lighting conditions slightly improve the scan quality, while bright lighting conditions slightly impair the scan quality. The insignificance of the lighting is caused by the adaptive exposure times of the camera system based on the overall surrounding lighting conditions, while the reflectiveness of the surface stays consistent. Evaporating coating spray for scanning applications was used to create matt notch surfaces. The matt surface significantly improves the scan quality and the preprocessing effort. With a coating thickness of 2–6 μm, the effect of the coating layer on the notch geometry is negligible, see chapter 3.1 and Table 2. If pointclouds with high resolution are recorded, vibrations from nearby machinery or close pedestrians can cause noise and incorrect pointcloud registration, even under laboratory conditions. Changes in temperature can affect the scan quality, but can be avoided under laboratory or workshop conditions by regular calibration.

Outdoors, sunlight has the biggest impact on the scan quality. Varying sunlight strength, lighting angle, clouds and shadowing of surrounding objects and the scanned structure itself cause widely changing lighting conditions even in short scanning periods. Direct sunlight can easily overpower or vanish the laser triangulation grid of the scanning system, creating areas with lower pointcloud resolution. Scans with high pointcloud densities are difficult to record, because they are subjected to higher changes in lighting during longer recording times. Additionally, direct sunlight heats up the scan system and the scanned surfaces immediately, causing incorrect pointcloud registration due to reference point movement and requires frequent recalibration of the scan system. These effects combined can lead to a very poor scan quality, especially for larger structures which require longer scanning periods. Locally shadowing the scanned part and applying a matt coating layer significantly increases the scan quality. Short scanning periods will reduce the number of scanning inaccuracies. Therefore, the lowest pointcloud resolution which still delivers correct stress results should be used.

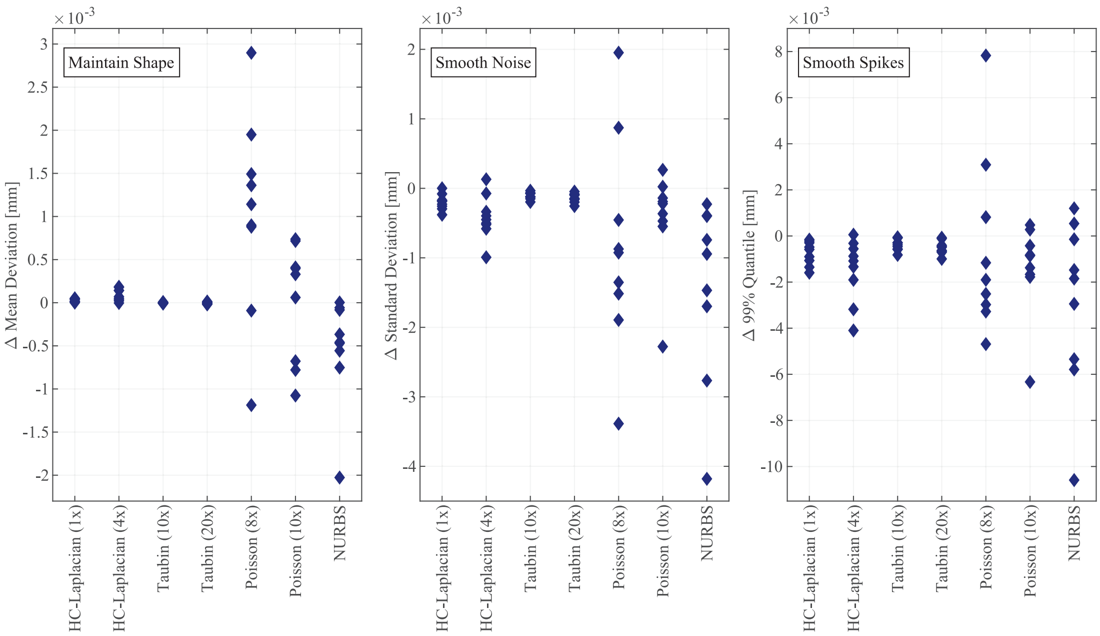


**Fig. 12.** Comparison of preprocessing algorithms on artificial notch surface scan data (r = 0.3/1.0/ 3.0 mm; ω = 60/90/120°) of nine notches regarding their ability to maintain the original shape, smooth noise and reduce spikes ($\Delta_{\mathrm{Deviation}} = \Delta_{\mathrm{pp.}} - \Delta_{\mathrm{raw}}$).

