A laboratory investigation of cutting damage to the steel-concrete interface

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ABSTRACT

The microstructure of the steel-concrete interface (SCI) in reinforced concrete is closely related to corrosion of reinforcing steel bars. Accordingly, characterization of the SCI is receiving increasing research attention. For microscopical observations of the SCI, a cutting process is needed to create a flat cross-section. Cutting carries the risk of damaging the SCI because of the considerable difference of hardness between concrete and steel. However, studies on characterizing the microstructure of the SCI rarely consider the damage induced by the potentially inappropriate cutting process. This study investigated the damage created by three cutting methods, namely, mechanical sawing, laser cutting, and combined laser-water cutting by the Laser MicroJet technology (LMJ). The SCI of the cut sections was imaged by scanning electron microscopy equipped with a backscattered electron detector. Additionally, the specimens were non-invasively studied by X-ray microtomography before and after cutting, to compare the impact of various cutting techniques on inducing damage to the SCI beneath the cutting surface. The results showed that if a bleed water zone (BWZ) is present, the cutting technique and protocol can significantly influence the morphology of this zone and adjacent regions. This study recommends an optimized mechanical sawing protocol with low feed speed as this led to considerably less SCI damage than laser and LMJ cutting. Moreover, it was found that adjusting the cutting direction can further significantly reduce the damage created during cutting. The least damage was found when the saw blade cut through the steel before cutting the BWZ. The main problem with laser cutting was heat generated even for a relatively low laser power; therefore, a heat-affected zone was created which significantly altered the microstructural features of the SCI not only on the cutting surface but also a certain depth below the surface. In LMJ cutting, this thermal effect was significantly reduced, however, the high-pressure water eroded the porous SCI and caused cracks. These effects can penetrate along the BWZ into the interior material. To complete this study, two applications demonstrate that the optimized mechanical sawing protocol is applicable to concrete specimens with rebars of actual size and corroded rebars.

1. Introduction

Concrete is the most widely used building material in the world. It possesses low tensile strength, which is generally counteracted by adding steel reinforcing bars (rebars). Corrosion of rebars is one of the main processes that lead to the degradation of reinforced concrete structures. The steel-concrete interface (SCI) [1] plays an important role in the corrosion behavior, including corrosion initiation [2–9], the kinetics of the corrosion process [10–12], and concrete cracking due to precipitation of corrosion products [13–16]. Moreover, the microstructural characteristics of the SCI affect the mechanical performance, such as bond strength of reinforced concrete [5,17–19]. Thus, the SCI strongly influences both the durability and the mechanical properties.

This impact of the SCI is generally explained by its high porosity and different cementitious phases composition compared to the bulk concrete [20,21]. In addition, so-called bleed water zones (BWZ) may form at the underside of horizontal rebars due to concrete plastic settlement and/or bleeding. Therefore, knowledge about the microstructural characteristics of the SCI is important for understanding and modeling the performance of reinforced concrete.

The microstructural characteristics of the SCI are generally studied by optical/electron microscopy for sample sections of steel embedded in concrete [5,12,20–24]. Scanning electron microscopy (SEM) with a backscattered electron detector (BSE) is commonly used to observe corrosion products [15,16,25–29] or concrete [30] at the SCI. For the preparation of such samples, a cutting and polishing process is
unavoidable. A particular challenge is that the cementitious matrix (sometimes with corrosion products) and the steel have significantly different mechanical properties. The cementitious matrix has lower stiffness and fracture toughness and is more brittle than the steel [31]. Therefore, to cut through steel, more energy is needed than for the cementitious matrix. When the cutting tool cuts through the SCI, damage to concrete may occur. A widely used cutting method for reinforced concrete is mechanical sawing, in particular by means of the diamond saw cutting (e.g., [15,29] for corroded rebar in concrete, which removes the material by abrasion. According to the literature [32–35], the cutting effect of the mechanical sawing of a reinforced composite can cause different types of damage. In summary, an inappropriate cutting method can alter the microstructure at the SCI, which may influence the interpretation of the obtained micrographs [23,24]. Therefore, to successfully characterize the microstructure of the SCI, problems during specimen preparation, in particular, the cutting damage, must be fully considered and investigated [2].

Factors such as the cutting speed and the specimen feed speed have noticeable effects on the cutting damage as the cutting force may increase with the cutting speed and/or the feed speed [34]. In addition, the roughness of the cutting surface was found to increase with the feed speed regardless of the saw types [35]. The effect of the cutting speed (blade rotation speed for a diamond saw) on the cutting force is generally smaller than the effect of the feed speed. Some studies even showed that the rotation speed had a negligible effect on the cutting force [32,35]. However, a high rotation speed tends to pull out the rebar and creates more serious vibrations, which are harmful to the macrostructure of the SCI. Another factor that can cause damage is heat generated during concrete sawing processes. To reduce heat as well as the cutting force, coolants/lubricants are used, such as propylene glycol or water [34]. Ethanol was used in some studies [26] but this should be avoided for cementitious materials as it is well known that ethanol can strongly react with hydration products (mainly calcium hydroxide) and cause expansion of cementitious materials [26–28]. Water may be a better choice for specimens with high water content.

Other cutting methods, such as laser and water-jet cutting systems, were often used for composite materials [39]. The advantages of laser cutting over other techniques are non-contact processing, speed, and amenability to a wide variety of materials. For most applications, laser cutting is accomplished by the process of melting and blowing or burning and blowing [40]. The laser beam is used to melt the material, and cutting is undertaken by blowing the molten material away with a sufficiently strong gas jet, such as oxygen or carbon dioxide, depending on whether the targeting materials react with the gas. Since the material must be heated to the ignition temperature, heat-related damage is unavoidable. Harada et al. [39] studied the damage of laser cutting to composite materials and found that the specimens clearly showed a heat-affected zone (HAZ) and both the static tensile and the fatigue strength of the cut specimens decreased in comparison with mechanical or water-jet cutting specimens. To minimize the local energy accumulation, laser beams with an extremely short pulse (a few ps) are preferred. Alternatively, the laser beam can move fast as long as the material can be cut through. Therefore, a high specimen feed speed can increase the cutting efficiency [41]. However, one must be aware of the fact that striations may be formed on the rough cutting surfaces.

