AN APPROACH FOR ULTRASOUND-BASED ULTIMATE LOAD PREDICTION OF FASTENERS IN CONCRETE

LÖSUNGSANSATZ FÜR EINE ULTRASCHALLBASIERTE TRAGLASTPROGNOSE VON BEFESTIGUNGEN IN BETON

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SUMMARY

At present, there is a lack of non-destructive testing methods to assess fastenings in concrete with regard to their load-bearing capacity. This assessment has always been carried out with destructive pull-out tests.

This study provides an approach for a non-destructive method to assess the load-bearing capacity of fastenings in concrete. When a fastening in concrete is loaded, tensions and the resulting micro-cracks form around this fastening, become more and larger as the load increases. This effect has characteristic effects on an ultrasonic signal which is introduced into the anchorage in the immediate vicinity of the fastening. A relative change in the measured ultrasonic signal with simultaneous application of a test load is therefore inferred to the maximum load without reaching it

ZUSAMMENFASSUNG

Bisher gibt es keine zerstörungsfreie Verfahren, um die Tragfähigkeit von Befestigungen in Beton zu ermitteln. Diese Ermittlung erfolgt bis jetzt durch zerstörende Auszugsversuche.

Diese Untersuchungen zeigen einen möglichen Lösungsansatz für eine zerstörungsfreie Methode zur Traglastbestimmung von Befestigungen in Beton. Wenn eine Befestigung im Beton belastet wird, bilden sich um diese Befestigung herum Spannungen und Mikrorisse aus, die mit zunehmender Belastung mehr und größer werden. Dieser Effekt hat charakteristische Auswirkungen auf ein Ultraschallsignal, welches in unmittelbarer Nähe der Befestigung in den Ankergrund eingeleitet wird. Es wird mit einer relativen Änderung des Messsignals bei gleichzeitiger Probelastaufbringung auf die Höchstlast geschlossen, ohne diese zu erreichen.

1. PULL-OUT TESTS TO BE CARRIED OUT ON CONSTRUCTION WORKS

In the construction industry, the problem arises more and more frequently that existing fixings have to be assessed with regard to their load-bearing capacity, or the load-bearing capacity must be proven in an unknown anchor base that is not described in the approval. In these cases, the actual load values can be determined and documented with destructive pull-out tests. In [1], the requirements are described how the load values are to be determined by pull-out tests directly on the building. So far, the actual load values have always been recorded with destructive pull-out tests directly on the building, which means that the fastenings can no longer be used at this point and the damaged areas have to be repaired. Due to this problem, the investigations presented here have dealt with finding or developing a test method with which the non-destructive assessment of fastenings is carried out and the tested fastening can be used further.

2. ULTRASOUND METHOD

Ultrasonic waves are usually used in two different ways in non-destructive material testing, on the one hand for the detection of macroscopic, locally limited, critical flaws, such as cracks and delamination (defectoscopy) and on the other hand for material characterization, whereby mechanical properties and property changes of the microscopic basic structure, e.g. due to creep, wear and aging processes, but also due to production defects are in the foreground [2], [3]. Furthermore, in the field of material characterization, ultrasonic investigations were carried out on loaded concrete specimens [4], [5]. It was found that the load on the ultrasonically examined specimens has an effect on the ultrasonic signal.

2.1 The principle of ultrasonic based load prediction

When an anchor is loaded in concrete/masonry, stresses and microcracks form around this anchor, become more and larger with increasing load (Fig. 1). This effect has characteristic effects on an ultrasonic signal which is introduced into the anchor base in the immediate vicinity of the anchor. In order to be able to detect the entire stress or fracture state, the ultrasonic signal is introduced in a ring around the anchor using a sensor array probe. A convenient, integrated system is yet to be developed from the existing prototype. The procedure then proceeds as follows: the anchor is loaded in steps. At the same time, the relative change of the ultrasonic signal with respect to the load steps is evaluated. At a clearly identifiable load level at which the anchor base is not yet damaged or only negligibly damaged, the maximum load can be inferred without having to reach it. Thus, a relative change in the measurement signal with simultaneous test load application is used to infer the maximum load without having to reach it.