 

On infrastructure buildings, times with low traffic should be preferred for scanning. Especially train traffic causes strong vibrations, which causes high amounts of noise and can create incorrect pointcloud registrations if reference points are moved.

## 4. Preprocessing

Unrelated to the scanning process and the pointcloud quality, the pointcloud must be preprocess to be meshed. During the scanning process, nearly every point on the surface which can be recorded by the scan system will be part of the pointcloud. Therefore, the pointcloud is not a regular mesh but consists more of areas and directions with varying densities and varying numbers of points. When these pointclouds get triangulated to create a closed surface, it results in non-uniform, non-isosceles and narrow facets. These facets can usually not be meshed properly and often create high numbers of singularities due to their spike shape. Additionally, the pointclouds usually include noise and scanning mistakes as described in chapter 3.2, which should be smoothed or erased before meshing. Reducing the number of facets is necessary if larger parts are scanned or very high pointcloud resolutions are used, see also chapter 5.2. Smoothing, remeshing, reconstructing and simplification of the pointcloud or surface without erasing stress critical notch details is crucial to achieve reliable numerical stress results.

Normalizing the facets is widely supported in common CAD software. It divides non-isosceles and narrow facets into a higher number of evenly sided and sized triangles without changing the surface geometry. Due to the unmodified geometry it doesn't affect the stress results, but results in a significant increased number of facets. As every facet will create its own surface area, normalizing the facets is therefore only suitable if smaller areas are of interest. Also, scanning inaccuracies mostly remain in the surface after normalizing, affecting the later stress distribution. For larger areas, but also to reduce calculation time, preprocessing algorithms which smooth, remesh or reconstruct the facets are more efficient. Unlike Normalizing, all preprocessing algorithms will change surface geometries, which can especially lead to smoothing or erasing of small notches and therefore reduced critical fatigue stresses. In total 20 algorithms were compared with Meshlab 2023.12 and Rhino 8, using the ground notch scan data. More algorithms are available, but most others required a high number of input parameters, extensive user knowledge and highly individual settings. The 20 preselected algorithms were shortly evaluated and four algorithms were selected for further comparison. For three of the four algorithms, several numbers of iteration steps were tested. Fig. 12 shows the comparison of the seven algorithm configurations.

In Fig. 12 the deviations of raw surface scan data to CAD data are compared to the deviations of preprocessed surface scan data to CAD data for nine different notches ($r = 0.3/1.0/\ 3.0$ mm; $\omega = 60/90/120^{\circ}$). By subtracting the deviations of raw data from the deviations of preprocessed data for different radii and notch opening angles, the performance of the algorithms regarding the important factors can be evaluated.

To ensure that the original shape of the notch geometry is maintained, the mean deviation of the raw and the preprocessed scan data is compared. While results close to zero mean that the original scan data is maintained, positive results show a smoothing of the notch and therefore a decrease in evaluated stress later. Negative results show a preprocessed surface closer to the CAD surface than the raw scan data and correct deviations as described in Fig. 4. Only NURBS (Non-Uniform Rational B-Splines) were able to create a surface more accurate than the raw scan data, but HC-Laplacian and Taubin both maintained the geometry of the raw scan data nearly unrelated to their respective number of iterations.

Evaluating the smoothing of noise is performed by the comparison of the standard deviation of raw and preprocessed scan data. A low standard deviation implies little noise and a more even surface. Negative results show reduced noise while positive results show increased noise. Values close to zero show no affect of the algorithm on noise. Similar to the comparison of the mean deviation, HC-Laplacian and NURBS show good results, with HC-Laplacian reducing the noise stronger for some notch geometries with increasing number of iterations. Taubin doesn't show sufficient results with regard for noise smoothing and Poisson even increased the noise for some of the scan data.