Both mechanical sawing and laser cutting can generate friction and substantial amounts of heat, which have the potential for damaging composite materials. In contrast, water-jet cutting is a low-temperature and controlled-erosion method that does not introduce any heat or heat-related stress to the material. Water-jet cutting works with either a mechanically or hydraulically driven intensifier that pressurizes water in a cylinder. The highly pressurized water erupts out through a very small nozzle with a high speed (see the review in [42]). In general, the quality of water-jet cutting surfaces is better than of the other methods when cutting across a variety of materials and thicknesses [39]. Nevertheless, when cutting thick materials, the surface quality may decrease as water pressure largely reduces with the depth; therefore, striations become noticeable [43].

For reinforced concrete, the effects of cutting methods on the microstructure of the SCI have been rarely studied in the literature. This study aims at finding a promising cutting method suitable for laboratory conditions. The above-mentioned methods, namely, mechanical sawing, laser cutting, and LMJ cutting (combined laser-water cutting with the Laser MicroJet technology), are compared in respect of preserving the microstructure of the SCI around steel tubes that are embedded in cement mortar. Imaging techniques, including scanning electron microscopy with a backscattered electron detector (SEM-BSE) and X-ray microtomography (XRμCT), are used to characterize the microstructure of the cut specimens and then to investigate the influence of the sample preparation protocols on the microstructure of the SCI. To complete this study with an outlook to practical applications, the optimized cutting method is applied to specimens with actual rebar that were cored from a concrete bridge deck and with corroded rebars to demonstrate the applicability of the proposed cutting protocol.

2. Experiments

2.1. Materials and sample preparation

The mortar specimens were prepared with a commercial ordinary Portland cement (OPC CEM I 42.5 N) with water-to-cement ratio 0.5 and sand-to-cement ratio 2. The detailed mix design is displayed in Table 1.

The sample preparation procedure is given as follows.

1) Cement was mixed with sand in a mixer with a low speed (approximately 140 RPM) for 30 s.
2) Water was added and mixing continued for 60 s at low speed.
3) Superplasticizer was added and mixing continued for 60 s at a high speed (about 580 RPM).
4) After mixing, the mortar slurry was cast in 40 × 40 × 40 mm³ cubic moulds (see Fig. 1). Prior to pouring the slurry, a stainless steel tube with 3-mm diameter was horizontally installed in the center of the mould. The purpose is to create a BWZ below the tube. A few specimens without the BWZ were also prepared by vertically placing the steel tube in the moulds to check how the presence of the BWZ can influence the cutting damage. The use of the stainless steel tube was to avoid corrosion during curing, because corrosion products may change the microstructure of the SCI. Before casting, the steel tubes were filled with cement paste with the same mix design as in Table 1, but without sand.
5) After pouring into the mixture, the moulds were vibrated for about 20 s on a vibrating table.
6) The moulds were covered with a plastic film and stored in a climate room with 95% relative humidity and a constant temperature of 20 °C for one day. Then, the specimens were demoulded and kept in the same room for curing.

The use of a 3-mm steel tube is different from the large and solid rebars in a real reinforced concrete structure. However, the specimen size directly constrains the range of achievable spatial resolution in 3D images obtained with XRμCT (also called tomograms). Indeed, such...
imaging technique, when implemented with laboratory X-ray sources, is a full field one based upon geometrical magnification. Thus, specimens to be imaged with X\(\mu\)CT must be small enough in order to allow resolving in the respective tomograms smaller cracks induced by cutting. In addition, preliminary X\(\mu\)CT measurements showed that a solid steel bar can cause too strong X-ray “metal artifacts” in the reconstructed tomograms. Such artifacts stem, among others, [1] from the very large mismatch in X-ray photoelectric absorption between the steel and the mortar matrix and [2] from the X-ray beam hardening [44]. The huge voxel value mismatch offsets the dynamic range of the tomogram’s voxel values: the steel bar voxel values are essentially “clipped” at the upper limit of the tomogram dynamic range, looking completely bright in a grey scale rendering of the tomogram. On the contrary, the mortar voxel values end up being at the very opposite of the dynamic range, close to its lower limit, with a very narrow range left available to allow sufficient contrast between the mortar’s distinct material phases, e.g., air voids, cement paste, and small aggregates. In addition, the whole thickness of highly X-ray absorbing steel induces strong beam hardening artifacts [45]. Such artifacts create an unphysical offset spatial profile along the radial direction of the specimen. As a consequence, they distort the imaged SCI, thus making it impossible to properly resolve it. By using the hollow steel tube, these problems can be reduced and the quality of the reconstructed 3D mortar structure can be improved. The steel tube was filled with cement paste to increase its stiffness in the radial direction during the cutting process and make it more similar, from a mechanical point of view, to a solid bar.

Even though the use of the steel tube is essential to X\(\mu\)CT, a solid bar is obviously stiffer than a hollow one and the cutting force works differently for solid and hollow bars. Therefore, the cutting damage may be expected to be somewhat different. While most of this study employs as steel tube as a model rebar, these concerns are addressed in Section 3.5 with SEM-BSE images, where actual rebars are employed.

After curing about 3 months, small cylindrical specimens, 10 mm in diameter (see Fig. 1), were core drilled from the cubes with the steel tube in the center to prepare specimens for SEM imaging, either before or after the cutting process depending on the cutting methods. In detail, the diamond saw cutting needs a thick mortar layer around the steel tube (a thin mortar layer can be easily flaked off during sawing), so that the drilling was done after cutting. The laser cutting and the LMJ cutting, on the other hand, require a thin layer of material to ensure that the specimen can be cut through, so the drilling was done before cutting. Afterwards, epoxy impregnation was done after cutting to prepare specimens for SEM imaging following the general practice in the literature (e.g., [15,29]).

