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REVIEW

High-Frequency Vibration Tests for Cement Concrete for Machine Tools (300–500 Hz)

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Abstract

Purpose Occasionally, cement concrete is used in the machine tool industry to reduce costs and improve the dynamic behavior of the machine. Due to a lack of information on the material behavior of cement concrete under dynamic loads with high frequencies, a test bench has been developed based on the principle of resonance at WZL. This paper presents the further development of the test bench to improve the testing and the evaluation of the results. Furthermore, the execution of dynamic tests with alternating loads in a high-frequency range of specimens of ultra-high-performance concrete (UHPC) is described. The aim of the described tests is to investigate the influence of frequency range and the autoclaving post treatment on the limiting load of UHPC specimens.

Methods To be able to react in situ to a change in the natural frequency of the system and thus to ensure a consistent level of dynamic loading, a control and regulation method was developed and implemented into the test bench. Additionally, dynamic tests of UHPC specimens with different load levels and frequency ranges are executed on the test bench also using the automatic test regulation. The UHPC specimens were autoclaved after production to achieve high material properties and to anticipate shrinkage deformation. The amplitudes of load applied to the specimens were determined as function of the previously determined static tensile strength. The amplitudes of load tested were set between 37 and 50% of the static centric tensile strength. The frequencies tested were at about 326 Hz respectively 475 Hz and therefore lie in a high-frequency range.

Results First tests with the new developed automatic test regulation show, that a consistent level of dynamic load can be achieved. The dynamic long-term tests of autoclaved UHPC specimens with different load levels and frequency ranges show, that the limiting load for alternating forces on UHPC in a high-frequency range lies in the area of 40% of the static centric tensile strength. These results confirm the conclusions of other researchers for the lower-frequency ranges and expand the conclusions to the examined frequency ranges. With the test set-up and the automatic test regulation, fatigue tests can be performed 40 to 50 times faster than with conventional test set-ups (with frequencies at about 10 Hz as a reference).

Conclusion By implementing an automatic adaption of the actual resonance frequency of the system, a consistent level of dynamic load on the specimens could be achieved. Furthermore, it can be stated, that the limiting load for alternating forces on UHPC at high frequencies is mostly unaffected by the actual range of high frequencies or the follow-up treatment of the specimens. Future research should issue a more detailed localization of the limiting force as well as other post-treatments and a transfer to the application of UHPC in real parts of machine tools.

Keywords Machine tools · Materials · Cement concrete · Vibration testing

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Introduction

The basic characteristics of machine tools are significantly determined by the design and the arrangement of the structural components. Also, the material used for the structural components has an important influence on the design and dimensioning of the machines. The materials predominantly used for machine tools are steel and cast iron. However, there are increasing efforts to substitute these through alternative

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materials to reduce costs and/or enhance the static, dynamic or thermal behavior of the machines. An overview of the research in the field of materials used for machine tools can be found in [1].

One of the alternative materials for machine tool components is cement concrete. With its comparatively low material costs and high material damping and due to a lack of raw materials in the beginning of the twentieth century, there have already been efforts to use cement concrete instead of steel or cast iron for turning machines [1]. Nevertheless, because of the multiple challenges in manufacturing and application and due to the development of polymer concrete, the research regarding cement concrete in machine tools was paused for a time. However, since the development of ultra-high performance concrete (UHPC), investigations regarding this topic are increasing again.

Nowadays cement concrete is occasionally used for machine beds or structural parts of machine tools with low-level loads, such as coordinate measuring machines or precision machines [1]. However, there is still a lack of fundamental research regarding the dynamic characteristics of cement concrete for use in machine tools. Especially the behavior under alternating dynamic loads in a high-frequency range (> 200 Hz) needs to be investigated. This is because in the field of building engineering, fatigue tests of cement concrete are mostly done using pressure swell tests in a low-frequency range (e.g., at about 10 Hz) [2–6]. These low test frequencies currently used in construction mean that tests are usually limited to 2 million load cycles and the test duration is very long. Tests with load cycles up to 10^8 in an alternating range and frequencies > 200 Hz, as they occur in machine tools, have been poorly researched so far. The results of [3] show, that the dynamic fatigue strength of plain concrete without reinforcement under compressive loads lies at about 50–60% of the static compressive strength. The development of the behavior of concrete in fatigue tests is characterized by three different phases: the crack-formation phase (phase I), the stable crack-propagation phase (phase II) and the unstable crack-propagation phase (phase III) [2]. Rare investigations of the dynamic fatigue behavior under tensile loads show, that the course of the fatigue behavior of cement concrete is similar to that under compressive loads and can also be described by the three characteristic phases [7–10] (see also Fig. 1). According to [11, 12], the dynamic fatigue strength under tensile load also lies in a range of 40–50% of the static tensile strength of cement concrete and different post-treatments have no significantly negative effect on the fatigue strength.