As a third criterium, the 99% quantiles are compared. The 99% quantile of the surface are single spikes (surface artefacts) caused by scanning inaccuracies which will create singularities in the later stress distribution. The results for smoothing the spikes are similar to the ones for smoothing noise. Only Taubin delivered slightly better results, while NURBS slightly enlarged spikes for two of the notch geometries.

As every marker stands for an individual notch geometry, wide spreading results imply a strong dependence of the algorithms performance depending on the notch shape. Closely clustered markers imply even results unrelated to the notch geometry. In this case, Poisson performs significantly lower than the other algorithms, unrelated to the number of iterations. HC-Laplacian and Taubin show little relation of their performance to the varying notch geometry. Contrarily, NURBS shows a significant relation, because the NURBS patch size was not adjusted for every individual notch geometry. Therefore, smaller radii were reconstructed with less patches than larger radii, benefitting an accurate surface reconstruction for larger radii. When adjusting the NURBS patch size according to the notch radius, significantly more accurate preprocessing results can be achieved.

In general, HC-Laplacian proves to be the most robust and efficient preprocessing algorithm out of the selected ones. Very little user defined input is necessary to achieve reliable results and performance simply increases with increasing number of iterations. For varying geometries and scanning parameters, a high number of HC-Laplacian iterations will preprocess the raw scan data sufficiently. NURBS can be used to create better results, especially if the raw 3D scan surface has large deviations to the actual surface. Therefore, it requires a high amount of user input and user knowledge and must be carefully adjusted individually for each geometry. If geometries and scan parameters are steady over many datasets, NURBS can once be accurately adjusted to one dataset and deliver overall better results. While NURBS have the potential to deliver accurate results, it also holds the potential to deliver non-conservative results if surface reconstruction parameters are not correctly adjusted to the individual use case. Especially large patch sizes and control point tolerances can smooth fatigue critical details.

Besides maintaining the shape, smoothing noise and reducing spikes, the number of facets created by each postprocessing algorithm is an important factor. It has significant impact on computing power and time during the numerical modelling. Each facet will create its own surface area, which due to the meshing constraint in FEM software must consist of at least one element. If the pointcloud surface is defined by the entire scanned pointcloud without any preprocessing (STL-format), each point would create one element. When normalizing is used, the number of elements multiplies. Preprocessing algorithms either reconstruct larger curved surfaces based on the pointcloud, e.g. using NURBS or smooth and remesh triangular facets into differently spaced and oriented facets, e.g. with HC-Laplacian. Both methods reduce the number of elements, either due to a possible coarser meshing or due to varying individual element sizes over the surface. In general, preprocessing algorithms which create larger surface areas reduce the number of elements more efficient, because less meshing restraints allow the FEM software to dynamically adjust element sizes. Out of the hereby selected algorithms, NURBS has the largest potential to reduce the number of elements, while the potential of the other algorithms is strongly depending on the defeaturing sizes in the meshing process later.

## 5. Numerical modelling

### 5.1. Meshing requirements

After preprocessing the surface, every FEM software will create a closed solid body which is further meshed with individual sized elements. When using a solid body based on a STL-format, either normalized or otherwise preprocessed, the element size can be set by the FEM software without any element size restrictions. As described in chapter 4, each triangular facet will create its own surface area and automatically require at least one tetrahedron element. Implying a sufficient pointcloud resolution, the automatically generated mesh will consist of appropriate element sizes, as the element size cannot be larger than the pointcloud resolution. If normalizing is used, the element sizes will automatically be smaller than the pointcloud resolution. If other preprocessing algorithms which create STL-format are used, the triangular facet size and therefore the element size will dynamically adjust to the area of interest. Due to the limited deviation between pointcloud and preprocessed surface, high curvature in surface geometries can only be accurately modeled using triangular facets of small size. Flat surfaces or low curvature areas are modeled with triangular facets of large size, but are typically not areas of interest, because they do not result in high calculated notch stresses.

