dacl10k: Benchmark for Semantic Bridge Damage Segmentation
– Supplementary Material –

Johannes Flotzinger Philipp J. Rösch Thomas Braml
University of the Bundeswehr Munich
{johannes.flotzinger, philipp.roesch, thomas.braml}@unibw.de

A. dacl10k

A.1. Additional statistics

Table 1 displays additional statistics of dacl10k. The average image has a picture format of 4:3 and comprises four megapixels. In total, dacl10k includes 40 billion pixels and 110,533 polygons. The average number of polygons per image amounts to eleven.

#images	9,920
Image width (min, mean, max)	336, 1950, 6000
Image height (min, mean, max)	245, 1581, 5152
#pixels of image areas	40,435,268,789
Average #pixels/image	4,076,136
Average #polygons/image	11

Table 1. Additional statistics on dacl10k.

A.2. Accessibility

The dacl10k dataset is made freely available to academic and non-academic entities for non-commercial purposes such as academic research, teaching, scientific publications, or personal experimentation. Permission is granted to use the data, given that you agree to the Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) license.

A.3. Class descriptions

In Table 3 (Concrete Defects), Table 4 (General Defects) and Table 5 (Objects) a detailed description and an example image for each class are listed. Within these tables, we describe the visual appearance and the cause of the defect, or rather the functionality of the given object. The examples include the annotations of the according class exclusively. Additionally, the class abbreviations – used in the tables and figures of this work as well as in the annotation files of dacl10k – are given in parentheses.

For a deeper understanding of the concrete defects it is important to note that ordinary concrete consists of cement, water, sand and coarse aggregate (gravel). In its unhardened state (wet concrete) the mix of cement and water is named cement paste, while the hardened paste is called cement stone. The cement paste – later cement stone – binds the other concrete components, sand and gravel, together. Regarding the concrete defects *Crack*, *Alligator Crack* and *Spalling* it is noteworthy that concrete has a high compressive strength but a low tensile strength (≈10% of its compressive strength). The overstressing of its tensile strength leads to the occurring of the according defect. The cause of the overstressing differs for each of these defects, which is further explained in Table 3.

A.4. Annotation-specific problems

Only a few related datasets are available (see main paper), which are limited to five RCDs. In addition, the labeling of dacl10k requires deep domain knowledge. Furthermore, dacl10k was labeled by two different groups of annotators, civil engineering students and a professional annotation team. On the one hand, civil engineers have in-depth knowledge about RCDs and bridge components. On the other hand, they are usually not familiar with computer vision problems and, therefore, are not aware of the caveats during the development of semantic segmentation datasets. The professional annotation team, against it, has no domain expertise in regards to bridge defects and objects. Thus, their understanding of important context is less pronounced.

A.5. Data-specific problems

In the following, we discuss the most challenging defects (see Figure 1) and general problems across the dataset (see Figure 2). The listed examples are problematic with respect to annotation and their prediction by our baselines – due to the low IoU reported in the main paper.

The images in Figure 1a display *Cracks* that are bordered by strongly varying background. The most left image shows an abrupt change regarding the background at the vertical edge of an abutment wall, where one side represents a clean concrete surface and the other is heavily weathered (*Weathering*). On the middle image, the *Crack* traverses different colors of a *Graffiti*. The most right sample displays vegetation which covers the underlying *Crack*. The two most left images in Figure 1b display defects that can be easily mixed up. *Alligator Cracks* are areas of multiple *Cracks* that are branched and arbitrary orientated, which makes their differentiation complicated. In the most left image, both of these classes are present. As mentioned in the main paper, differentiating between *Weathering* and *Wetspot* is problematic because they often overlap with each other (see middle image in Figure 1b). Another problematic class is *Restformwork* which is under the lower five classes regarding the achieved IoU by our best model. In the most right image of Figure 1b *Restformwork* is covered by concrete slurry. Furthermore, *Restformwork* can be made of wood and the color of the polystyrene may vary. Thus, this class has many different visual appearances, which the model has to learn to summarize in one damage class. In Figure 1c, we display the three classes of dacl10k which are the most complicated to differ: *Spalling*, *Rockpocket* and *Washouts/Concrete corrosion*. While they look very similar, their cause and assessment differ decisively (see Table 3).