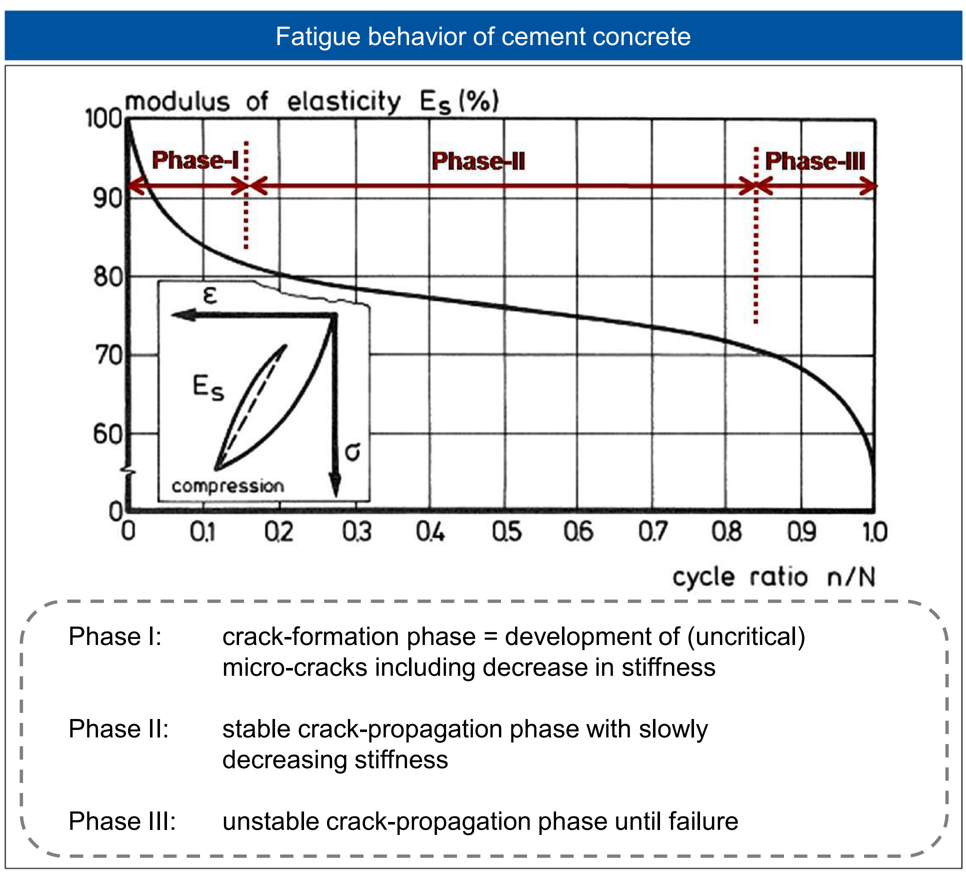


Fig. 1 Phases of fatigue behavior of cement concrete according to [2]

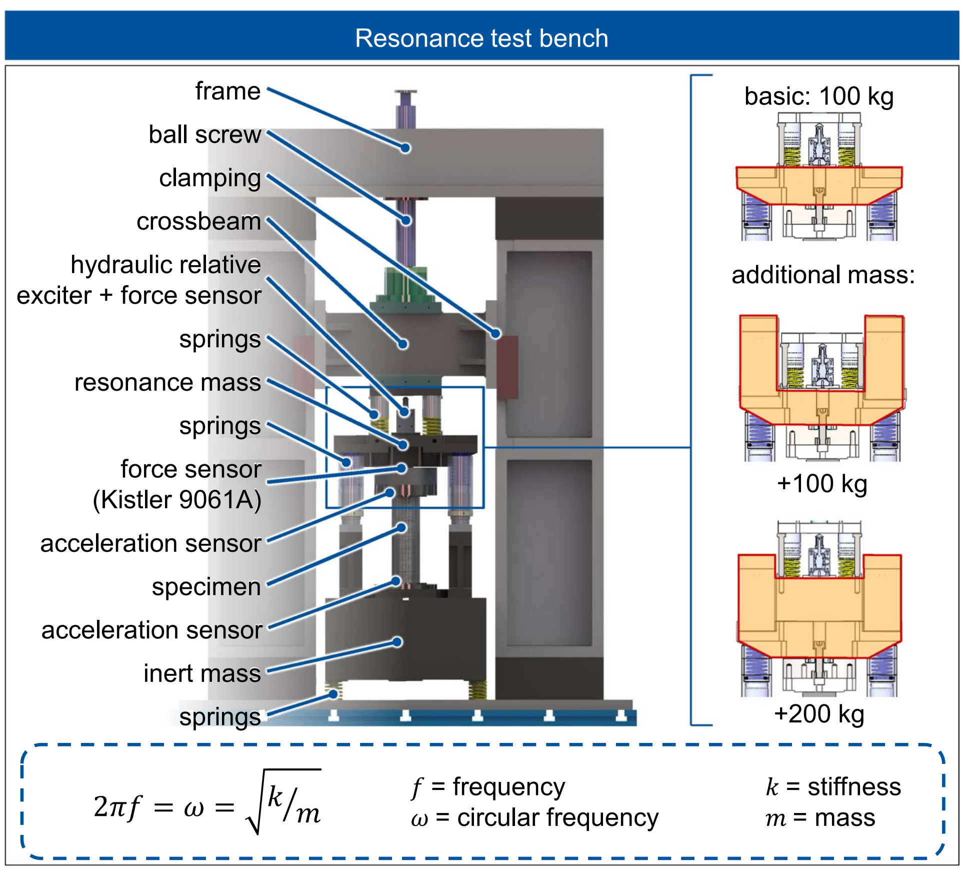
Description of the Test Bench

To investigate the behavior of cement concrete under alternating dynamic loads in a high-frequency range, a test bench has been developed at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University based on the principle of resonance. In this test bench, specimens of cement concrete can be applied with alternating loads in a frequency range up to 550 Hz and with amplitudes of force up to 25 kN. The set-up of the test bench and first tests with different types of cement concrete have been described in [12–14], but a summary is also given in this article.