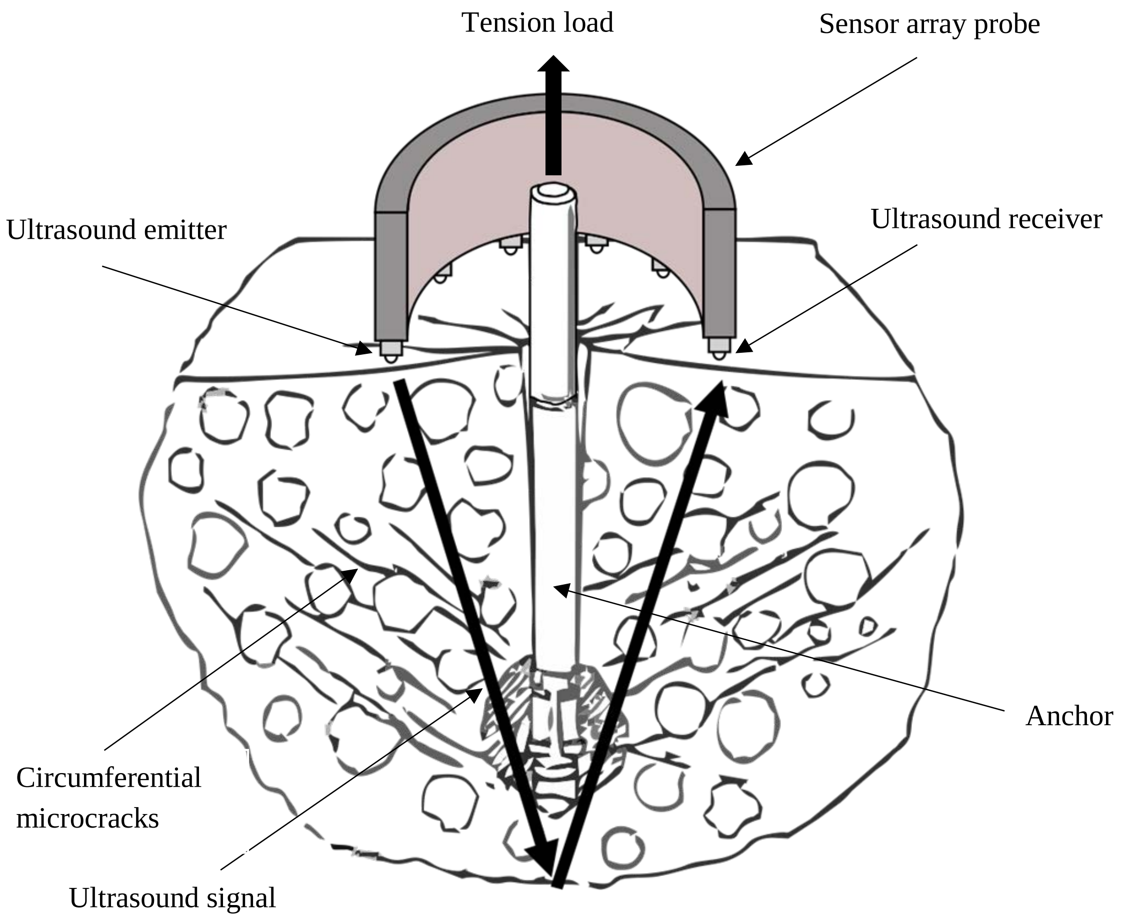

Fig. 1: Schematic representation of the ultrasonic signal path in the loaded condition of an expansion anchor in concrete

2.2 Solution approach for non-destructive load prediction

The investigations described here are a completely new approach for the non-destructive load prediction of fasteners in concrete, which has not been realized so far. The idea is the application of the technology described in [4], [5] to fasteners in concrete. The tested fasteners can remain on site and be reused. The core of the method is the mathematical processing of the measured signal by means of a window function and subsequent signal analysis with the Fast Fourier transform (FFT). By means of the FFT, the evaluation can be limited to a narrow frequency range in which the signal change due to load action can be clearly identified. The anchor base, the mechanism of action as well as the diameter and anchorage depth of the fastening have little or no influence on this frequency range and the signal shape. Measurements are done in reflection, while all previous investigations [4], [5] (in which, however, no fasteners were investigated) were done in transmission. The measurement in reflection has the advantage that the component to be examined must be accessible from only one side. This limited one-sided accessibility is given in the vast majority of cases when testing fasteners and is often the only possibility for testing in many structures, such as tunnel walls.

In previous investigations [4], [5] on ultrasonic signal changes due to load, the signal amplitude or sound velocity was evaluated. In the procedure to be used in this approach, an algorithm for filtering or weighting a signal part, a so-called window function, is first applied to the raw ultrasonic signal and then an FFT of the windowed signal is performed (Fig. 2).

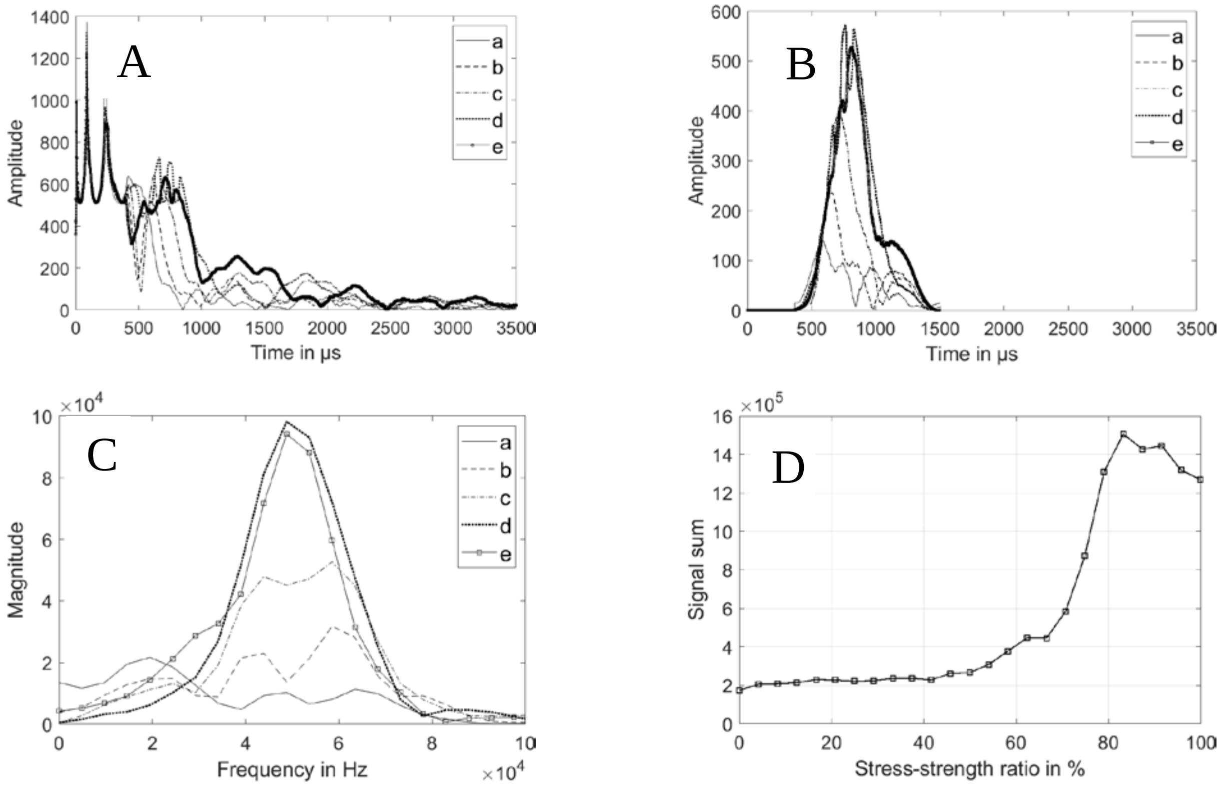

Fig. 2: Flow chart (from A to D) of signal processing in ultrasound-based load prediction of fasteners in concrete. Diagram (A) top left: A-scan (raw data) of a test at different load levels, a=0%, b=30%, c=40%, d=50%, e=60%. Diagram (B) top right: Signals from diagram (A) after applying a window function (Hann window) in the range 350-1500 µs. Diagram (C): Plot of signals from diagram (B) after an FFT has been applied. Diagram (D) bottom right: Correlation curve, integral values of the curves from diagram C at the respective load level (all load levels of the test are shown here)

Now the integral of the FFT is formed and the result is displayed as a function of the load. An increase of load causes an increase of the determined signal sum. The correlation curve obtained in this way must now be implemented in a program so that a real-time evaluation can be performed when a fixture is loaded. Thus, the procedure described above is executed in real time during the loading of a fixture. The values obtained in this way can be compared with the values already stored in the program, i.e. an existing correlation curve is "traced". The correlation curves (Fig. 4, bottom right) must be determined for different concretes and fasteners. If a load level can be clearly identified, the loading of the fastener can be stopped. The identification, which is also being worked out in the present examinations, is to be carried out in the load range below 50% in order to ensure the continued use of the loaded fastening. Below the load level of 50%, the anchoring base is only negligibly damaged and the full load-bearing capacity of the fastener is retained.