Figure 2 includes images representing class-independent difficulties (not exclusively for one class) and image quality problems across the dataset. Often, defects show no clear border, leading to inconsistent annotations and predictions. This "smearing of damage borders" can be observed for *Efflorescence*, *Weathering*, *Wetspot* and *Rust*. An example of the latter is shown in the most left image tile of Figure 2a. In addition, objects and defects can reach from the foreground to the background (see middle image in Figure 2a), and some defects may show weak differences to their surrounding area due to low contrast (see most right image in Figure 2a). Further problems concern the image quality, such as lens flares, partial overexposure due to the usage of flashlight or reflections (see Figure 2b).

B. Baseline experiments

B.1. Additional training informations

For each of the six combinations of encoder and semantic segmentation architecture, we examined a grid search for the learning rates $1e^{-4}$, $5e^{-4}$, $1e^{-3}$ and $5e^{-3}$ where the best value is chosen based on the validation loss.

B.2. Auxiliary multi-label results

In Table 2 we display additional metrics from the auxiliary head of the best model on the test split.

Class	Precision	Recall	F1 Score	#images
Crack	0.77	0.52	0.62	485
ACrack	0.78	0.61	0.68	97
Efflorescence	0.82	0.60	0.69	460
Rockpocket	0.68	0.55	0.60	529
WConccor	0.42	0.24	0.31	33
Hollowareas	0.84	0.77	0.81	312
Spalling	0.80	0.76	0.78	1010
Restformwork	0.69	0.51	0.59	251
Wetspot	0.59	0.42	0.49	298
Rust	0.88	0.72	0.79	972
Graffiti	0.87	0.67	0.76	235
Weathering	0.75	0.68	0.72	916
ExposedRebars	0.80	0.59	0.68	234
Bearing	0.85	0.82	0.83	203
EJoint	0.74	0.67	0.70	93
Drainage	0.88	0.54	0.67	294
PEquipment	0.88	0.81	0.84	396
JTape	0.75	0.58	0.66	264

Table 2. Test results for auxiliary head of the best model.

C. Bridge inspection

In the following, we describe the currently practiced bridge inspection process (analogue inspection), its limitations and the concept of the digitized inspection including the automated damage recognition enabled by multi-label semantic segmentation models. Thereby, we use the process of hands-on inspections in Germany as an example. It is important to note that inspection processes worldwide, and especially the defect documentation, are similar.

C.1. Analogue inspection

Currently practiced bridge inspections are carried out by a professionally trained civil engineer (bridge inspector). Usually, the inspector observes the complete surface of the given building while capturing each defect. During hands-on inspections, it is mandatory to detect visually recognizable defects and *Hollowareas*, which can be detected by hammering the concrete surface. Thus, *Hollowareas* are recognized based on the sound the hammering provokes[1]. After the detection of a defect the inspector takes an image and notes, the damage class, size and location (damage-information) in a handwritten damage sketch. In Figure 3 such a sketch is displayed. In this case, the inspector numbered the defects chronologically and named the corresponding class and size (if necessary) of each damage, *e.g.*, #32: Cracks ("Risse") with a thickness of "$\leq 0.2mm$", approximately 7m from the cross girder ("Querträger"), between the left side of the web and flange of the most left T-beam (cross-section 4-5). After the inspection was completed, some inspectors additionally transfer the handwritten sketch to a CAD sketch.