Basically, the test bench consists of a frame, a hydraulic exciter, a resonance mass and an inert mass (see Fig. 2). The hydraulic exciter is placed relatively between the frame and the resonance mass and induces vibrations of the resonance mass. The specimens of cement concrete are mounted between the resonance mass (on the upper end) and the inert mass (on the lower end). To ensure that the resonance mass is able to vibrate, it is elastically mounted on four springs which are placed on the inert mass. When the resonance mass is vibrating, this vibration is induced into the specimen and leads to a compression respectively an elongation of the specimen due to its fixation on the inert mass. The whole system of inert mass, specimen and resonance mass is decoupled from the environment by additional springs and can be approximately described as an oscillator with a single degree of freedom. By exciting the resonance mass with the natural frequency of the system, an amplification of the force applied to the specimen can be achieved. This way it is possible to use exciters (such as the mentioned hydraulic exciter), which are usually used to investigate machine tools. [13]

The preload of the specimen can be adapted by a cross-beam, which is part of the frame and can be moved up and down by a ball screw. The springs between the resonance mass and the inert mass are installed in preload, which leads to pre-tension of the specimen. Therefore, the cross-beam is compensating this preload when it is moved downward respectively turning the pre-tension of the specimen into a pre-compression when it is moved further downward. [13]

Because—as described above—the vibrating system of the test bench can be described as an oscillator with a single degree of freedom, it is obvious that the natural frequency depends on the total stiffness and the vibrating mass. With a given stiffness of the system of test bench and specimen, it is therefore possible to influence the natural frequency by adapting the vibrating mass. As can be seen in the equation in Fig. 2, increasing the vibrating mass leads to a descent



$$2\pi f = \omega = \sqrt{k/m}$$

Fig. 2 Test bench for alternating loads on specimens of UHPC in a high-frequency range according to [13] of the natural frequency and vice versa. Therefore, different additional masses are existing, that can be mounted on the resonance mass to increase the vibrating mass. This way the frequency range of the vibration tests can be adjusted. Nevertheless, the definite natural frequency of the tests depends on the material and the form of the test specimen. This is, because, due to its position in the direct force flux, the stiffness of the specimen directly influences the total stiffness and therefore the natural frequency of the system.

During the vibration tests, various integrated sensors in the test bench collect different types of data. A force sensor at the hydraulic exciter measures the exciting force, while another force sensor measures the amplified force induced into the specimen of cement concrete. This second force sensor is integrated between the resonance mass and the specimen and is preloaded by a compression of 80 kN. By analyzing the ratio between the two force signals, the factor of amplification depending on the frequency of excitation, can be determined. The factor reaches its maximum at the natural frequency of the system.

Additionally, two uniaxial acceleration sensors are mounted on the adapter plates of the specimen (one at the top and one at the bottom of the specimen). By integrating the acceleration signals two times, the relative elongation respectively the relative compression of the specimen can be determined. Figure 2 shows the test bench and its components as well as the different possible additional masses.

As it is mentioned above, the natural frequency of the vibrating system depends on the value of the resonance mass on the one hand and on the other hand on the form and stiffness of the specimen. Therefore, the natural frequency has to be determined at the start of each new test. This is achieved by measuring the frequency response function (FRF) of the system, by exciting it with a sinusoidal-sweep signal induced by the hydraulic exciter. Afterward, a sinusoidal signal with the determined natural frequency of the system is configured for the exciter and the amplitude of the exciter is adjusted in a way that the required force is induced into the specimen. The duration of each test is set to 10^8 load cycles, because the usual duration of 10^6 load cycles (considered e.g., for fatigue behavior of metals) is reached in less than an hour when using the interesting range of high frequencies. Using a duration of 10^8 load cycles, the tests last about two to three days.

It can be assumed, that the stiffness as well as the mass of the test bench stays constant for each test. Therefore, changes of the natural frequency during the test are caused by changes of the stiffness of the specimen due to microcracks in the material. However, a change of the natural frequency also leads to a decrease of the amplification factor and therefore to a decrease of the force induced into the specimen. Because of this, it is necessary to control and adapt the natural frequency of the system as well as the amplitude of the force induced into the specimen during the tests. Adjusting the load manually leads to an inconsistent and mostly lower load than required (especially in the night and on weekends). Therefore, the existing program for the recording of the measured values is adapted and enhanced by an automatic control and regulation of the force and the natural frequency. The measurement strategy realized with this program is explained in the following.

Measurement Strategy with Program for Automatic Test Regulation

During the long-term tests with automatic control of the force and the natural frequency, different stages occur that each leads to different modes needed. Figure 3 shows the structure of the program for the automatic test regulation. The possible modes of the test are:

- manual mode without automatic control of the level of load for initial phase of long-term tests (phase I from Fig. 1)
- normal vibration test including storing the measured data
- measurement of the frequency response function parallel to the current vibration test
- adaption of the natural frequency or amplitude of the excitation signal
- finished test after reaching the maximum alternation of load or premature end of test

During the first phase of the vibration tests, the setting behavior of the cement concrete leads to a fast decrease of the natural frequency (see phase I in Fig. 1). In this phase, the required force would not be reached for some time, because the speed of the adaption process is limited. Therefore, the vibration tests are first carried out in the original manual mode, without automatic control of the level of load. This means a sinusoidal-sweep signal is generated to excite the resonance mass and the specimen and the measurement values from the sensors described above are used to determine the current FRF and the initial natural frequency of the test. As described above, a sinusoidal signal with the determined natural frequency is generated afterward and the amplitude is adjusted manually at the control unit for the hydraulic exciter. When a drop of the amplitude of force is noticed, a new FRF measurement is started to manually adapt the natural frequency. After the setting of the material is done (which takes place in the first minutes of the vibration tests), the automatic control of the force can be turned on.

When executing the vibration test with automatic force control, the signal for the exciter with the current natural frequency and given amplitude is generated and the measurement values are continuously acquired and stored.