When preprocessing algorithms are used which create curved surfaces, an element size should be defined. Due to the individual surface properties, a universal applicable element size cannot be specified. It is recommended to perform a convergence study for a typical surface area to define the largest element size returning the stress distribution without any singularities on the individual use case.

Regarding the element type, solid tetrahedron elements with a quadratic trial function will perform the most efficient while creating the least meshing errors. A convergence study using the numerical models based on the ground notches showed, that the element growth rate from surface into the body should not exceed 1.5 to prevent singularities under the surface affecting surface stress results. A defeaturing size higher than zero might be necessary when using data with poor scan quality or poor postprocessing to create meshes without errors. Still, the defeaturing size should be set to zero and only increased in small steps if the FEM software is not able to mesh the surface. Meshing algorithms tend to smooth small, sharp notches if the defeaturing size allows it, resulting in lower notch stresses.

### 5.2. Submodelling

As every facet creates an own surface area, large scan data quickly exceeds the number of facets which normal workstations are able to handle. Modelling just the critical hotspot areas in full resolution and simplifying the surrounding areas is necessary in this case.

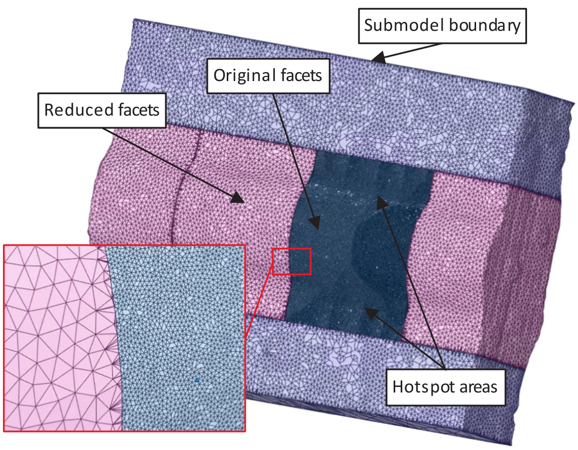


**Fig. 13.** Submodel of a butt weld with reduced facet areas based on scan data.

When it comes larger structures, only small parts are scanned and later inserted into the ideal model of the entire structure. In both cases, submodelling can reduce calculation time significantly. If submodels inside CAD geometries are created, the contact surfaces of main- and submodel fit exactly. This is not the case if the submodel is based on scan data. Real structures deviate from the ideal geometry, making an exact cross section fit impossible. Similar, smoothing, reducing or remeshing scan data can create differing cross sections. While FEM software keeps the equilibrium of forces, the cross section differences combined with a sharp change in element size create strong singularities. To prevent the stress concentrations caused by the singularities to spread into the areas of interest, the submodel boundary should be defined in a sufficient distance to it, preferable in an even, regular cross section.

Inside the submodel, the facet size in areas further away from the hotspot can be increased and therefore element numbers considerably reduced. The transition between the differently sized facets can still cause stress concentrations, but due to the smaller change in geometry significantly lower than those at submodel boundaries. The area with the original facet size returns the relevant notch stresses, while the areas with the reduced facets usually show lower stress and singularities at the submodel boundaries. As exemplarily pictured in Fig. 13, the area with original facets can be moved along the weld seam, covering the entire weld seam in multiple meshing and calculation steps.

The transition of the facet size should not exceed a ratio of ten times the original facet edge length to prevent the singularities appearing in reduced facets areas from affecting the results in the original facets area. Fig. 14 shows the submodel of the butt weld from Fig. 13 with increasing facet edge length ratios. The mainmodel is rigidly fixed at one end and subjected to a tensile uniform stress of 1 MPa on the other end, resulting in a nominal tensile load of 1 MPa at both submodel boundaries. Using a 1:10 ratio still delivers the maximum stress concentration in the accurate location of the original facet area. A 1:20 ratio already shifts the maximum stress concentration to a singularity in the reduced facets area, while the 1:40 ratio creates high stress concentrations in the reduced facets area which spread into the original facets area. Additionally, models with high facet size ratios are significantly more likely to contain meshing errors. For larger models requiring facet site ratios larger than 1:10, creating submodels is highly recommended. It is recommended to adapt and verify the facet site ratio if other meshing procedures or element types are used than recommended in the previous workflow described in chapter 5.1. Similar, the facet size ratio should be reduced for weld details exhibiting very low weld quality e.g. very steep weld toe angles.