Finally, the assessment of the building is determined by calculating the condition grade, which is similar to grades in school, and preparing the inspection report. According to the damage-information noted in the damage sketch, the

[1] *Hollowareas* and *Cracks* are marked with chalk markings to make them easy to find in successive inspections.

defect ID, which is defined by the German standard, can be assigned. For each defect and its ID, the country-specific standard recommends grades with respect to structural integrity, traffic safety and durability. Based on the expertise of the inspector, these recommendations are adapted. In the inspection report all defects are listed including their grades and recommendations regarding restoration, traffic load limitations or building a new construction. Furthermore, the defect sketch is attached to the report in order to enable a visual comparison with other – especially consecutive – inspections. This is important for tracking the defect development.

C.2. Limitations of the analogue inspection

The process components of the analogue bridge inspection, such as classifying, measuring, locating and assessing the defects, is often inconsistent, error-prone, and lengthy. Oftentimes, this is due to the previously described cumbersome damage documentation.

According to Phares *et al*. [1] the assessment results of bridge inspections vary greatly between inspectors. Thereby, Inspection reports from 49 bridge inspectors from 25 different state departments of transportation (DOTs) at seven structures, each in the United States, were evaluated. It was found that approximately 56% of the condition ratings deviated significantly from the reference condition rating (ground truth). The main reasons for the strongly diverging ratings is the variability in inspection documentation (e.g., field inspection notes, photographs, etc.). Additionally, inspection notes concerning important structural defects or corresponding photographs were often omitted.

We think, in addition, the following components of the analogue inspection contribute to the widely varying inspection results:

- The correct image must be found for the corresponding defect in the defect sketch after the inspection. This is problematic, especially on bridges with many defects that are close together.

- Damage size is measured with a pocket rule, thus, it's imprecise.

- Damage localization is often estimated or determined by measuring the distance to the next bridge pillar, which is inaccurate (or impossible) on bridges with a big span.

C.3. Digitized inspection

The basis for a digital building inspection (DI) is a Building Information Model (BIM), which is created during the building's planning phase or, in the case of existing bridges, before the inspection. At the structure the inspector records all defects making use of an UAV or smartphone. For non-hands-on inspections, UAVs can be used to record the defects because only visually recognizable defects have to be documented during this type of inspection. For hands-on (or close-up) inspections, smartphones or tablets are the most suitable devices to support the inspector, as they are handy and easy to use. In addition, close-up inspections require the detection of *Hollowareas* which are detected by hammering the concrete surface, thus, making use of UAVs is not possible. Independent of the device, the automated damage detection is the central part of the inspection process, provided by a multi-label semantic segmentation model. The model enables the classification, measurement and localization on a pixel-level in order to assign an ID to each defect and to obtain the grading recommendations. These properties of each detected defect are stored as metadata for each DI. As a result, the BIM can be merged with the metadata of any performed inspection, allowing the generation of a digital twin. This allows for easily tracking the development of the bridge's condition over time. Consequently, instead of comparing damage sketches and inspection reports that are available in paper form, the evolution of the digital twin are assessed.

The described DI has the goal to assist the inspector as much as possible in performing inspections and the consecutive evaluation within the framework of existing standards. The DI is simpler and more efficient than the analogue inspection, while the inspector remains the central decision-maker (human oversight). The acceleration of the inspection mainly results from the automated damage detection and the elimination of damage documentation on the defect sketch. For each detected damage, the DI-application provides a suggestion for the properties, or rather metadata. This recommendation can be corrected and saved by the inspector on site. This results in a direct quality management, which is particularly important for defects that require visual contextual knowledge.