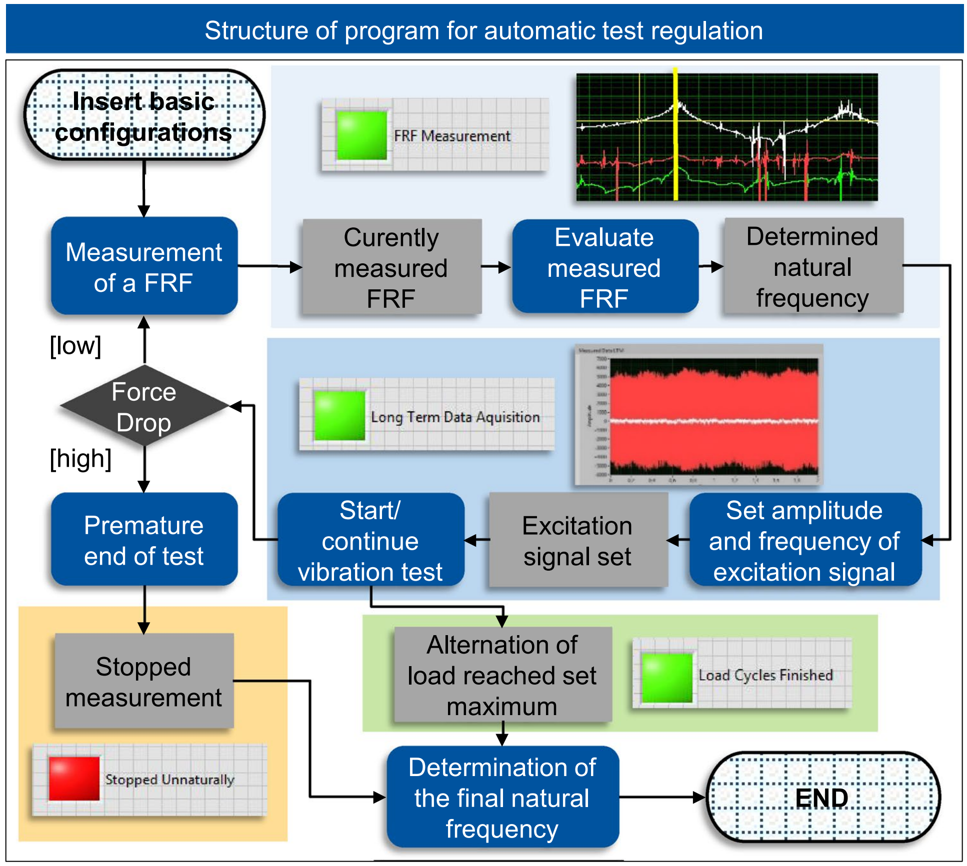


Fig. 3 Structure of the program for automatic test regulation

Additionally, the current number of load cycles is determined to control the duration of the vibration test.

To control the level of force during the test, for each interval of measurement data, it is checked, if the amplitude of force differs less than 7% from the required load and that no significant and sudden losses of amplitude take place. A sudden loss of amplitude could be caused by macro-cracks in the cement concrete or by other important malfunctions of the vibration tests and therefore, this is a criterion for a premature end of the vibration tests. If only an amplitude difference of more than 7% from the required force is detected, a new FRF measurement is started automatically and the control of the force is paused. This means, that again, only the measurement values are acquired and stored.

Meanwhile, a white noise signal is added to the sinusoidal signal for the exciter and the current time is stored in a protocol for the FRF measurements. When the excitation with the new white-noise-added signal has lasted for one second, so that the system had time to settle, the program is put into the mode of FRF measurement. This means, that ten packages of measurement data are collected and used to determine an averaged FRF and automatically detect the new natural frequency. To prevent a false detection of natural frequency, the detection only takes place in a previously determined range of frequency, which can be configured before starting the vibration test. Afterward the newly measured FRF is stored separately and the new natural frequency is added to the measurement protocol. Then, the program switches again into the mode, in which only the measurement data are acquired and stored and one of two different possible cases is executed: the adaption of the natural frequency or the adaption of the force amplitude.

If the difference between old and new natural frequency is more than 1 Hz, a stepwise adaption of the excitation frequency has to take place. The frequency can only be adjusted in steps of 1 Hz, because otherwise problems with the signal control unit cause impulse-like breaks in the excitation signal. If the difference between old and new natural frequency is less than 1 Hz, the frequency can directly be adapted and the mode for adapting the amplitude can be started. The adaption of amplitude after setting the new natural frequency is necessary, because a change of the amplification factor of the force is possible with the new excitation frequency.

First, the control of the force is turned on again and the ratio of required and current force is used to determine a scaling factor for amplitude adaption. However, if the value of the scaling factor is too high, the same problems occur as if the frequency is adapted with steps bigger than 1 Hz. Therefore, a maximum and a minimum value for the scaling factor can be configured. This limits the scaling factor used for the adaption of the amplitude, but also makes it necessary to adapt the amplitude in iterative steps until either the required force is reached or no change in the force amplitude over a number of consecutive steps is detected. In the latter, it is to assume, that the maximum amplitude of the hydraulic exciter is reached. In this case, an automatic note is stored in the protocol and the vibration test runs with the current amplitude until a new FRF is measured. This can again lead to another change of the force amplification factor and therefore it is possible, that the required force can be reached again.

The excitation signal is stopped after either the maximum number of load cycles is reached or the test is stopped manually or automatically. After that, the remaining intervals of measurement data are stored and the program is stopped.

First tests with active automatic test regulation show that the program significantly improves the progress of the applied force amplitude on the specimen. The progress of force takes a much more continuous course and is significantly closer to the required force amplitude. Figure 4 compares the results of two long-term tests—one without automatic test regulation and one with active automatic test regulation. Both specimens were post-treated with the autoclaving process and the required forces in both tests were similar to each other. The reason why the forces are not identical lies in the natural variance of the centric tensile strength between different batches of cement concrete. And, as described in detail below, the applied levels of load are determined as percentage of the centric tensile strength.