3. EXPERIMENTAL INVESTIGATIONS

At the present examinations, eight single shear-wave transducers with a medium centre frequency of 50 kHz, made by the company ACS-Solutions, are used. The transducers are Dry Point Contact (DPC) transducers, which has the advantage that no coupling medium is necessary. The sensors are pressed to the concrete surface with a constant load by means of a special spring construction (Fig. 3, left). In the prototype setup, the sensor brackets are glued on the concrete surface around the anchor with hot glue (Fig. 3, right).

So far, 24 tests have been carried out to prove the feasibility in principle. Fasteners with different mechanisms of action and different sizes were used and installed in concrete (C20/25) and solid sand-lime brick. The fasteners were loaded in stages until failure; the used loading setup is shown in (Fig. 4). At each load level, a measurement of the ultrasonic signals was done. For measuring the ultrasonic signals, the device A1220 Monolith made by ACS-Solutions was used. Based on the failure load, the respective load level in percent with the corresponding ultrasonic signals could be determined. The ultrasonic signals at the respective load levels were evaluated by means of window function and FFT as described above. The oscillation directions and the distances between the anchor and the transducers are shown in chapter 4.

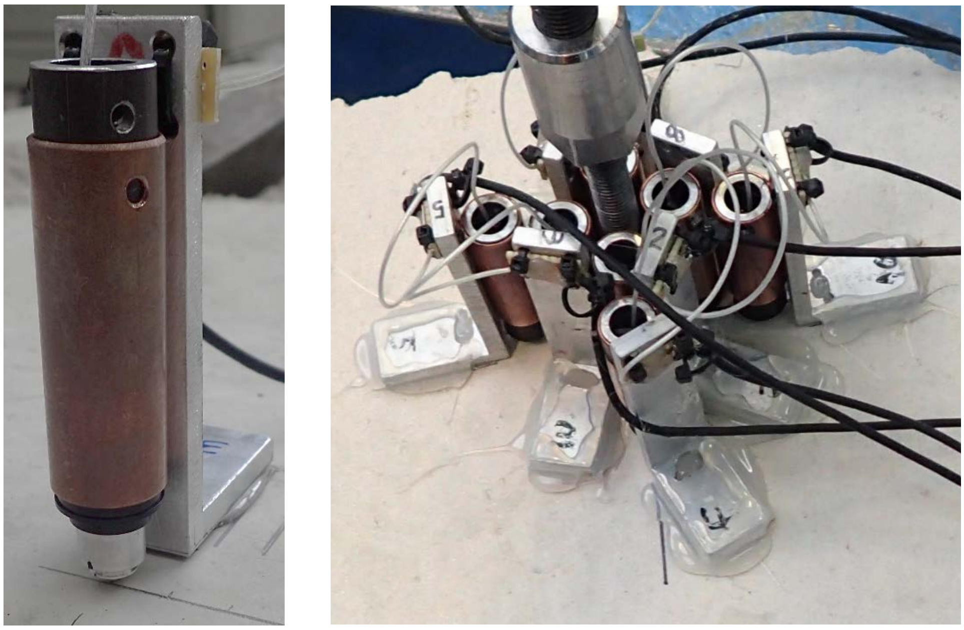

Fig. 3: ACS-DPC Transducers in the test setup. Left: Construction to ensure a constant contact pressure of the transducers. The spring in the tube is loaded by pressing down the upper inner tube piece. This piece is then fixed by a bolt that is inserted through a hole in the tube wall. Right: Transducers are glued with hot glue around the anchor on the concrete surface