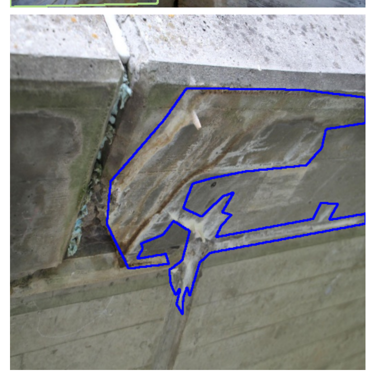
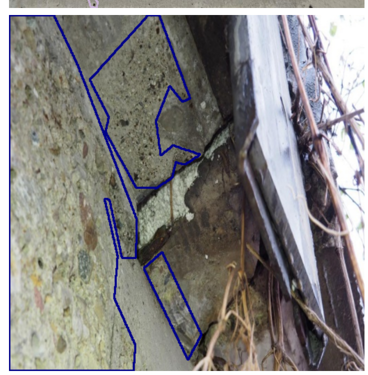
Damage	Visual appearance	Cause	Example
Crack	• Elongated and narrow zigzag line • Clearly darker compared to the surrounding area or black	• Concrete's tensile strength is exceeded • Too high bending or shearing load • Settlement of the substructure	
Alligator Crack (ACrack)	• Many branched cracks • Mostly arbitrarily orientated • Usually with a small crack width (compared to *Crack*)	• Inadequate post-treatment or concrete recipe (shrinkage) • Too high temperatures during hardening of the concrete • Formation of expansive phases leading to a volume increase in the concrete as a result of chemical action	
Efflorescence	• Mostly roundish areas of white to yellowish or reddish color • Strong efflorescence can look similar to stalactites. • Often appears in weathered (*Weathering*) or wet areas (*WetSpot*) of the building and in combination with *Crack* and/or *Rust*	• Dissolving of salts (calcium, sodium, potassium) from the cement stone or aggregate by humidity changes or water ingress, *e.g.* constantly running water through the building part or along its surface • The salts consequently carbonate leading to the final visual appearance. • Note: Water ingress can be caused by other defects imposing the draining of water, *e.g.*, *Restformwork* or damaged *Drainage*. *Efflorescences* are also called Calcium leaching.	

Table 3. Concrete defects, their visual appearance, cause and example images with according annotation.

Damage	Visual appearance	Cause	Example
Rockpocket	• Visible coarse aggregate • Often in tilts of the formwork and the bottom of building parts (opposite side from which the concrete is poured into the formwork)	• Inadequate rheological properties (viscosity, yield point) of the concrete • Appears due to bad compacting after having poured the concrete into the formwork. Therefore, insufficient deaeration of the concrete follows, causing areas where the cement paste didn't fill the volume between the coarse aggregate completely (*Rockpocket*). • Note: Hence, the concrete cover of the reinforcement as well as the bond between the bars and the concrete is not provided or reduced. *Rockpockets* are also called Honeycombing.	
Cavity[1]	• Small air voids • Mostly on vertical surfaces	• Inadequate rheological properties (viscosity, yield point) of the concrete • Appears due to bad compacting after having poured the concrete into the formwork. Therefore, insufficient deaeration of the concrete follows causing small "dots" on the surface. • Note: At these spots the concrete cover is reduced. Cavities of usual size have no impact on the building assessment.	
Concrete Corrosion (ConcreteC)	• Includes the visually similar defects: Washouts, Concrete corrosion and generally all kinds of planar corrosion/erosion/abrasion of concrete. • Note: We summarize all these "planar corrosion defects" in this class because they are visually hard to differ. According to inspection standards they have to subdivided which requires strong expertise in building defects.	• Washouts appear on building parts that are constantly in contact with running water leading to the erosion of the concrete, *e.g.*, abutment walls or bridge piers in rivers. • *Concrete corrosion* can appear as a result of frost-thaw cycles, loss in succession to chemical attacks or abrasion (mechanical or action of acid and salt solutions). • Note: In dacl10k_v1 *Concrete Corrosion* (ConcreteC) was called "Washouts/Concrete corrosion" (WConccor).	

[1] *Cavity* was added in dacl10k_v2 which was formerly included in *Rockpocket*.