The sample preparation for X\(\mu\)CT was identical to laser cutting and LMJ cutting. However, the sample cut by diamond saw for X\(\mu\)CT needed a special preparation to prevent the thin mortar layer around the steel tube to be heavily damaged by cutting. It followed: drilling from the cube ➔ X\(\mu\)CT ➔ epoxy impregnation (without vacuum) ➔ cutting ➔ drilling ➔ X\(\mu\)CT ➔ epoxy impregnation for SEM imaging. Therefore, by checking the damage to the SCI observed in SEM-BSE images and X\(\mu\)CT results, it would be possible to evaluate different cutting methods.

2.2. Cutting methods

For the mechanical sawing, this study employed a high-precision smart diamond saw cutting machine. The preliminary cutting tests were performed on the specimens without the BWZ with a feed speed of 6 mm/min and a rotation speed of 600 RPM. Results did not show any damage to the SCI. For the specimens with the BWZ, an optimized cutting procedure was adopted: the feed speed was 0.3 mm/min and the blade rotation speed was 300 RPM, because the extremely slow feed speed has the benefit of significantly reducing the force applied during the sawing process [34]. Specimens were not rotated, as rotation may create unstable cutting regions with chatter [46]. Water was used as the coolant to reduce the heat generated during the concrete sawing processes as well as to decrease the cutting force [34] (see Table 2 for more technical parameters). Considering cutting effects and the existence of the BWZ, four cutting directions were identified (see Fig. 2) which were tested to check whether the cutting direction shows different patterns of damage to the SCI.

Laser cutting was firstly tested on a Selective Laser Melting (SLM) machine with the power of 5 kW and using carbon dioxide to blow the broken pieces (denoted by Laser cut 1 hereafter). This setup was found to create serious damages to the SCI as SEM-BSE images show a gap around the steel and cracks in the mortar. Therefore, a TruLaser Cell Series 7000 laser system (Cell 7020) was used to improve the cutting performance by reducing the power to 100 and 10 W (denoted by Laser cut 2 and 3, respectively). Specimens were rotated during laser cutting. The other technical parameters are displayed in Table 3.

The LMJ cutting was performed by using a Synova LCS 150 machine, which is operated based on the Laser MicroJet® technology and combines the advantages of a high-energy pulsed laser and a hair-thin water jet. While the laser is used for material ablation, the high pressure water jet works to guide the laser light and cool the edges. The technical parameters used for cutting the reinforced mortar are provided in Table 4.

![Fig. 1. Schematic drawing of the geometries of a prepared mortar cube and the core drilled cylindrical specimen.](image-url)
A specimen was checked with an optical microscope. If the surface should be kept as short as possible [54]. The dried specimen was impregnated by a low-viscosity epoxy resin in a vacuum chamber with pressure about 0.05 bar to ensure that most pores are filled with the epoxy resin. After about 24 h, when the epoxy resin had hardened, the embedded specimen was subjected to grinding and polishing, following the protocol reported in [53] with slight modifications. Due to the fact that mortar and steel have different hardness and wear rates, they are removed at different rates during polishing and grinding. The long preparation duration may damage the SCI by creating artifacts, such as steel edge rounding and relief (rough surface at the SCI). To limit such artifacts, the preparation duration should be kept as short as possible [54].

The grinding started from the 120 grit SiC grinding paper, which was just used to quickly remove the epoxy resin on the specimen surface, and gradually increased to 2000 grit. The Struers DP-Lubricant for water-sensitive materials was used for the purpose of cooling and lubricating. Every grinding process lasted about 5 min and then the specimen was checked with an optical microscope. If the surface condition was satisfied,1 the grinding continued to the next step; otherwise, an additional 5-min grinding was performed. Before checking and proceeding to the next step, the specimens were washed in isopropanol to remove any impurities on the surface. After grinding, only very tiny scratches should be seen on the steel. The polishing was achieved with the assistance of oil-based monocrystalline diamond suspensions, in which the sizes of the diamond particles progressively decreased with the polishing step, such as 9, 6, 3, and 1 μm. Similar to the grinding process, after each 5-min polishing, specimens were checked with the optical microscope until the scratches disappeared and the aggregates were clearly seen.

After grinding and polishing, the specimen should be imaged as soon as possible to avoid damage during the storage. The specimens were coated with a thin layer of carbon (less than 10 nm thick). A FEI Quanta 600 environmental SEM with a BSE detector was used to image the polished surface under the low vacuum mode with 0.83 Torr in the specimen chamber. The low vacuum mode was preferred because high vacuum can significantly remove water from mortar and lead to vacuum damage to the material.

### 2.3.2. X-ray microtomography (XRμCT)

To compare the impact of various cutting techniques on creating damage to the SCI beneath the cutting surface, X-ray micro-tomography (XRμCT) was performed. XRμCT allows to visualize and quantify, in a non-destructive way, part of the damage created due to cutting [55]. For each specimen, the same XRμCT measurement configuration was used. Its details are reported in Section S1 of the Supplementary Data in Appendix A.

In order to increase the signal-to-noise ratio of the tomograms, thus to allow for a clearer identification of microstructural features at the length scale of tens of μm, a 3D anisotropic diffusion filter was applied to the raw tomograms. This filter is based on an edge-preserving denoising algorithm which was implemented as an ImageJ plugin in the Xlib set [56], originally formulated by Tschumperlé and Deriche [57,58].