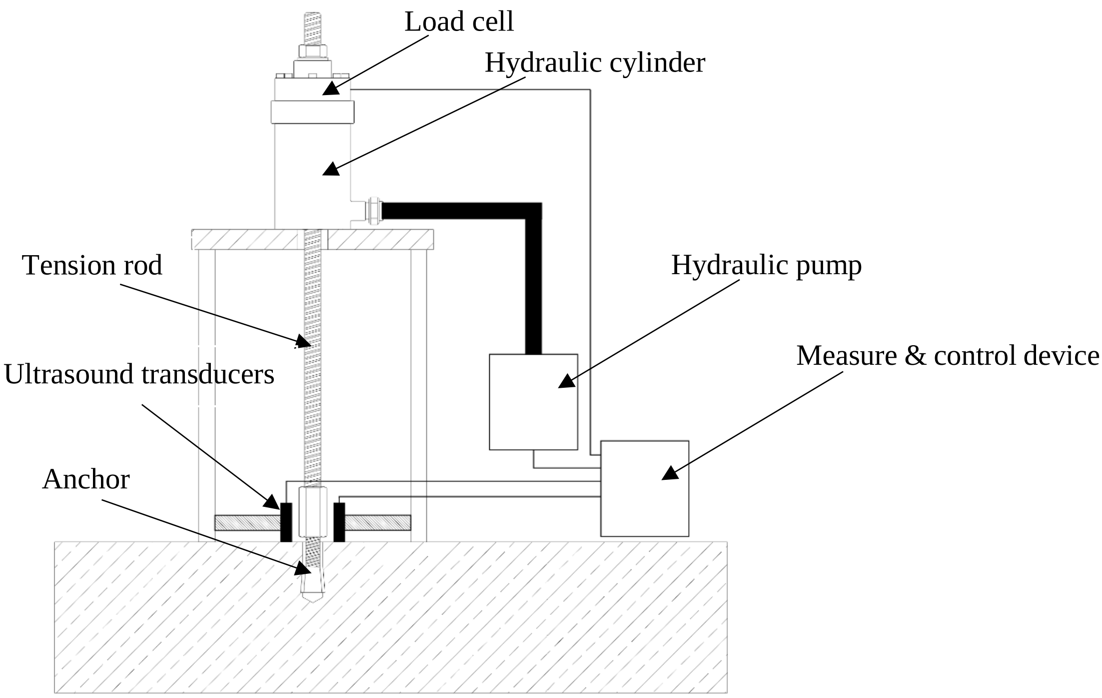

Fig. 4: Schematic load and ultrasound test set up used in the examinations

4. TEST RESULTS

The basic feasibility of the method was proven, the behaviour of the load-signal correlation curves of the 24 performed tactile tests were the same. An increase of load causes an increase of the determined signal sum.

The 24 tests included two series, V19 and V30, with five tests each that are directly comparable with each other. Here, the same conditions were given in terms of anchor, anchor base, and anchoring depth. A bonded anchor M16 with anchoring dept 80 mm and concrete C20/25 as anchor base was used. The arrangements, spacing and direction of oscillation of the transducers were varied and are shown in the figures below.

The development of stresses and the associated formation of microcracks, starting from the load application point, is described in [6]. These stresses and microcracks cause an increase in the energy respectively amplitude of the received ultrasonic signal, as was found in the investigations in [4]. In regard to these investigations, the strong increase of the signal sum beginning at a stress-strength ratio of approximately 40% well observable in (Figs. 5, 6, 8). In these figures, an abrupt drop of some curves after the load level of 50% can also be seen. This is probably due to the formation of incipient cracks from the microcracks and the associated signal weakening and signal redirection. Due to the inhomogeneities in the concrete and the not always perfectly vertically installed anchors, the cracking usually does not occur symmetrically and at different load levels. This could be the reason why the curves from measurements in the same test and with the same transducer positions always differ a bit from each other. Yet, they have the same behaviour up to the load level below approx. 50% (e.g. Fig. 5, V19.31 vs. V19.32). However, from the curves shown here, it is clear that the abrupt signal drop occurs only after the 50% load level. From previous investigations [6] it is known that the formation of the circumferential tension cracking that leads to the concrete cone failure, begins at this value. The influence of this behaviour on the signal depends on the actual formation and size of the cracks.

The fact that the course of the stresses and the associated microcracks have a direct effect on the ultrasound can also be seen very clearly when comparing (Fig. 5 with Fig. 7) or (Fig. 8 with Fig. 9). Here, the only difference was the distance between the anchor and the transducer.

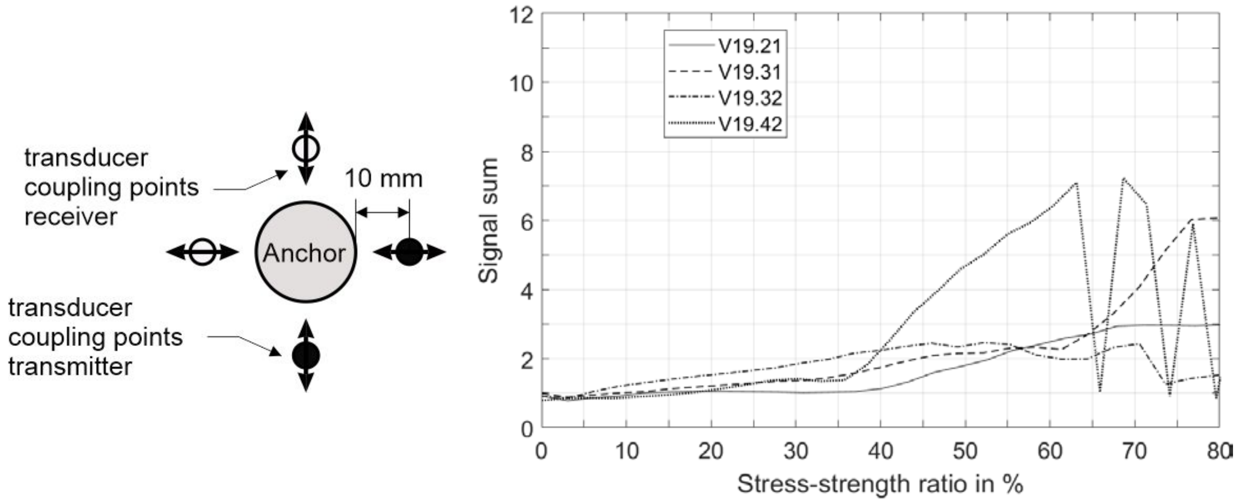

Fig. 5: Sensor arrangement and measurements of test V19.2, V19.3 and V19.4 (oscillation direction of the transducers "inline") transmitter(black) and receiver(white) each opposite

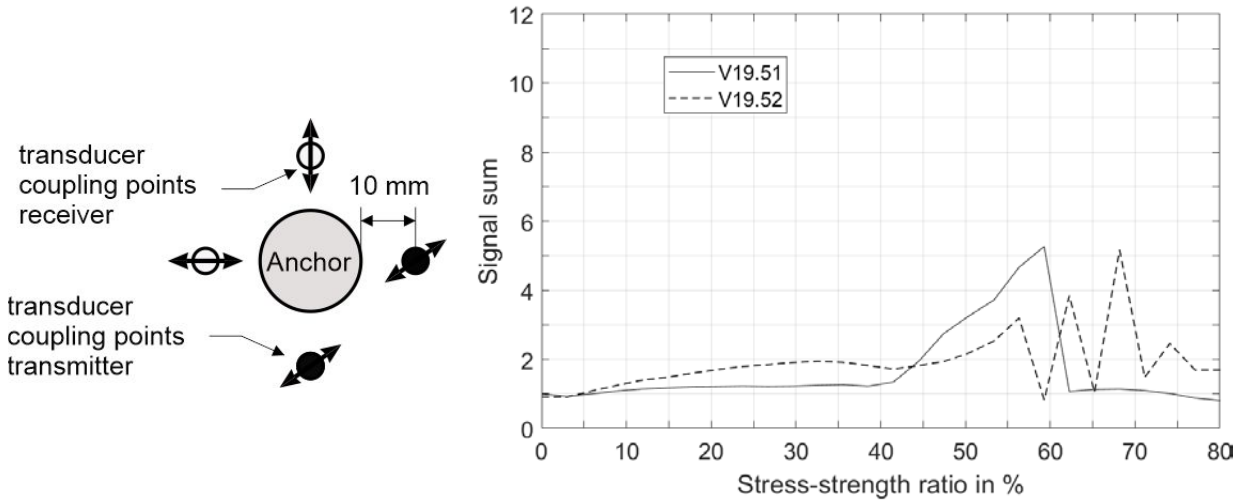

Fig. 6: Sensor arrangement and measurements of test V19.5 (oscillation direction of the transducers "in angle of approx.45°") transmitter(black) and receiver(white) each opposite