Table 3. Concrete defects, their visual appearance, cause and example images with according annotation. (continued)

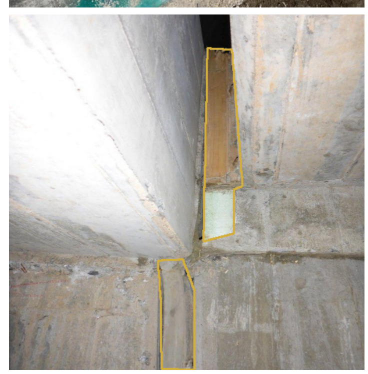
Damage	Visual appearance	Cause	Example
Hollowarea	• *Hollowareas* are not visually recognizable but their markings made with crayons (mostly yellow, red or blue) during close-up/hands-on inspections. • Note: The outer edge of the marking is considered as the boundary of the according area. We annotate every chalk marking that approximately forms a closed geometric figure. Single lines are not labeled as *Hollowarea* as they are often used for the marking of *Cracks*.	• Corrosion of the subjacent reinforcement which leads to a volume increase surrounding the reinforcement bar and detaching of the concrete area that covers the bars. • *Hollowareas* are usually the preliminary stage of *Spallings* and *Exposed Rebars*. • Note: Recognizing *Hollowareas* is very important as the falling concrete parts can cause severe damage. Therefore, hollow sounding areas are usually removed instantly.	
Spalling	• Spalled concrete area revealing the coarse aggregate • Significantly rougher surface (texture) inside the *Spalling* than in the surrounding surface	• Corrosion of the subjacent reinforcement leading to an increase in volume and consequent spalling of the concrete cover • Frost-thaw cycles of intruded water (deeper than *Washouts/Concrete corrosion*) • Impact from vehicles, damaging during assembly of the building part or removal of the formwork, manufacturing faults	
Restformwork	• Left pieces of formwork in joints or on the structure's surface • Restformwork can be made of wood and polystyrene (PS). • PS is often used as a placeholder in joints during concreting.	• After the concrete hardening has ended, PS is often forgotten to be removed (*e.g.*, in the joint between the abutment wall and the superstructure). • Note: If *Restformwork* is not removed, water may be hindered to drain which can lead to other defects (*e.g.* *Spalling*, *Exposed Rebars*, *Rust*).	

Table 3. Concrete defects, their visual appearance, cause and example images with according annotation. (continued)

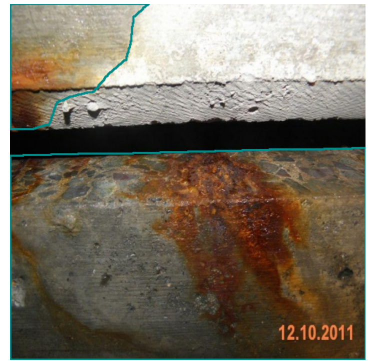
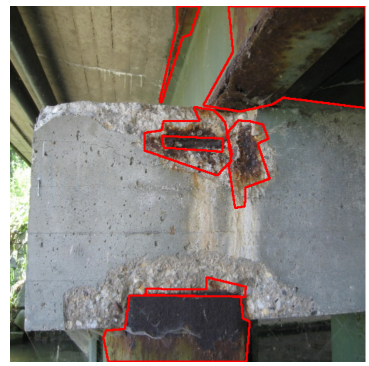
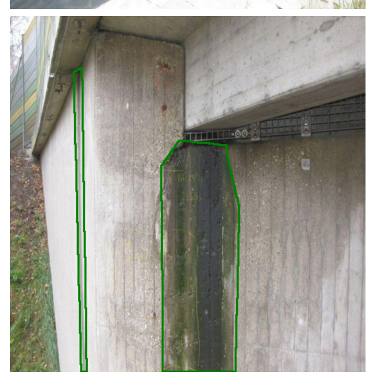
Damage	Visual appearance	Cause	Example
Wetspot	• Wet/darker mirroring area	• Water is hindered to drain (through *Restformwork*) or can't drain properly due to damaged *Drainage*, leaky *Expansion Joints*, *Joint Tapes*, or *Cracks* in the bridge deck. • Note: There may be temporary *Wetspots* due to recent rainfall which can be irrelevant for the bridge assessment. But, they may also indicate that the according area has to be observed in detail due to the greater exposition. In addition, the water can carry deicing salt (on road bridges). Usually, those areas are chosen to execute further investigations such as drill tests in order to determine the carbonation depth or chloride content.	
Rust	• Reddish to brownish area • Often appears on concrete surfaces and metallic objects	• Rust on the concrete surface originates from oxidation of the subjacent or neighboring reinforcement bars, or neighboring metallic building parts. The bars can corrode as a result of loss of the alkaline protective layer provided by "un-carbonated" concrete (pH value > 9.5). If the pH value drops due to the further carbonation of the concrete (pH value ≤ 9.5), which is unavoidable over time, the reinforcement can oxidize. • The carbonation is accelerated by *Cracks* *Rockpockets* and porous concrete because of faster intruding of water and carbon into the building part. In addition, the oxidation is intensified by deicing salts which is one of the most severe problems on road bridges.	
Graffiti	• All kinds of paintings on concrete and objects apart from defect markings		
Weathering	• Summarizes all kinds of weathering on the structure (*e.g.* smut, dirt, debris) and Vegetation (*e.g.* plait, algae, moss, grass, plants). • Weathering leads to a darker or greenish concrete surface compared to the rest of the surface.	• Directly weathered areas • Result of *Wetspot* • Note: *Weathering* itself is not a severe defect. The main issue is that it can obscure other defects (*e.g.* corroded reinforcement or cracks). *Weathering* is also called Contamination.	