After filtering of the tomograms, a systematic 3D image analysis procedure was optimized and implemented to identify (“segment”) the tomograms’ voxels belonging to [1] the specimen volume, [2] the resolved cracks and [3] the steel tube. The segmentation of such volumetric regions of each tomogram was needed for the 3D visualization of the cracks and of the steel tube (qualitative analysis) and for computing the crack volume fraction (quantitative analysis), defined as the ratio of crack volume and specimen volume. The overall segmentation procedure is described in details in Section S2 of the Supplementary Data in Appendix A. Here, we only provide a succinct list of its main sequential parts and respective targets. Notice that each tomogram was stored on file as a 16-bit unsigned integer 3D image. Thus, the range of voxel values was [0; 2^{16} – 1].

(I) Segment the specimen-surrounding volume, in order to be able, by complementarity, to segment the specimen volume itself (total volume of the tomogram “minus” such surrounding volume).

(II) Reassign a value of 0 to the filtered tomogram’s voxels, in order to make them different, in value, from those corresponding to empty pore space inside the specimen volume.

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1 The criterion depends on the grinding and polishing step. For the steel reinforced mortar, we chose the steel surface as the check location since the steel is more homogenous and brighter than mortar under an optical microscope, so that any impurities and scratches can be seen. After grinding with the low grit sandpapers (e.g., 120 and 500), the epoxy on the steel surface must be removed and only a few scratches should be seen. After grinding with the high grit sandpapers (e.g., 1000 and 2000), the large scratches should not be seen and only some small scratches remain on the steel surface. During the polishing, the small scratches should gradually disappear with the decrease of the particle size of the diamond suspensions.

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Table 3

| Pulse duration | Spot size | Pulse frequency | Feed rate | Feed speed | Number of specimens |
|----------------|-----------|-----------------|-----------|------------|---------------------|
| 1 ps           | 0.03 mm   | 400 kHz         | 250/μm/s  | 131 mm/min | 3                   |

Table 4

| Laser power | MicroJet spot size | Water pressure | Pulse duration | Feed speed | Number of specimens |
|-------------|--------------------|----------------|---------------|------------|---------------------|
| 34 W        | 0.05 mm            | 350 bar        | 175 ns        | 20 mm/min  | 2                   |

Fig. 2. Schematic drawing of four cutting directions for specimens with a BWZ. In the first one, the blade cuts the steel before the BWZ and the concrete. The second one is opposite to the first one. The last two are similar, but owing to the round shape of the cutting wheel, the blade may firstly cut the steel or the concrete.
Segment the volumetric regions in the tomogram with small voxel values, corresponding to either specimen-surrounding space or pore space inside the specimen.

Exclude from the results of (III) the specimen-surrounding voxels by using the results from (I).

Exclude from the results of (IV) the voxels corresponding to pores not being cracks, based upon geometrical features of such regions of connected voxels.

Compute the crack volume fraction as the ratio between the total number of selected voxels from (V) and the difference between the total number of tomogram’s voxels and the total number of voxels selected in (I).

Segment the voxels corresponding to the steel tube volume.

3. Results and discussion

3.1. Surface condition

After cutting and before any further surface preparation step, the surface was visually inspected and some examples are shown in Fig. 3 for different cutting methods. The example for the diamond saw cutting corresponds to the cutting direction 2 in Fig. 2. As expected, steel chips moving along the blade rotation direction (perpendicular to the cutting direction) and entering the mortar are clearly seen on the surface (see Fig. 3a). The scratches created by the blade on the steel are very obvious. Different to the steel surface, the mortar surface is much smoother because of its low stiffness and the very slow feed speed.

No matter which power was used for the laser cutting, heat from the laser burnt the material, as shown by the color change for both steel and mortar. The steel surface is totally covered by a dark solid, which is believed to be iron oxides/carbonates. With the high-pressure gas that blows the molten material, it can be seen that these iron-based compounds spread on the mortar surface. The burning effect seems to become less apparent with the decrease of laser power (see Fig. 3c-e).

Compared with the laser cutting, the cross-section cut by the LMJ is cleaner (see Fig. 3b). Unlike the diamond saw cutting, no steel chips can be seen along the path of laser and water. However, striations can be seen on the steel surface, indicating that the feed speed may be too fast. Around the steel tube, a dark (empty) circle can be seen that is larger than the BWZ generally observed in the literature [20].

3.2. SEM images

SEM-BSE images from several locations around the steel tube on the cross-sections cut by the different methods examined in this paper are shown in Fig. 4 to Fig. 13. The preliminary diamond saw cutting was performed on the specimens without the BWZ. The purpose is to check whether the BWZ can influence the cutting damage. Indeed, it has been reported that one of the reasons for low mechanical properties of the SCI is the presence of the BWZ [5,17–19]. The SEM-BSE images in Fig. 4 show no obvious damage to the SCI around the steel tube. This preliminary result suggests that sample preparation with diamond saw cutting does not introduce obvious damage if the SCI is not weakened by the BWZ.

For specimens with the BWZ, all images are repositioned to the layout that the BWZ is at the underside (see an example in Fig. 5), so that based on the position of the steel tube, one is able to know the location of image on the cross-section.

Fig. 4 shows SEM images for the specimen that was cut by diamond...
saw in direction 1 (see Fig. 2). No significant damage to the SCI can be seen. The BWZ is filled with some solids (most likely hydration products), which largely reduce its thickness, from around 100 μm to only about 20 μm. This may help to resist the cutting force and to reduce the damage. At the upper side, no damage to the SCI can be seen as there is no gap between mortar and steel, which agrees with the observation in Fig. 4.

In Fig. 6, because the saw blade came from the bottom and passed through the mortar before the BWZ, some parts of mortar were crushed and fell into the gap (see Fig. 2 for the cutting direction 2). It is surprising to see more mortar debris at the lower left and right sides than in the central part of the BWZ. These two sides are the two ends of the BWZ. Similar to Fig. 5, at the upper side, there is no gap between mortar and steel and no damage to the mortar can be seen.