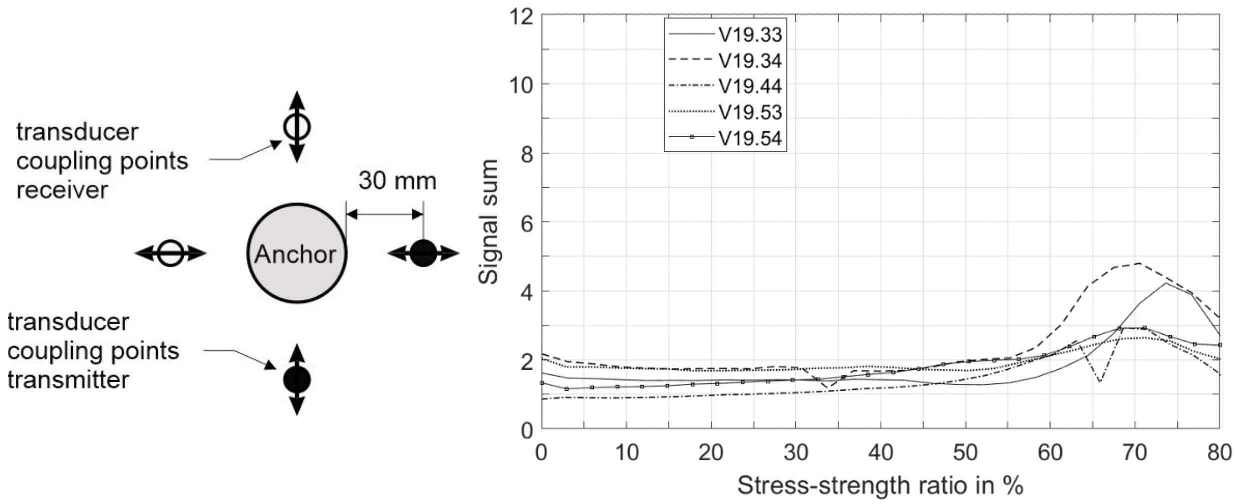

Fig. 7: Sensor arrangement and measurements of series V19.3 and V19.4 (oscillation direction of the transducers "inline") transmitter(black) and receiver(white) each opposite

It is easy to see that the signal increase occurs much later, after a load level of 50%, in the measurements with larger distance between anchor and sensor (Fig. 7, Fig. 9). From these facts it can be concluded that a position of the sensors as close as possible to the anchor is required in order to use the ultrasonic measurements for a load prediction. This is the only way to obtain a clear, load-dependent signal change at a low load level.

The oscillation direction of the DPC transducers also has an influence on the behaviour of the correlation curve, shown best at (Fig. 5 vs. Fig. 8). The signal increase in (Fig. 8) is clearly larger, steeper and can be seen earlier, but it is more scattered. Which oscillation direction is best suited for the load prediction must still be investigated in further studies.

In the V30 test series, the effects on the correlation curve were investigated when the ultrasonic signal is sent by several transmitters and detected by several receivers simultaneously. The influence of different transducer arrangements is also investigated. The aim was to improve the correlation curve in terms of a clear course with low scatter and clearly visible signal change at the lowest possible load levels. The basic transducer arrangement of test series V30 can be seen in (Fig. 10).

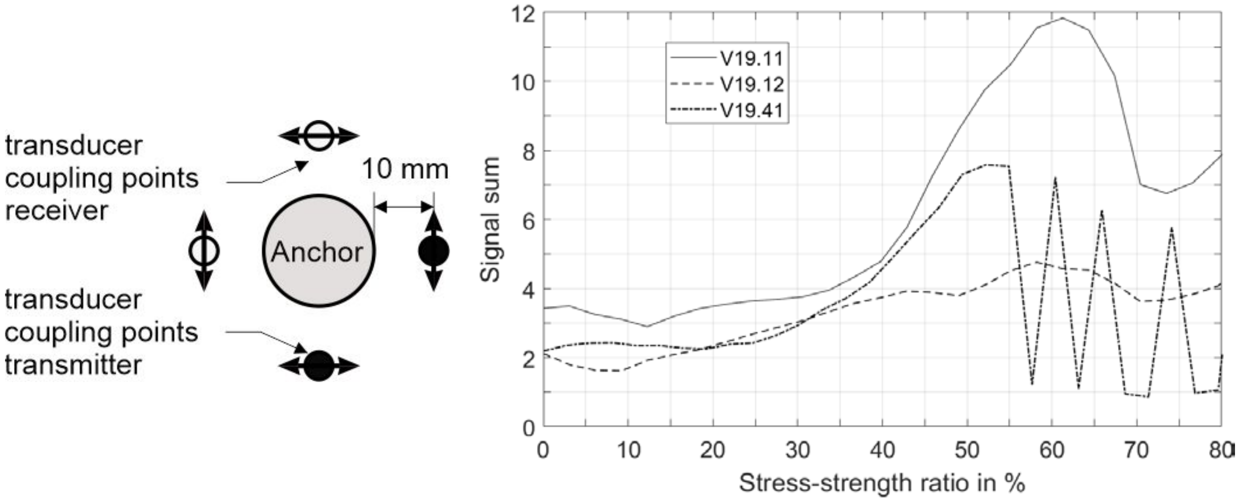

Fig. 8: Sensor arrangement and measurements of series V19.1 and V19.2 (oscillation direction of the transducers "parallel") transmitter(black) and receiver(white) each opposite