Table 4. General defects, their visual appearance, cause and example images with according annotation.

Object	Visual appearance	Functionality	Example
Exposed Re-bars	• Exposed Reinforcement (non-prestressed and prestressed) and cladding tubes of tendons • Often appears in combination with *Spalling* or *Rockpocket*, and *Rust*	• In reinforced concrete structures, the reinforcement's task concerning the load transfer is to absorb the tensile forces. • *Exposed Rebars* occur due to insufficient concrete cover or corrosion and the consequent *Spalling* of the concrete cover. • The reduction of the reinforcement's cross section due to *Rust* significantly influences the structural integrity of the according building.	
Bearing	• All kinds of bearings, such as rocker-, elastomer- or spherical-bearings	• Bearings transfer the load from the superstructure to the substructure. • Note: Bearings can show *Rust* and *Cracks* as well as deformation due to settlements in the abutments, overloading or creeping of the bridge. The deformation or damaging of bearings can result in load redistribution which is not considered in the structural design of the bridge.	
Expansion Joint (EJoint)	• Located at the beginning and end of the bridge • Assembled cross to the longitudinal bridge axis	• *Expansion Joints* compensate the thermal longitudinal expansion of the bridge deck and superstructure. • Note: Mostly, *Expansion Joints* are corroded (*Rust*) and weathered (*Weathering*) which hinders their ability to compensate the enlargements due to changes in temperature.	

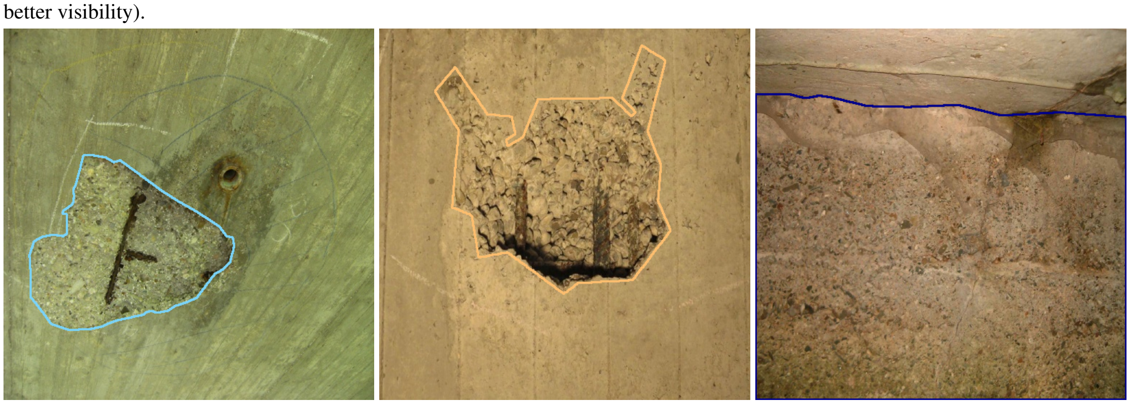
Table 5. Objects, their visual appearance, functionality including their role for the bridge assessment and example images with according annotation.