To prevent singularities and reduce stress concentrations, a suitable submodel mapping function must be applied. The submodel mapping function distributes the deformations from the global model nodes to the submodel nodes. All mapping functions will transfer the deformations from the mainmodel to the submodel, but the mapping function causing the lowest stress concentrations allows for a submodel boundary closer to the hotspot area. For all weld seams modeled with submodels in this work, the kriging function showed the smoothest transition in stress concentrations. Triangulation interpolates between nodal stress results inside triangle shaped areas and distance based averaging applies a weighing function based on the distance of nodes to each other, which both create significant singularities at the submodel boundary. Similar to distance based averaging, kriging applies a weighing function based on the distance of nodes to each other, but takes the spatial correlation of the nodal stress results into account. Therefore, the nodal stress results closer to each other are more statistically related than those further apart, leading to significantly reduced singularities at the submodel boundary compared to the other mapping functions. Fig. 15 shows the first principal stress distribution at the butt weld submodel boundary for different submodel mapping functions.

While all mapping functions create singularities, some mapping functions can result in extremely high singularities at the submodel surface, see Fig. 15. Still, the most suitable mapping function choice gets less important with more accurate boundary cross sections and a greater submodel boundary distance to the area of interest. Additionally, singularities are usually spreading fast due to the natural small element size of scan data submodels.

### *5.3. Critical stress evaluation*

Stress distributions in models created form scan data usually show more uneven patterns than the ones created from CAD data. First, because real surfaces and parts have imperfections, second because the scan data and the resulting mesh is less regular. Especially irregular scan surfaces caused by scanning mistakes can result in high local stress deviations which are often difficult to identify because of their small size. Due to these irregularities, stress concentrations are recommended to be determined by averaging over small areas instead of evaluating single element or nodal results. Similar, absolute maximum or minimum values determined over an entire surface should be verified to exclude stress concentrations caused by scanning imperfections. Fig. 16 gives an example of critical stress evaluation resulting from a ground notch.

An accurate postprocessing procedure, see chapter 4, is important for a reliable stress evaluation. When small hotspots occur, the scan data should be manually checked to verify that the hotspot is actually caused by a geometric imperfection and not by a scanning inaccuracy. Even small geometrical imperfections usually create a regular mesh, while scanning inaccuracies usually result in a highly irregular mesh. Before numerical models are automated, multiple models should be checked manually to ensure reliable results.

The dimensions of the stress-averaging area are highly dependent on the individual fatigue critical detail, especially on the local notch geometry. To ensure correct dimensions of the stress-averaging areas, it is recommended to create numerical models based on CAD geometries which resemble similar notch geometries as found in the 3D surface scan data. Sensivity studies concucted based on CAD geometries can deliver suitable stress-averaging areas for each individual fatigue critical detail.

## 6. Reference shape development and proposed procedure

While chapter 3, 4 and 5 present a workflow on how to create numerical models from 3D-scan data, achieving reliable numerical