Fig. 5. SEM images from different positions around the steel tube for the diamond saw cutting (cutting direction 1 in Fig. 2, in which the blade cuts the steel before BWZ and mortar).

Fig. 6. SEM images from different positions around the steel tube for the diamond saw cutting (cutting direction 2 in Fig. 2, in which the blade cuts the mortar and the BWZ before the steel).
Fig. 7 shows the results from the cutting direction 3 in which the blade came from the left-hand side. The damage to the mortar at the lower left end of the BWZ seems slightly more serious than at the lower right end. No broken pieces are found in the BWZ because the saw blade cut the steel before cutting the mortar. Very similar to the previous images, no damage is observed above the steel tube.

The SEM images in Fig. 8 are very similar to those in Fig. 6, showing obvious damage at the two ends of the BWZ, some broken mortar in the BWZ and no damage to the region above the steel tube.

Based on the above SEM images, one can conclude that diamond saw cutting induces damage to the SCI. Two types of damage can be identified. The first type was found at the two ends of the BWZ, which are the contact points of mortar and steel. Damage at these two points may be caused by two reasons: a) the cutting force when the blade pushes the steel and b) the vibration of the steel tube. When the steel tube is pushed toward the cementitious matrix at the upper side of the steel tube (see results in Fig. 6 for cutting direction 2 as illustrated in Fig. 2), since no gap is present at this location, the cutting force can be transmitted from the steel tube to the cementitious matrix through a large area and thus the local damage is not noticeable (see Fig. 9 which is partially adapted from [59]). However, if the steel tube is pushed toward the BWZ, the cutting force is transmitted from the steel to the

Fig. 7. SEM images from different positions around the steel tube for the diamond saw cutting (cutting direction 3 in Fig. 2, in which the blade cuts the left-hand side before the right-hand side).

Fig. 8. SEM images from different positions around the steel tube for the diamond saw cutting (cutting direction 4 in Fig. 2, in which the blade cuts the right-hand side before the left-hand side). The remaining steel chip in the BWZ indicates that the blade moved from the top right to the bottom left and rotated from the right-hand side to the left, which exactly corresponds to the cutting direction 4 in Fig. 2.
mortar mainly through the contact points; thus, the mortar at these two points is easily crushed (see results in Fig. 7 and Fig. 8 for cutting directions 3 & 4 illustrated in Fig. 2). With a similar damage mechanism, when the steel tube vibrates, the mortar at the two ends of the BWZ can be heavily damaged, while no damage to the cementitious matrix at the upper side of the steel is observed. Theoretically, this type of damage is difficult to eliminate but can be minimized by using a very low feed speed, which reduces both the cutting force and the vibration of the steel.

The second type of damage manifests as filling of the BWZ by the broken cementitious materials. By choosing the right cutting direction, this type of damage can be avoided. If there is a BWZ, the best cutting direction is to let the saw blade cut through the steel first and then go to the BWZ and the mortar, which is well demonstrated in Figs. 5 and 7. If doing the reverse way, the mortar material is easily damaged, as shown in Figs. 6 and 8. However, as stated in the previous paragraph, the suggested cutting direction may cause damage at the contact areas. Therefore, when characterizing the microstructure of the SCI, one should bear in mind that these areas (that is, where the BWZ ends and where mortar meets the steel) are disturbed when attempting to quantitatively characterize the microstructure of the SCI.

Fig. 10 shows the results of the first laser cutting by using the SLM instrument. Clearly, a gap of a few microns in thickness can be seen around the steel tube. This is known as a heat-affected zone (HAZ) and is commonly reported in the literature when cutting a composite material [39]. The HAZ may have formed due to the different thermal expansion of different constituents in the composite material when the laser heats it up. If reinforced concrete is heated, the cementitious matrix is expected to expand more than the rebar. In fact, while concrete has a thermal expansion coefficient similar to that of steel due to the large content of aggregates, cement paste has a thermal expansion coefficient about twice that of steel and mortar about 50% higher than steel [60,61]. In addition, the thermal conductivity of steel is about twenty times higher than that of the mortar [62]. Thus, locally, at the cutting section, the mortar is expected to always exhibit a higher temperature than the steel, because the absorbed heat in the steel can dissipate relatively rapidly through conduction along the longitudinal axis of the cylindrical specimens. The confined expansion of the materials during laser energy absorption may lead to cracking of the cementitious material and thus to partly irreversible displacements. Upon interrupting the laser, the steel is expected to cool down faster and to contract more reversibly than the surrounding (potentially damaged)
cementitious matrix. This may finally lead to the observed gap around the steel tube.

In addition to the different thermal expansion behavior of mortar and steel, another reason for the cracks formed in the mortar might be the different thermal expansion between cement paste and aggregates (limestone in this study). Limestone aggregates have a thermal expansion coefficient in the range of 3–10 × 10^{-6}/°C [63,64], which is lower than cement paste (10–20 × 10^{-6}/°C [65]). Furthermore, dehydration of cement hydration products at high temperatures might contribute to cracking and damage as well [66].

Figs. 11 and 12 show SEM images from laser cutting specimens with relatively low energies. Even though the laser power is largely reduced in the second laser test by using the TruLaser instrument, a gap still exists between mortar and steel. Thermal damage to the mortar can be clearly seen (as indicated by arrows in Fig. 11). Further reducing the laser power seems to be able to decrease the width of the HAZ (from about 20 μm in Fig. 11 to a few microns in Fig. 12), but cracks in the mortar are still very clear as displayed in Fig. 12. These images imply that to avoid the cutting damage for the laser cutting, even smaller power is required, which may limit the size of the specimen that can be cut with this technique.