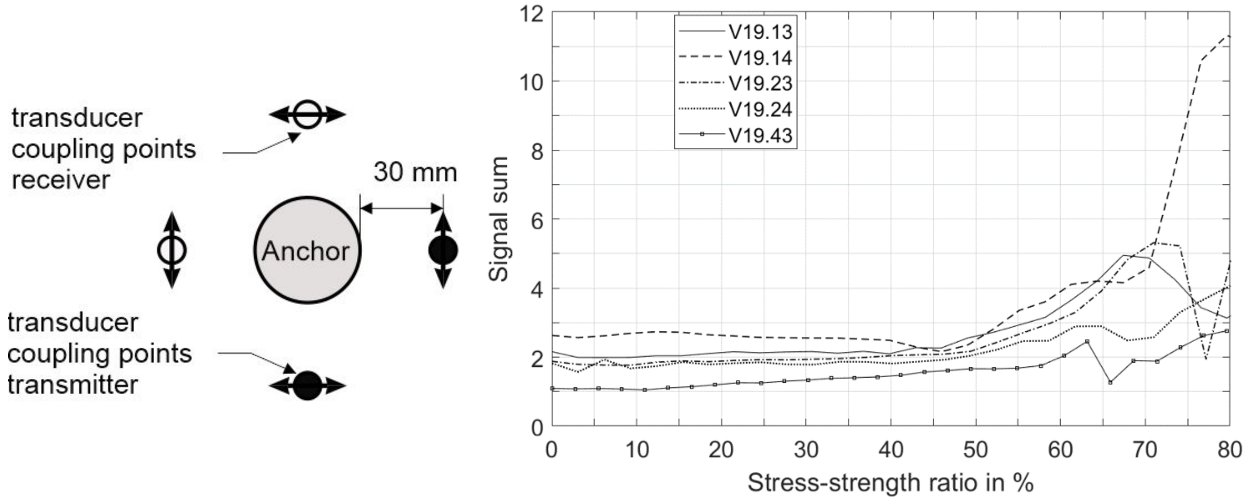

Fig. 9: Sensor arrangement and measurements of series V19.3 and V19.4 (oscillation direction of the transducers “parallel”) transmitter(black) and receiver(white) each opposite

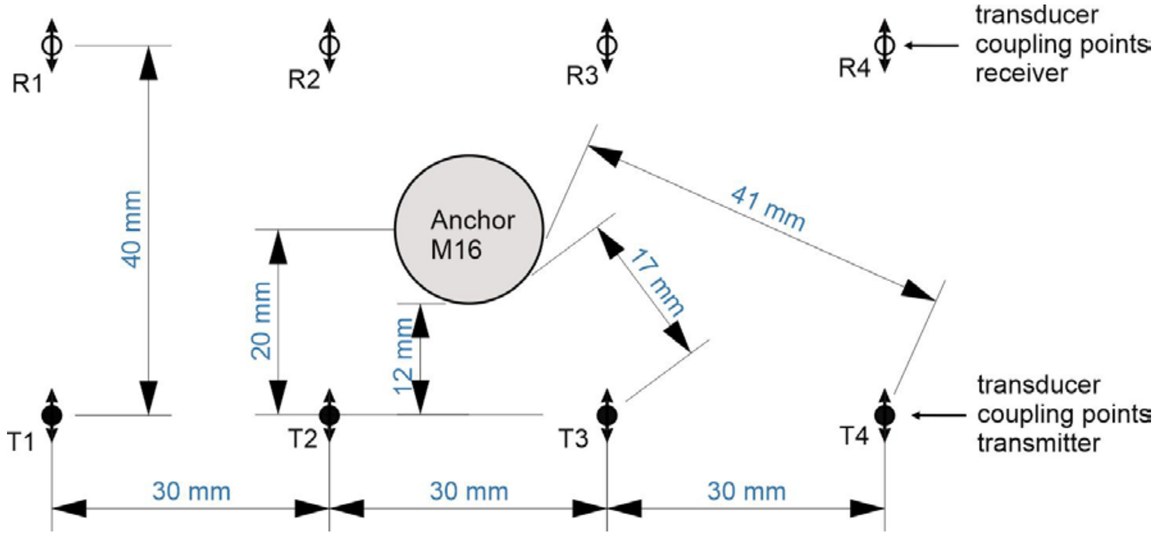

Fig. 10: Basic sensor arrangement of series V30, transmitter(black) and receiver(white) each opposite

The large influence of the sensor distance could also be determined for series V30. Looking at the arrangement in (Fig. 11), it seems logical that no load-dependent signal increase can be seen here, since the zone in which stresses and microcracks are generated by the load application is too far away. Whereas the measurements with the sensor arrangement in (Fig. 12) suggest an influence of the "stress zone" as it is located between transmitter and receiver. But apparently the sound field of the ultrasonic sensors is influenced very slightly with this arrangement and is not usable for our purpose.

The only difference between the measurements with the sensor arrangements (Fig. 12 and Fig. 13) is an additional receiver located closer to the anchor. However, this extra receiver brings a decisive difference as can be seen when comparing the measurement results of (Fig. 12 and Fig. 13). Now a signal increase in the load range from about 40% is clearly visible and the curves generated in this way could be used to create a load-signal change correlation curve. If this arrangement (Fig. 13) is further optimized, a signal increase could perhaps be detected from even smaller load levels.