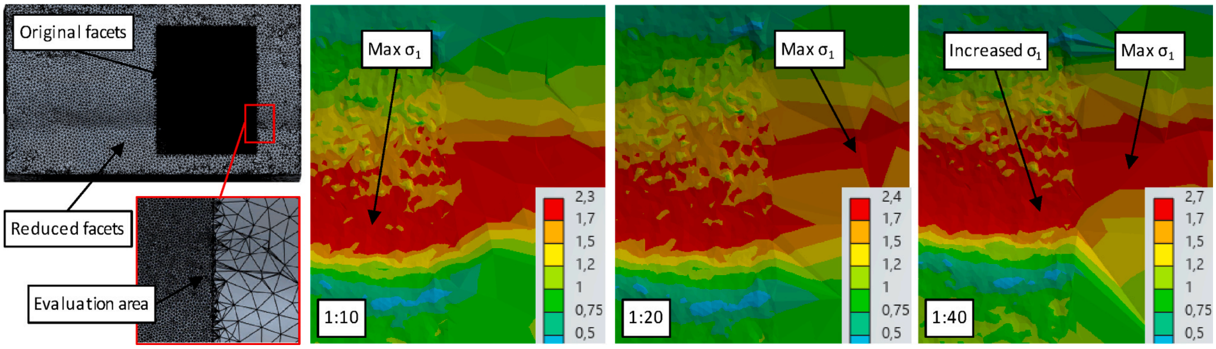


**Fig. 14.** First principal stress distributions for increasing facet size transitions at an exemplary weld toe location under nominal load of 1 MPA at the submodel boundary.

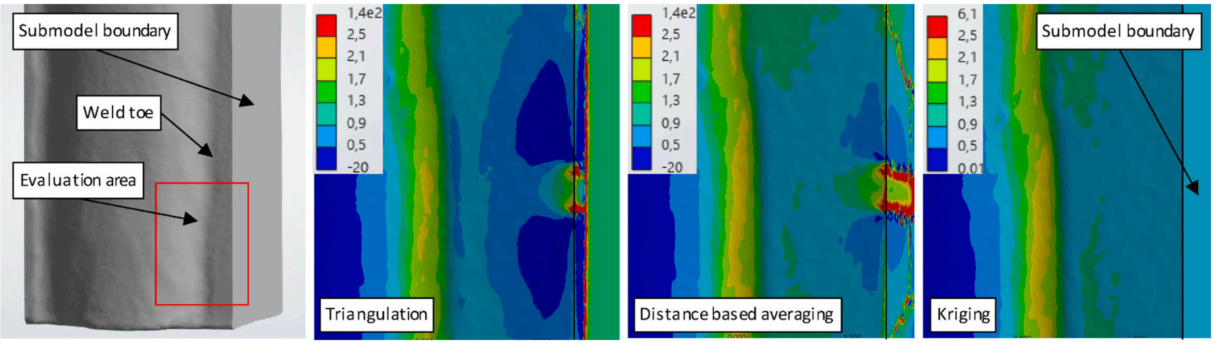


**Fig. 15.** First principal stress distribution for different mapping functions (Triangulation, Distance based averaging, Kriging) at a submodel boundary between a CAD based mainmodel and a scan data submodel under nominal stress.

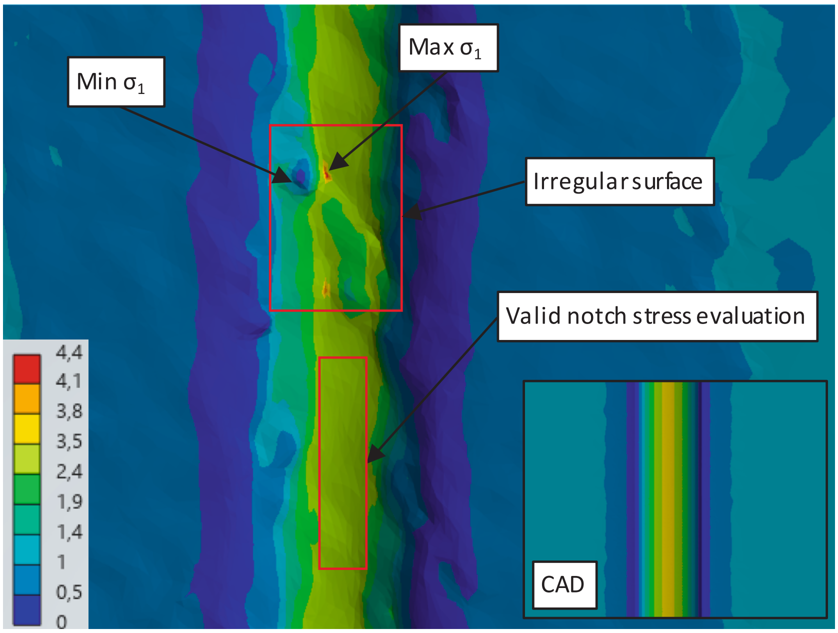


**Fig. 16.** First principal stress distribution of a scanned ground notch (r = 1.5 mm, ω = 60°) with partly irregular surface conditions under nominal load.