The software used for the automatic test regulation is LabVIEW, because it offers ready-to-use interfaces for the communication with the measurement systems used to collect the data and to control the hydraulic exciter. The program offers input possibilities for the required configurations for the vibration tests as well as the buttons to start and end the tests (see Fig. 5). Additionally, signal lamps and diagrams with the curves of the current measured values visualize the state of the running test.

Design of Experiments of Long-Term Tests

The concrete specimens for the long-term tests were manufactured and post-treated at Ibac. The concrete selected was an UHPC with a maximum grain size of 8 mm. Cylinders with a diameter of 100 mm and a height of 300 mm were produced for the investigations and then ground plane parallel. Of each batch of specimens, three specimens were used to determine a mean value for the centric tensile strength. This value is used to determine the maximum strain and thus the force amplitude applied on the specimens during the

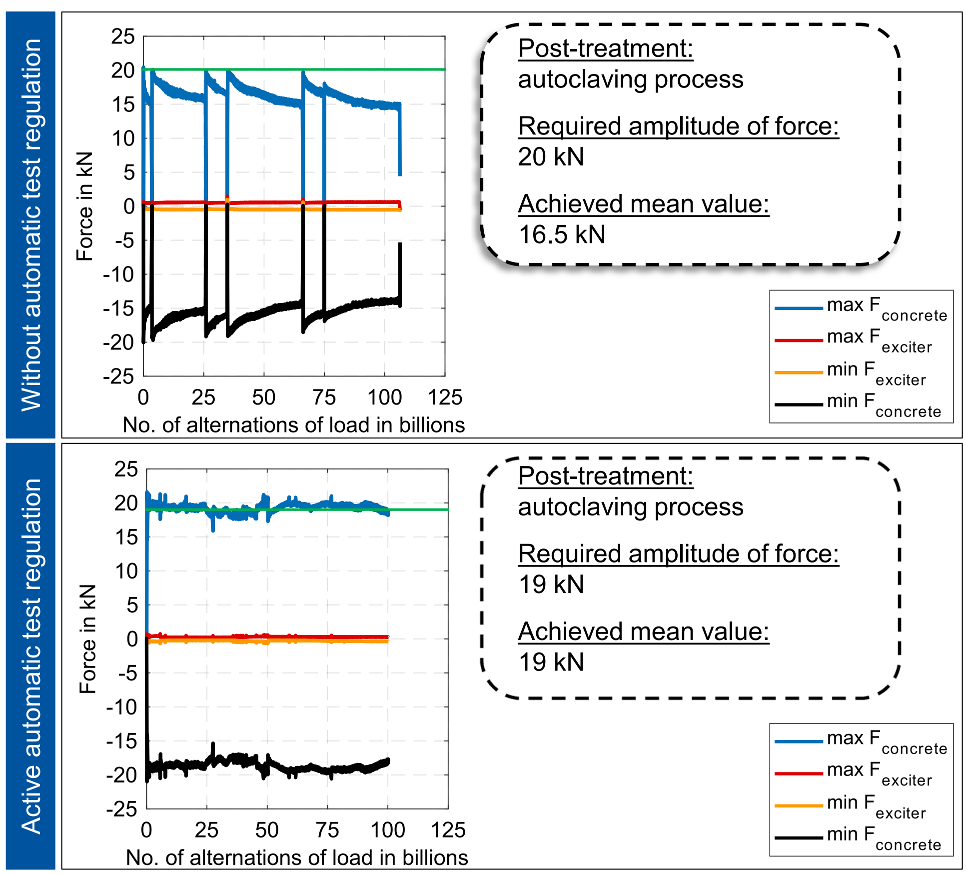


Fig. 4 Validation of the program for automatic test regulation

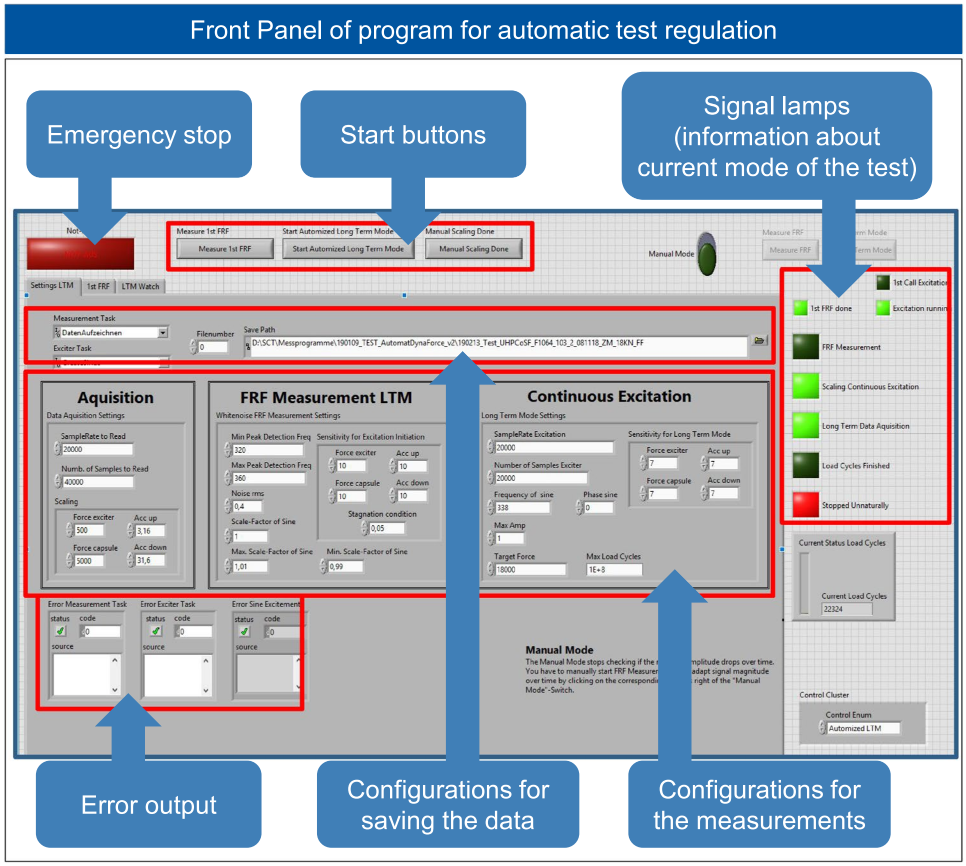


Fig. 5 Front Panel of the program for automatic test regulation

long-term tests. Afterward, each specimen is provided with two adapter plates made of steel (one at the top and one on the bottom of the specimen). The connection between the adapter plates and the specimen is ensured by a 2-component epoxy resin adhesive. The plates were additionally sand-blasted before bonding to achieve a greater bonding surface. The adapter plates are necessary to attach the specimen to the resonant mass at its top and to the inert mass at its bottom. When installing the specimen in the test bench at WZL, it is put under a compression of 2 kN to prevent damages due to tension while tightening the screws at the adapter plates. Afterward, the compression is relieved to get the required neutral preload of the specimen. To start the long-term test, the initial natural frequency of the system is determined and the required dynamic load is set. The test is terminated when 10^8 cycles of load were reached or a failure of the concrete specimen occurred before. At the end of the test, the final natural frequency is determined and if no visible crack of the specimen has occurred, the remaining tensile strength of the specimen is determined at Ibac.

In previous investigations described in [12–14], specimens made of normal cement concrete (NC) and UHPC (with and without added steel fibers) were tested with different load amplitudes. The results indicate that a dynamic load between 40 and 50% of the centric tensile strength leads to a significant damage of the specimens before reaching the maximum number of load cycles. This is in accordance with the results of other researches in the field of long-term tests with alternating loads (with lower frequency) [11].

High demands are placed on the concrete for use in machine tool components, particularly in the areas of dimensional stability, tensile strength and fatigue. Since the concrete shrinks because of hydration, especially in the first few days after production, various curing options were tested in [12]. The focus was on heat treatment and autoclaving. Autoclaving greatly increased the tensile and compressive strength of the concrete. In addition, the high temperatures of up to 190 °C allowed hydration to be accelerated and shrinkage deformation to be anticipated [12].