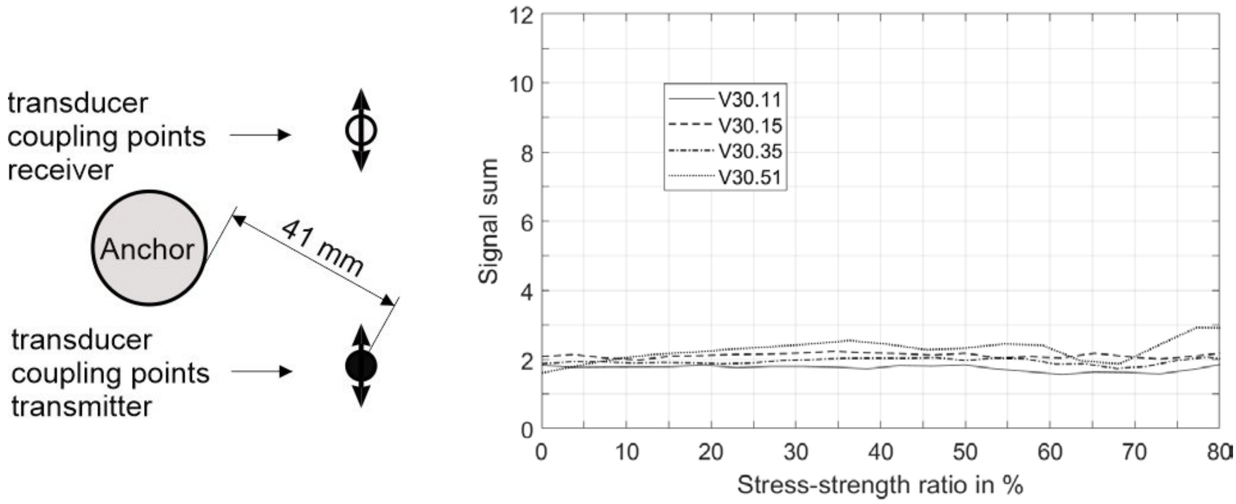

Fig. 11: Sensor arrangement and measurements of series V30 (oscillation direction of the transducers “inline”)

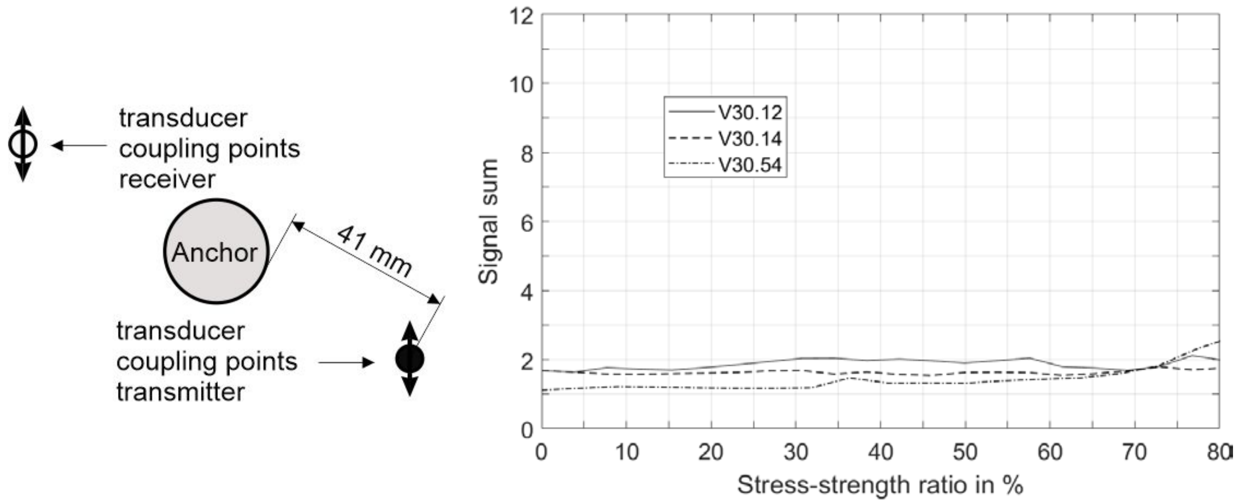

Fig. 12: Sensor arrangement and measurements of series V30 (oscillation direction of the transducers “shifted-parallel”)

In (Fig. 14), measurements are shown where all sensor arrangements had a sensor pair where the transmitter and receiver were directly opposite and had the smallest distance to the anchor. Compared to (Fig. 13), the signal rise starts much earlier and has a clear slope between 30%-60% load. This is most likely due to the proximity to the anchor and the "stress zone". However, the curves of the measurements also scatter a bit more.

The common feature of the measurements shown in (Fig. 15) is that in each case measurement were made with one transmitter at the smallest distance from the anchor and two receivers. At first glance, the arrangements look quite similar. On closer inspection, however, it can be seen that the distance between the transmitter and receiver is 10 mm greater in measurements (V30.42 and V30.43) than in measurements (V30.33 and V30.45). The fact that measurements are made along the "stress zone" (V30.33 and V30.45) and through the center of it (V30.42 and V30.43) does not seem to make much difference when the curves in (Fig. 15) are compared. However, since only two tests per sensor arrangement were performed here, no general statement is yet feasible. As already described above in the tests of V19, abrupt signal drops also occurred in the V30 series. However, as with V19, this only occurred after a load level of 50%, which indicates that damage to the anchor base only occurs after this load level. If the load prediction takes place in the range before 50% load and the load is then stopped, the method described here could be considered as a non-destructive test method.

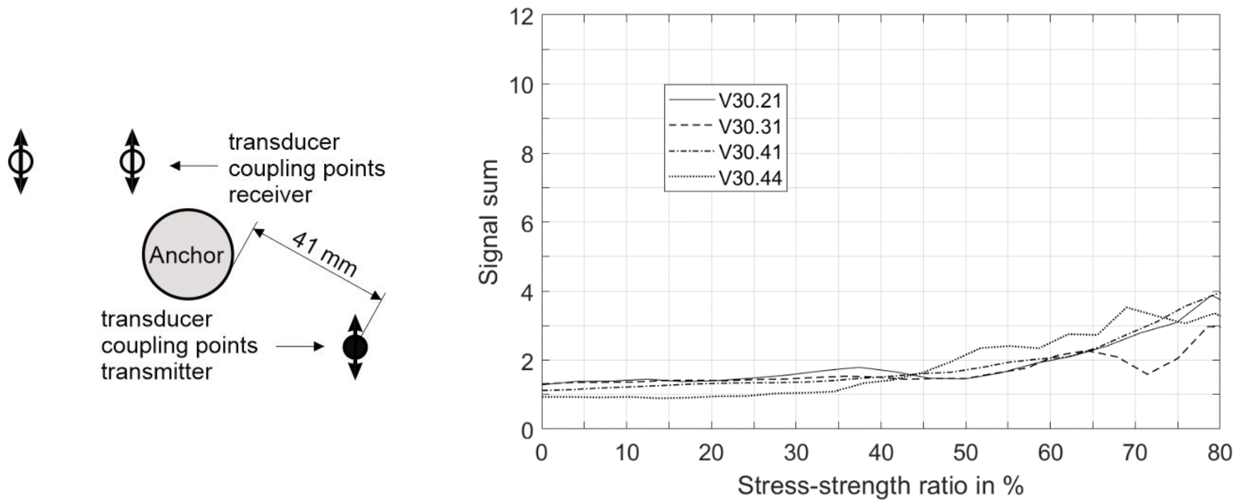

Fig. 13: Sensor arrangement and measurements of series V30 (oscillation direction of the transducers "shifted-parallel")