Since the thermal expansion shows a significant impact on the microstructure of the SCI, the water MicroJet was introduced to cool down the specimen during laser cutting. Results of LMJ cutting in Fig. 13 show that the thermal effect is largely reduced and no continuous gap around the steel tube can be seen. However, the LMJ cutting causes new damage, such as some large empty voids of a few hundred microns around the steel tube. Initially, at the top-right side of the steel tube, no gap between the steel and the mortar is expected. However, after cutting, large voids were formed and some cement paste around the aggregates disappears. Similar damage is found for the BWZ, where the mortar is broken into small pieces which, as well as cement paste, are removed, while large aggregates remain. This kind of damage was presumably created by the high-pressure water. The erosion of mortar at the SCI can happen because of the presence of the BWZ and the relatively low mechanical properties of the SCI compared with the bulk mortar [17,18].

3.3. Results from XRμCT

XRμCT was used to assess, first of all only qualitatively, the extent of cracking and the crack morphology prior to cutting. For this purpose, XRμCT was performed on three specimens, one for each cutting method. Fig. 14 shows, as an example, three planar cross-sections (called “slices”) extracted from the filtered tomogram of the uncut specimen prepared for the saw cutting and respectively located at distinct positions along the specimen’s symmetry axis. Cracks located generically both at the aggregate-cement matrix interfaces and inside the aggregates themselves can be easily recognized by the naked eye, although their thickness is close to the spatial resolution of the tomograms. The interface cracks are either gaps created during the casting process or are due to volume changes during hardening. The cracks within the aggregates are commonly observed and are likely imperfections of the rock or created during aggregate production. The arrows in Fig. 14a point to an example of the first crack type, while that in Fig. 14b highlights one example of the second crack type. Similar types of cracks were also found in the filtered tomograms of the two other uncut specimens. This qualitative, visual inspection of each specimen’s tomogram, before cutting, allowed us identifying crack-like features pre-existing the cutting and detectable by the naked eye in the tomograms obtained with the chosen optimal settings for the XRμCT measurements. One important feature of such pre-existing cracks is that their thickness is close to the spatial resolution of the tomogram. Thus, they are resolvable by human visual processing but not by image processing algorithms, unless with significant errors, e.g., in their segmentation. The resolvability of the cracks by visual processors (human
or computer) is an important feature to be reminded of: any object with, e.g., thickness smaller than the spatial resolution of the tomogram (about 28 μm) cannot be resolved in such type of 3D images. Any object with thickness close to the tomographic spatial resolution cannot be reliably enough detected and analyzed by computer algorithms. The former feature implies the impossibility to confirm or reject the hypothesis of the existence of cracks, thinner and/or shorter than 28 μm, before cutting and propagating from the SCI into the surrounding mortar volume or being mainly aligned along its surface. However, this limitation also defines the size range of the crack-like features that could be examined in the tomograms of the same specimens but after cutting, in order to assess qualitatively and quantitatively the microstructural changes provoked by the cutting itself. The second feature implied that any crack in each specimen, identified in the tomogram after cutting, by the 3D image analysis procedure we implemented was essentially a new crack, produced by the cutting itself. Thus, any quantitative estimate of a crack feature variable, e.g., the crack volume fraction (see Fig. 16), refers essentially only to cracks generated after cutting.

The filtered tomogram of each of three specimens after cutting is visualized in Fig. 15. Fig. 15a–c show three slices orthogonal to each other and extracted from the tomogram of the specimen cut with the diamond saw method, the laser-based method, and the LMJ method, respectively. For each specimen, the three mutually orthogonal slices were chosen because they allow highlighting and exemplifying the most relevant crack features newly generated from the respective cutting. Fig. 15d–f show a single slice from the tomogram of each specimen and located approximately at the “cut surface”.

In both sets of images, new cracks with features distinct from the two previously-described ones are clearly resolved in every specimen, independently from the cutting technique respectively used: some of the cracks start (or terminate) at the SCI and are approximately or oriented along the radial direction (see specifically the green arrows in Fig. 15b, d and e), while others appear as delamination regions at the

![Fig. 13. SEM images from different position around the steel tube for the Laser MicroJet (LMJ) cutting.](image)

![Fig. 14. Planar cross-sections (also called “slices”) extracted from the X-ray tomogram of the specimen prepared for the saw cutting, acquired before cutting the specimen. (a) A slice from the part approximately representing the region of interest for cutting. (b) A slice 2 mm underneath the slice in (a). (c) A slice 4 mm underneath the slice in (a). The arrows point to crack-like features either inside aggregates or at the aggregate-cement matrix interfaces and not directly localized nearby or starting from the SCI.](image)
SCI (see specifically the blue arrows in Fig. 15b, c, and f). Cracks with such geometrical features, with size above the spatial resolution of the tomograms, cannot be observed in the tomograms acquired before the cutting. In addition, they are more predominant closer to the cutting surface (Fig. 15d–f).

The cracks on the cutting surface resolved in the tomograms could be compared to the SEM images (Fig. 7 for the diamond sawing, Fig. 11 for the laser cutting and Fig. 13 for the LMJ cutting) acquired.
approximately from the same planar surfaces shown in Fig. 15g–i. Just by visual comparison of the damage on the cutting surfaces of different specimens, it seems that the laser and the LMJ cutting produced more extensive cracking. On the contrary, the optimized diamond sawing seems to have led to the lowest level of cracking of the cutting surface. Laser cutting created a large number of fine cracks that are uniformly distributed. On the contrary, the LMJ cutting produced local but extensive steel-mortar delamination as well as additional radial cracks.

In order to support what inferred only qualitatively by the visual inspection of the after-cutting tomograms and by the SEM images of the cutting planes, we used the crack segmentation procedure described in Section 2 to enable more precise qualitative and quantitative comparisons of the cracks in the specimens subjected to the distinct cutting techniques. The 3D segmented crack ensembles for each specimen (diamond sawing, laser, and LMJ cutting, respectively) are labelled both in Fig. 15g-i and Fig. 15j–l. In the former, the voxels belonging to the crack binary tomogram and to the visualized planar cross-sections are colored in blue (color in the online version of the manuscript). In the latter figures, the ensembles of crack voxels are rendered in blue color while the yellow surface shows the steel tube. In Fig. 15j–l, only one planar cross-section extracted from the filtered tomogram is shown in order to provide an idea about each specimen's spatial extent.