Therefore, further long-term tests at the WZL test bench with the new automatic test regulation were conducted with autoclaved specimens to investigate the long-term resistance to dynamic loads. Because of the high effort regarding test runtime, the focus was on UHPC specimens with a maximum grain diameter of 8 mm without steel fibers. The material mixture is given in [12].

Two different levels of load were used to investigate the influence of the test frequency. To adjust the different frequencies, the resonant mass was adapted by an additional mass as described above. Resonance masses of 100 kg and

200 kg were selected for the tests. The resonant mass of 100 kg leads to an initial natural frequency of the system of about 470 Hz and that of 200 kg to about 320 Hz. The amplitude of alternating load for the tests was set to a range of 37–40% and 41–45% of previously determined centric tensile strength. It is necessary to define a range for the level of load because of the tolerance given for the adjustment of load in the automatic test regulation. For reasons of comparison with the previous investigations, further tests are conducted with autoclaved specimens with the two levels of load, but without the automatic test regulation. In addition to that, long-term tests with the new automatic test regulation and the two different load levels were performed on specimens that were not autoclaved but stored under water after demolding until the seventh day and then at 20 °C and 65% rel. humidity until testing (L7). Finally, tests were conducted with automatic test regulation, a resonant mass of 100 kg and a load level of 47–50% of the centric tensile strength.

The determination of the centric tensile strength as well as the performance of fatigue tests on concrete specimens is complex from a test engineering point of view, especially in force application. In addition, concrete is an inhomogeneous material, which means that comparatively high scatter can occur in the tests. Therefore, six specimens of a batch were tested. Only in the case of series L7 with a lower amplitude of load, three specimens were investigated. Table 1 provides an overview of the long-term tests conducted at WZL.

Evaluation of the Test Results

There are no fixed criteria so far defining when a part made of cement concrete is not usable for machine tools anymore, apart from visible and gaping cracks. However, during the long-term tests on the test bench, no visible cracks occurred in the specimens, even if the target force suddenly dropped and could not be reached anymore and the tests had to be terminated before reaching the maximum number of load cycles. Even if the maximum number of cycles is reached, it is not obvious in which phase (see Fig. 1) of the fatigue behavior the test has been ended. Theoretically, it is possible that the number of 10^8 load cycles lies shortly before the end of phase II and that phase III, where the visible and gaping cracks would occur, would be reached with some more cycles of load. Hence, other criteria had to be determined to evaluate if a specimen is damaged in the course of the long-term tests.