stress calculation is still sensitive to numerous individual factors. Considering every factor affecting the final geometry would result in strict scanning procedures. While such strict procedures can be followed by research institutes under laboratory conditions, it is no practical solution for industrial purposes e.g. on site. Especially for the civil engineering sector, surrounding conditions are often unpredictable und can only be adjusted to a certain extend. Equally, other available scan systems work with several scanning techniques, responding differently to varying surrounding conditions.

To ensure consistent results while allowing varying scan systems, scan parameters, surrounding conditions and preprocessing methods, the use of a reference shape is hereby introduced. Notch radii are ground into a steel surface, resembling critical local weld seam geometries, see Fig. 17. Each user can manufacture their own reference shape according to Fig. 17. For the manufacturing, tolerance class M7 defined in ISO 286-2 [23] must be maintained. In ISO 286-2, standard tolerance classes and limit deviations for holes and shafts are defined. Tolerance class M7 allows for a tolerance of 15 µm in negative direction and zero tolerance in positive direction. This aligns with the acceptable deviations found in this study, but prevents false results due to an addition of scanning and manufacturing deviation. The reflectiveness of the surface should be similar to the intended weld details to be scanned. The reference shape should be scanned with a minimum scanning resolution of 0.1 mm, as determined in chapter 3.1. After preprocessing the scan data and transferring it into a numerical model, the calculated stress concentrations can be compared to the provided results for the reference shape, see Table 2. As described in chapter 5.3, a reliable stress evaluation can only be achieved by averaging over small areas. Therefore, a verifying area with specific dimensions is defined for every notch. If the calculated average first principle or the von Mises stress results inside the verifying areas are within the acceptable deviation for the user, the users individual procedure, from scanning, over postprocessing until the numerical modelling, is suitable for numerical stress calculations. The model is fully clamped on one side and loaded with uniform tensile stress on the other side.

It should be noted, that the stress calculations for this reference specimen are notch shape factors which are solely geometry based in order to validate numerical models based on 3D-scan data. The given stresses don't account for micro structural support effects or residual stresses, like the commonly used notch stress concept does [22]. Depending on the quality and regularity of the scan data, von Mises equivalent stress calculations can deliver more uniform results, because multi-axial stress concentrations caused by small scanning deviations are getting more evenly distributed. If the later recorded scan data of the actual weld seam is used to calculate first principal stress results, the first principal stress values from Table 2 should be used for verification respectively. Table 2 only provides values for deviations at the notch bottom. Deviations at the notch edges as described in chapter 3.1, led to the same average stress distribution compared to the ones without.

## 7. Conclusion

The correct setting of many parameters is important to create not only a working numerical model, but also to calculate reliable and evaluable stress results. From hardware settings like the pointcloud resolution, over surrounding conditions and preprocessing algorithms to the numerical model, an extremely wide range of parameters affects the final calculated stress results. Based on the scientific investigations conducted in this research, the following recommendations to ensure a practical and reliable workflow are proposed:

- The pointcloud resolution and deviation must be maintained in certain ranges according to chapter 3.1.
- Surrounding conditions reduce scanning inaccuracies under steady, non-bright lighting conditions and matt surfaces.
- Scanning inaccuracies, missing points and detached facets must be repaired, while noise and surface artefacts should be smoothed as much as possible.