A larger crack volume in the specimen cut by LMJ, compared to the other specimens, can be already identified simply by visual inspection of Fig. 15g–l. However, we additionally performed a crack analysis to quantify the crack density within the scanned volume of the specimens. The crack density for the tomographed volume was calculated as the total volume of segmented cracks (excluding air voids) divided by the total volume of the tomographed region of the specimen (excluding the steel tube volume). The crack density of the LMJ cut specimen (0.98%) is about 1.2 times higher than that of the laser cut one (0.78%) and 2 times higher than that of the diamond saw cut specimen (0.48%), as shown in Fig. 16. 1D, vertical profiles of crack (surface) density computed on each cross-sectional plane orthogonal to the symmetry axis of the cylindrical specimen. The profile extends itself from the cutting surface to the specimen's interior and it was computed along a 1D grid having step size equal to the voxel size (13.66 μm). (a) Diamond saw (direction 3), (b) laser (cut 2) and (c) LMJ cut. The volumetric crack density (total crack volume divided by specimen volume) is provided in each case as well. The corresponding rendering of the segmented cracks and steel hollow bar are also shown next to the respective vertical profiles.

A 1D, spatial profile of the local crack density along the vertical axis of the specimen is plotted in Fig. 16, as well, to visualize the variation of the crack ensemble from the top to the bottom of the specimen (Fig. 16 a-c for diamond sawing, laser, and LMJ cutting, respectively). The profile simply represents the crack surface density on each slice (the number of crack voxels on the slice divided by the total number of specimen voxels on the same slice), with thickness of one voxel and perpendicular to the vertical axis of the specimen. Side-views of the 3D crack patterns are also illustrated next to their corresponding profiles, to visualize the variations in their corresponding profiles. The crack density is higher in the shallower sub-surface regions where the specimens were cut, while it gradually decreases with increasing depth of the regions. The LMJ cutting creates the highest damage on the cutting surface due to erosion of the mortar, caused by the high-pressure water flow. As Fig. 16 shows that the interior crack density is also very high, it is most likely that the water flow can penetrate into the mortar along the steel tube through the BWZ. Therefore, the total volumetric crack density in the LMJ cutting specimen is higher than that of the other cutting methods. Although the total volumetric crack density in the LMJ cutting specimen is higher than that of the laser cutting (1.2 times higher), the laser cutting seems to create more cracks underneath the cutting surface. This indicates that the interior material is expanded during the course of laser cutting. This expansion in the steel bar might have led to the propagation and enlargement of the pre-existing cracks, with a size smaller than the spatial resolution of the tomograms, as well as to the nucleation and propagation of new cracks. The diamond saw cutting shows a similar degree of damage from the cutting surface to the interior, which was presumably generated by the vibration of steel during cutting. However, the magnitude of cracks along with the steel, particularly in the surface near zone, is considerably smaller than that for the other two cutting methods. Therefore, compared to the other methods, the diamond saw-based one seems to be the safest technique to prepare steel-mortar interface specimens with the least cutting damage.

3.4. Recommendations

Our results demonstrate that an appropriate cutting method is important for preserving the microstructure of the SCI, particularly in the presence of a BWZ, which is a common subject of study. The advantages and disadvantage of compared cutting methods are compared in Table 5.

Many studies in the literature characterize the SCI without considering the effect of cutting during specimen preparation. If the cutting methods used in those studies can alter the microstructure of the SCI, the validity of the characterization results presented in those studies must be questioned. A common damage to the BWZ is that it is filled with eroded mortar, which leads to errors when quantifying the gap width or the porosity of the matrix. Unfortunately, the degree of damage to the BWZ is difficult to estimate, and thus, post-imaging corrections are virtually impossible on a general basis. Some papers show a gap layer at the upper side of the rebar (see a discussion in [23]). Based on the results of this paper (see SEM images in Figs. 5–8), an inappropriate cutting procedure, such as diamond saw cutting with high feed speed or laser cutting with high energy, could be one of the reasons that create the gap layer. However, these studies generally do not provide sufficient information regarding the cutting method and do not evaluate the cutting damage.

The three laser cutting tests show that the cut quality is improved when the laser power is reduced, but that damage could here still not be avoided. Further work would be needed to optimize laser cutting protocols toward minimizing the introduced damage. Nevertheless, a diamond saw machine is more feasible than a high-precision laser cutting machine, as machines for the latter may often not be available at mortar and concrete testing laboratories. Therefore, the optimized diamond saw cutting is recommended as the first choice for preparing high quality cross-sections for reinforced concrete.

3.5. Applications

Based on observations from the SEM images, the diamond sawing with low feed speed can better preserve the microstructure at the SCI than the laser and LMJ cutting methods. However, this study employed a 3-mm hollow steel tube filled with cement paste and embedded in mortar. Thus, one may argue that the cutting damage to specimens with a solid rebar in concrete may be worse than that in the model system studied in this paper. To demonstrate the applicability of the proposed cutting protocol, diamond saw cutting was applied to specimens with 8 mm-diameter rebars in concrete (max aggregate size 32 mm). Specimens were cored from a concrete bridge deck in the Swiss Alps which has been in service for more than 40 years [67]. An example of the acquired SEM-BSE images in Fig. 17 clearly shows no gap at the upper side and a clean gap (BWZ) under the rib. This suggests that the proposed cutting protocol is suitable to study the steel-concrete interface around actual rebars in concrete.