Table 1 Design of experiments for long-term tests with alternating loads on specimens of UHPC

Levels of load (% of centric tensile strength)			37–40%	41–45%	50%
Post treatment	Resonant mass [kg]	Automatic test regulation			
Autoclaving	100	–	6	6	-
	100	yes	6	6	6
	200	yes	6	6	-
L7	100	yes	3	6	6

To evaluate the long-term tests, different aspects of the measured values are considered. As described above, the remaining tensile strength of the specimens after the end of the long-term test was tested at Ibac and the percentage deviation to the mean value of tensile strength of the tested batch is analyzed. Additionally, the natural frequency of the system (specimen + test bench)—as an indicator for the stiffness of the specimen—is used to evaluate if a specimen is damaged during the long-term tests. The stiffness at the Tool Center Point (TCP) of machine tools is an important criterion for the usability of the machine. Hence, the initial natural frequency of each test is compared to the value of the natural frequency measured directly after the test and the percentage deviation is calculated. In addition to that, the measured accelerations at the top and the bottom of the specimen are used to calculate the relative displacement (elongation or compression of the specimen) and this relative displacement is correlated to the actual load. The resulting specific elongation/compression is—similar to the Young's Modulus—a characteristic value of the material and should be constant for the duration of the test. Therefore, deviations in the diagrams of the specific elongation/compression indicate a damage of the concrete during the long-term test. An example for the diagrams and characteristic evaluation values for the long-term tests is given in Fig. 6. Because the boundary conditions of the testing changed—among other things—due to the use of the new automatic test regulation, the evaluation procedure and criteria are differing from the analysis of the previous tests described in [12].

The most obvious criteria for a damage of the specimen are the percentage deviation of the tensile strength after the long-term tests and the percentage deviation of the natural frequency with respect to the initial natural frequency. An analysis of the test results shows that, if the remaining tensile strength after the long-term test decreased more than 45% with respect to the mean value of the centric tensile strength of the tested batch, mostly also the natural frequency decreased more than 4% with respect to the initial natural frequency. Therefore, each specimen for which these two limits are exceeded is evaluated as a damaged specimen. Even, if the maximum number of load cycles is reached, it is not very likely, that this significant decrease of the tensile strength only occurred due to scattering of the tests for determination of the tensile strength, because the decrease of the natural frequency already occurred during the long-term test in these cases. The scattering of the tests

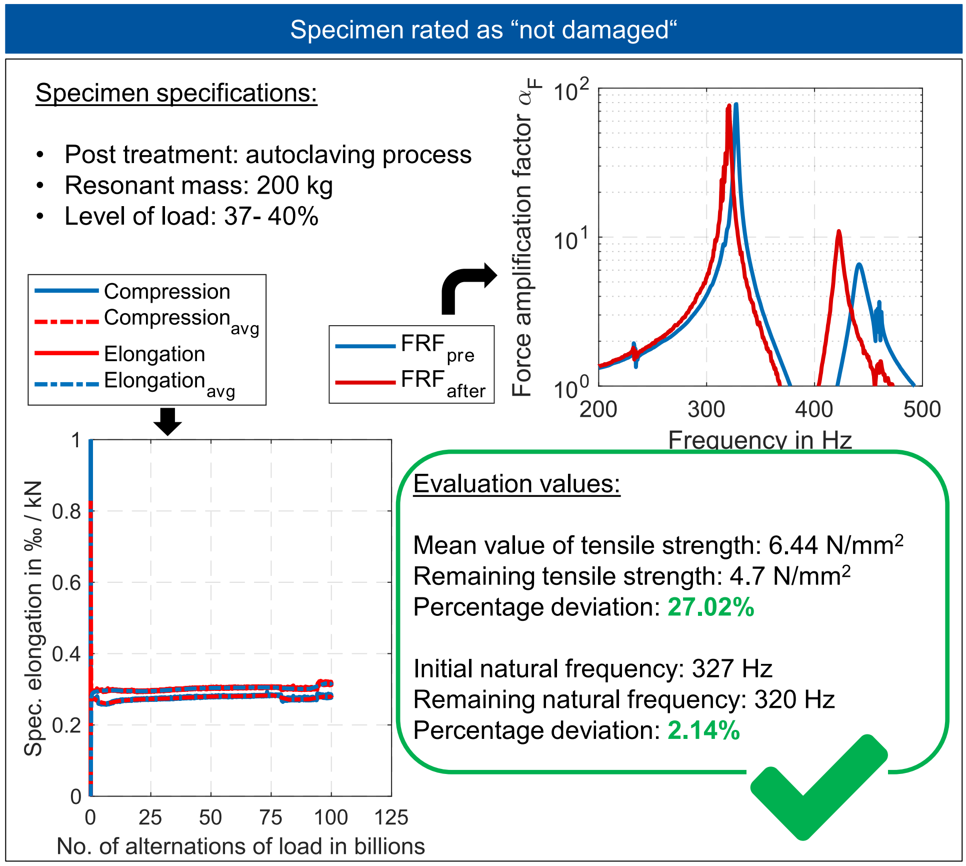


Fig. 6 Diagrams and characteristic evaluation values for the long-term tests of a not damaged specimen

for determination of the tensile strength is also the reason why the limiting value for the remaining tensile strength after the long-term tests of 45% is set comparatively high. An example for the evaluation criteria of a damaged specimen is shown in Fig. 7.

The specimens for which only one limit is exceeded (decrease of frequency or decrease of tensile strength) or which were automatically stopped before they reached the maximum number of load cycles are further analyzed with respect to the specific elongation/compression. If the development of the specific elongation/compression shows significant deviations over the duration of the test, it can be presumed that there are significant changes in the material, which indicate an existing or incoming damage of the specimen. These specimens are marked as “probably” damaged. If, in addition to the deviations of the specific elongation/compression, the decrease of frequency and/or tensile strength is near the limit of 4% or 45%, the specimen is evaluated as damaged.