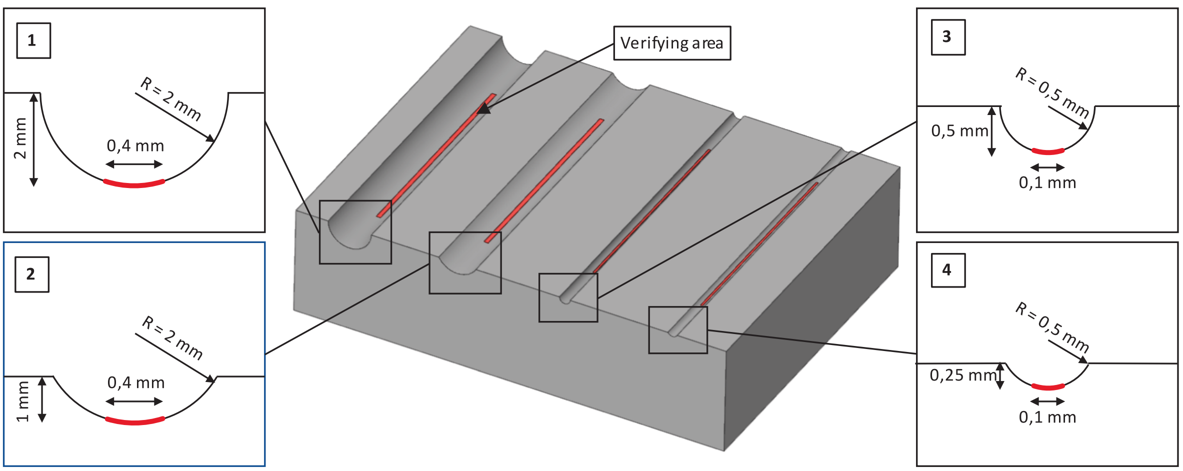


**Fig. 17.** Reference specimen with ground notch dimensions and verifying areas (red).

**Table 2**
Average first principal stress values and average von Mises stress values for the verifying areas of the reference specimen.

| Notch number | Deviation notch bottom [mm] | Average first principal stress [MPa] | Average von mises stress [MPa] |
|---|---|---|---|
| 1 | 0 | 3.77 | 3.40 |
| | 0.02 | 3.74 | 3.38 |
| | 0.05 | 3.70 | 3.34 |
| | 0.1 | 3.63 | 3.27 |
| 2 | 0 | 2.63 | 2.43 |
| | 0.02 | 2.60 | 2.40 |
| | 0.05 | 2.55 | 2.36 |
| | 0.1 | 2.47 | 2.29 |
| 3 | 0 | 3.10 | 2.82 |
| | 0.02 | 3.03 | 2.77 |
| | 0.05 | 2.97 | 2.71 |
| | 0.1 | 2.82 | 2.58 |
| 4 | 0 | 2.41 | 2.21 |
| | 0.02 | 2.31 | 2.13 |
| | 0.05 | 2.17 | 2.00 |
| | 0.1 | 1.89 | 1.76 |

- For the preprocessing of the surface, HC-Laplacian provides decent results with the need of little user input only. NURBS can provide significantly more accurate results than all other preprocessing algorithms, but require high input and testing.
- During the numerical modelling, the automatically generated mesh will deliver correct results when accurate preprocessing was performed and the defeaturing size is zero or neglectable small. Submodels and areas with reduced pointcloud resolution significantly reduce calculation time and deliver equal results, if submodel boundaries are set in sufficient distance and facet size transition do not exceed certain ratios. Kriging proved to be the most suitable mapping function for submodelling.
- Stress results should always be determined by averaging over small areas, not by evaluating single node or element results.

To provide a universal verifying method, a reference specimen is suggested. Using the suggested reference specimen and the corresponding stress values allows each applicant to verify their individual scanning parameters, surrounding conditions, preprocessing methods and numerical modelling. The recommendations and limitations for the most important parameters and processes provided in this paper shall provide a “guideline” to a working numerical model for fatigue critical notch stress evaluation.

## CRediT authorship contribution statement

**Kai Stephan Betz:** Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Philipp Weidner:** Writing – review & editing, Supervision. **Thomas Ummenhofer:** Writing – review & editing, Supervision.

## Declaration of competing interest

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.

## Data availability

Data will be made available on request.

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