The experiments of this study were done on specimens with uncorroded steel in mortar or concrete. One of the relevant interests is to apply the proposed cutting protocol to specimens with corroded rebars. Utilizing similar specimens as the one shown in Fig. 17, accelerated corrosion tests were carried out in our laboratory by immersing the
Fig. 16. 1D, vertical profiles of crack (surface) density computed on each cross-sectional plane orthogonal to the symmetry axis of the cylindrical specimen. The profile extends itself from the cutting surface to the specimen’s interior and it was computed along a 1D grid having step size equal to the voxel size (13.66 μm). (a) Diamond saw (direction 3), (b) laser (cut 2) and (c) LMJ cut. The volumetric crack density (total crack volume divided by specimen volume) is provided in each case as well. The corresponding rendering of the segmented cracks and steel hollow bar are also shown next to the respective vertical profiles.

Table 5
Results of compared cutting methods.

| Cutting method          | Advantages                                  | Disadvantages                                |
|-------------------------|---------------------------------------------|----------------------------------------------|
| Diamond sawing (feed speed: 0.3 mm/min) | Less damage to BWZ at SCI;                 | Longer cutting time                          |
|                         | No damage if no BWZ under steel;            |                                              |
|                         | Good instrument availability                |                                              |
| Laser cutting           | Fast                                        | Create a heat-affected zone along steel;     |
|                         |                                              | Damage at all locations around steel         |
| LMJ cutting             | Fast;                                       | Erosion of cementious matrix                 |
|                         | Less heat damage                            |                                              |
specimens in NaCl solution to initiate corrosion [67]. After corrosion initiation was detected, the specimens were cut by the proposed mechanical sawing protocol and imaged in the SEM. An example of results shown in Fig. 18 displays corrosion products with different types of morphologies. The needle-like structure of the corrosion products was well preserved, and no obvious damage to the SCI and corrosion products was found. These results further prove the applicability of the proposed cutting method to study corroded rebars in concrete.

4. Conclusions and outlook

This study compared the potential damage that different cutting methods may cause to the SCI when used to prepare specimens for microscopy. The studied cutting techniques were mechanical sawing, laser cutting, and laser MicroJet (LMJ) cutting. The microstructure of the SCI was imaged by scanning electron microscopy (SEM) and by X-ray microtomography (XRμCT). The majority of the tests in this study were conducted on specimens with 3-mm steel tubes, which were optimized for image quality and resolution in XRμCT. The main conclusion is that an optimized diamond saw cutting procedure with low feed speed (here 0.3 mm/min) introduces considerably less damage than laser cutting and LMJ cutting. In addition, the following conclusions are drawn:

1. Diamond saw cutting primarily leads to damage in areas where a BWZ is present. Since it is often exactly these regions that are of interest, it is important to consider selecting an appropriate cutting procedure. Two types of possible damage were identified: i) mortar crushed at two ends of the BWZ (where mortar meets the steel), and ii) the BWZ filled with broken mortar. The first type of damage is caused by too high cutting force (fast feed speed) and vibration of the steel. This study suggests to use low feed speed to minimize this type of damage, but it was found that the damage can hardly be avoided completely. The second type of damage can be avoided if the cutting direction is chosen in such a way that the blade cuts first the steel before passing the BWZ.

2. This study recommends that the areas where the BWZ ends and where the mortar meets the steel are generally excluded from attempts to characterize quantitatively the microstructure of the SCI, because they will almost always be in a disturbed state after the cutting and sample preparation procedure (see conclusion 1).

3. The laser can heat up the composite material and thus cause differential thermal expansion and other temperature-induced damage which creates a gap around the steel. The XRμCT results show that this damage can penetrate relatively deep (here of the order of millimeters) into the interior of the sample (below the cutting surface), which makes it difficult to remove this HAZ by polishing and grinding.

4. The high-pressure water flow used in LMJ cutting can erode the porous cementitious material. This causes more serious damage to the SCI on the cutting surface than the other cutting methods.

5. Finally, two applications of the optimized diamond saw cutting procedure were provided to demonstrate the applicability of the proposed method. One was to cut specimens with 8-mm rebars from an actual reinforced concrete structure. Results show that the concrete at the upper side of the rebar is well preserved and no damage to the bleed water zone at the underside can be seen. The other application was to cut specimens with corroded rebars, in which the fine microstructure of corrosion products was preserved. These results indicate that the proposed cutting protocol can be applied to the study of the interfacial zone around large, solid and corroded steel bars in concrete.

Further research work may study the applicability of the proposed sample preparation protocol to a wider range of systems, including the interfacial transition zones (ITZs) around aggregates. Since the ITZs have a similar microstructure with the SCI, it is expected that the proposed cutting method can be applied to a certain extent. On the other hand, aggregates have different mechanical properties and geometries compared to rebars and thus the proposed method will need to be adjusted.

Author contributions

Z.Z. and U.A. conceived and designed the study. Z.Z. prepared the specimens and performed SEM imaging. M.S. performed the XRμCT measurements. M.S. and M.G. performed the 3D image analysis. Z.Z. and M.S. drafted the manuscript. U.A., M.G and P.L. aided in interpreting the results and contributed to the manuscript.

Fig. 17. An example of SEM-BSE images for a rib of an 8 mm-diameter rebar embedded in concrete (the specimen retrieved from a concrete bridge deck). The rebar was horizontally placed in the deck. By using the proposed cutting protocol, there is no obvious gap at the upper side and a bleed water zone under the rib can be seen.

Fig. 18. SEM-BSE images for a specimen with a corroded rebar (left: the underside of the rebar with the BWZ; right: the upper side of the rebar). The specimen is similar to the one in Fig. 17. After extraction from the bridge deck, it was immersed in NaCl solution to initiate corrosion [67].
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.

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Appendix A. Supplementary data

https://polybox.ethz.ch/index.php/s/G6kVvHtM1YYrDx

Supplementary data to this article can be found online at doi:https://doi.org/10.1016/j.cemconres.2020.106229.

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