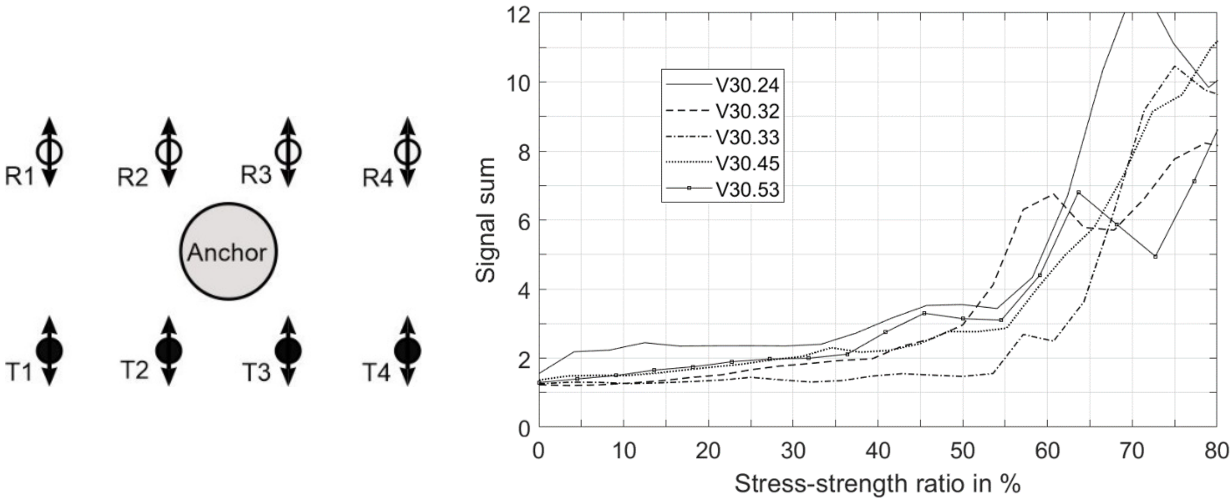

Fig. 14: Sensor arrangement and measurements of series V30 (oscillation direction of the transducers with the main influence on the measurements "inline", sensor arrangement in table 1, below)

Table 1: Sensor arrangement of the measurements in Fig. 14

	T1	T2	T3	T4	R1	R2	R3	R4
V30.24			X	X			X	X
V30.32			X	X	X	X	X	
V30.33			X				X	X
V30.45			X				X	X
V30.53			X		X		X	

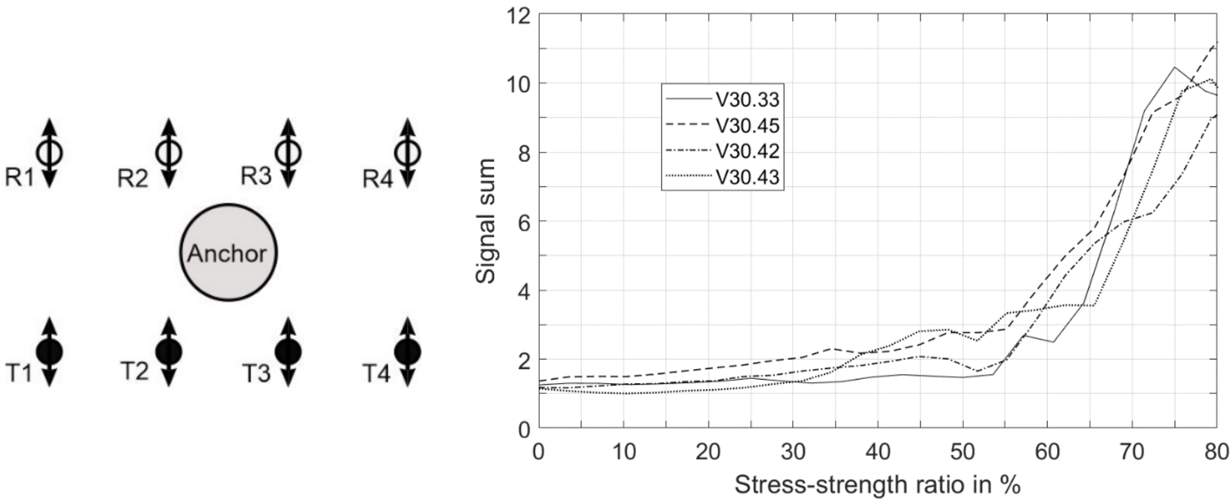

Fig. 15: Sensor arrangement and measurements of series V30 (oscillation direction of the transducers "shifted-parallel & inline", sensor arrangement in table 2, below)

Table 2: Sensor arrangement of the measurements in Fig. 15

	T1	T2	T3	T4	R1	R2	R3	R4
V30.33			X				X	X
V30.45			X				X	X
V30.42			X		X	X		
V30.43			X		X	X		

5. SUMMARY OF TEST RESULTS

The tests show that it is possible to influence the measurements with a suitable sensor position in such a way that signal-load correlation curves are obtained which can be used for load prediction.

The distance between the anchor and the sensor has the greatest influence. If the distance is too close to the anchor, a signal change due to the anchor load can be detected very early, but the correlation curves then also scatter quite strongly. If the distance is too large, no or only a very small signal change due to the anchor load is detected. If the distance is selected optimally, the correlation curves scatter little and the signal increase due to loading can be identified well in a range before 50% loading and used for load prediction.

The influence of the oscillation direction of the sensors could not yet be clearly determined; there is need for additional investigation here. When looking at the curves of V19 of the "parallel" and "inline" aligned sensors, a clear difference is visible. In contrast, no difference can be seen when comparing the curves of V30.

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