Object	Visual appearance	Functionality	Example
Drainage	• All kinds of pipes and outlets made of Polyvinylchlorid or metal mounted on the bridge.	• The *Drainage* directs water (often contaminated with deicing salt) away from the bridge. • The draining of water is important for the durability of the bridge. If the water can't drain properly, especially when it's contaminated with deicing salts, the bridge's deterioration is accelerated leading to defects, such as *Spalling*, *Exposed Rebars* or *Rust*	
Protective Equipment (PEquipment)	• Railings, traffic safety features (*e.g.*, steel rail, guide rails, impact attenuation device)	• Geometric adequacy and structural capacity of the *Protective Equipment* is important with respect to the traffic safety. • The rail types and installation heights and minimum clearances must be checked. • Note: Mostly, they are corroded (*Rust*) or deformed due to vehicle impact.	
Joint Tape (JTape)	• All joints that are filled with elastomer or silicon • Note: Originally, *Joint Tape* means an elastomer strap at the end and beginning of relatively small bridges.	• *Joint Tapes* compensate longitudinal enlargements due to changes in temperature (like *Expansion Joint*). • Note: A *Joint Tape* is damaged when it's ruptured or twisted. *Joint Tape* is also called Bridge Seal.	

Table 5. Object classes, their visual appearance, functionality including their role for the bridge assessment and example images with according annotation. (continued)

(a) Challenging samples showing a *Crack*: in combination with strong *Weathering*, in combination with *Graffiti* and partially overlapped by vegetation (*Weathering*).

(b) *Crack* vs. *Alligator Crack*, *Weathering* vs. *Wetspot*, *Restformwork* covered with concrete slurry (no ground-truth annotation for better visibility).



(c) *Spalling*, *Rockpocket*, *Washouts/Concrete corrosion*.

Figure 1. Challenging defects. All subcaptions describe the images from left to right.

(a) No clear border of the defect (*Rust*), the class (*Protective Equipment*) is stretched from fore- to background.Many overlapping classes with partially low contrast like the border and hatching of the *Hollowarea* (pale red), and the *Efflorescence* (dark blue) next to the bright, dry and healthy concrete surface.

(b) Image quality problems: lens flares, partial overexposures due to flashlight, and sunlight.

Figure 2. General problems across the dataset. All subcaptions describe the images from left to right.

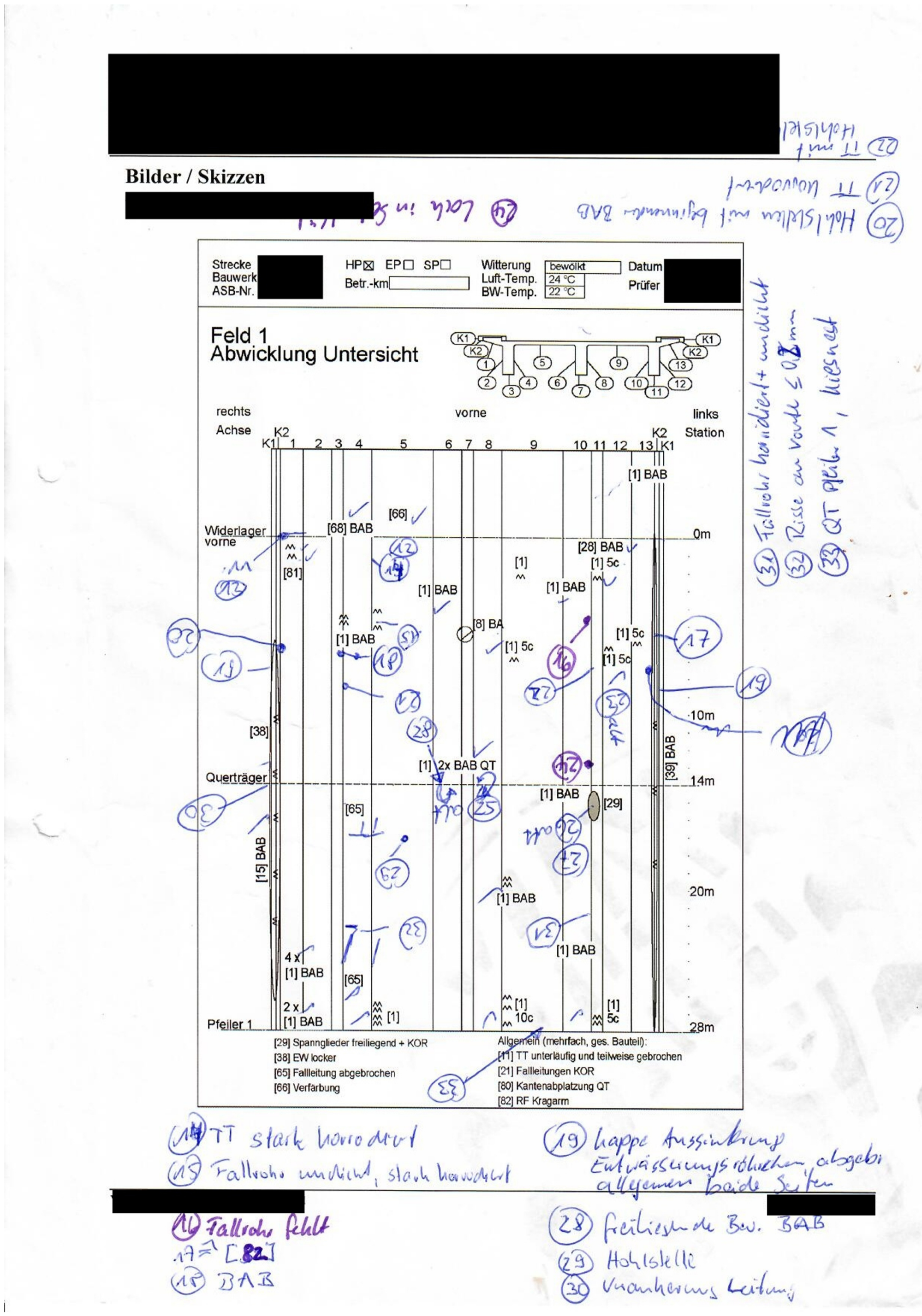


Figure 3. Damage sketch from a real bridge inspection with three T-beams. The sketch represents the bridge flipped-open along its longitudinal axis. Thus, the "vertical lines" represent the edges of the bridge cross-section. The defects are numbered in chronological order. Exemplary damage-information separated by comma (damage-number, damage-class, longitudinal, and cross-section dependent localization): #28, *Spalling* ("BAB") with *Exposed Rebars* ("freiliegende Bewehrung"), at the cross girder ("Querträger"), on the left side of the web (6); #29, *Hollowarea* ("Hohlstelle"), approximately 3m from the cross girder ("Querträger"), on the flange (5); #31, *Drainage* ("Fallrohr") with *Rust* ("korrodiert") which is leaking ("undicht"), approximately 7m from the cross girder ("Querträger"), on the bottom of the web (11).

References

[1] Brent M. Phares, Glenn A. Washer, Dennis D. Rolander, Benjamin A. Graybeal, and Mark Moore. Routine highway bridge inspection condition documentation accuracy and reliability. *Journal of Bridge Engineering*, 9(4):403–413, July 2004. 3