To evaluate if the specimens were already damaged before the long-term tests (e.g., during handling or the transport), the initial natural frequency of the test is used similar to [12]. For each combination of resonant mass and specimen with different post-treatments, a mean value of the initial natural frequencies as well as the average absolute deviation of this mean value is calculated (see Table 2). Each test that has an initial natural frequency, which is less than the average absolute deviation subtracted from the mean value, is therefore potentially pre-damaged and has to be evaluated separately. If a potentially pre-damaged specimen is additionally damaged at a very early stage of the long-term tests (less than 200,000 cycles of load), this fact is another indicator that the specimen is pre-damaged and should not be considered during evaluation.

One of the 54 specimens tested was evaluated as pre-damaged and therefore is excluded from the final evaluation. As was expected, the specimens tested without the automatic test regulation could not hold the required level of load properly, so that the mean value of the load applied on the specimen had to be set as real load-level tested. This explains the specimens with low-level loads in the evaluation. Unfortunately, there was also a problem with the batch of autoclaved specimens that were to be tested with 41%–45% of centric tensile strength, 100 kg resonant mass and active automatic test regulation. The required range of load could not be reached during these long-term tests. Instead, these specimens had to be tested with 37–40% of centric tensile strength, too. However, in comparison with the batch tested with 50% of centric tensile strength, there is still a statement

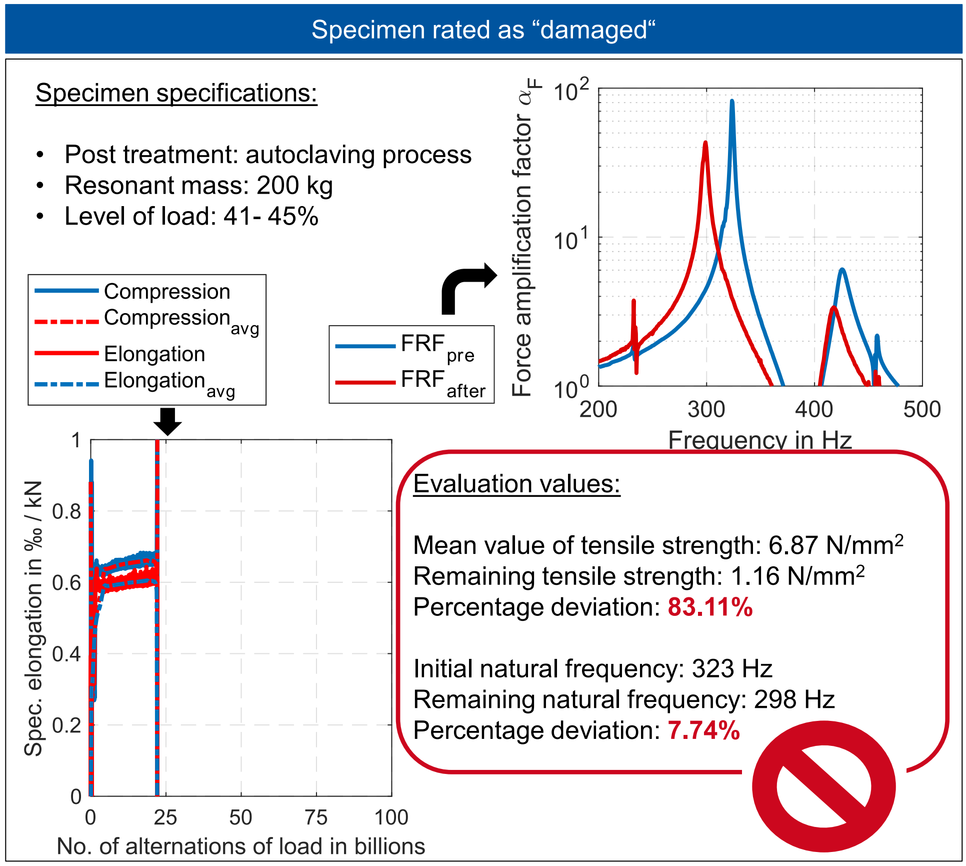


Fig. 7 Diagrams and characteristic evaluation values for the long-term tests of a damaged specimen

possible regarding the limiting range of load for dynamic long-term loads on UHPC in a high-frequency range.

Figures 8 and 9 show the results for the different configurations of test parameters. The diagrams show the number of tested specimens on the vertical axis for the respective ranges of level of load on the horizontal axis. The colors of the bars in the diagrams indicate the evaluation of the specimens as "damaged" (= red), "probably damaged" (= yellow) or "not damaged" (= green). Below the load-level range of 37–40%, the majority of the specimens is rated as "not damaged", above of this load-level range the majority of the specimens is rated as "damaged" or "probably damaged". Therefore, the evaluation of the presented tests shows that the limit for long-term loads in a high range of frequencies lies close to 40% of the centric tensile strength. That means that the general limit for long-term cyclic loads on UHPC already known from low-level frequencies seems to be also applicable for high-level frequencies and that the autoclaving process and the actual range of high frequencies do not significantly affect this limit. However, it is to consider that several damaged/probably damaged specimens already occurred at 38% to 39% of the centric tensile strength. Based on the results, when UHPC is used for machine tools, the limit of cyclic loading in the high-frequency range should be set at 36% of the centric tensile strength to be on the safe side.

Table 2 Mean values of the initial natural frequencies and their average absolute deviation

Post treatment	Resonant mass [kg]	Mean value of the initial natural frequency	Average absolute deviation
Autoclaving	100	475	6
	200	326	5
L7	100	481	4

Conclusion and Outlook

This article describes the further development of a test bench for long-term tests of specimens made of cement concrete under alternating loads in a high-frequency range. To improve the testing and the evaluation of the results and to achieve a consistent level of dynamic load on the specimens, an automatic adaption of the actual resonance frequency of the system is described and implemented into the test bench. First tests with the new automatic test regulation show a significant improvement of consistency in the applied load level. Additionally, the design of experiments for long-term

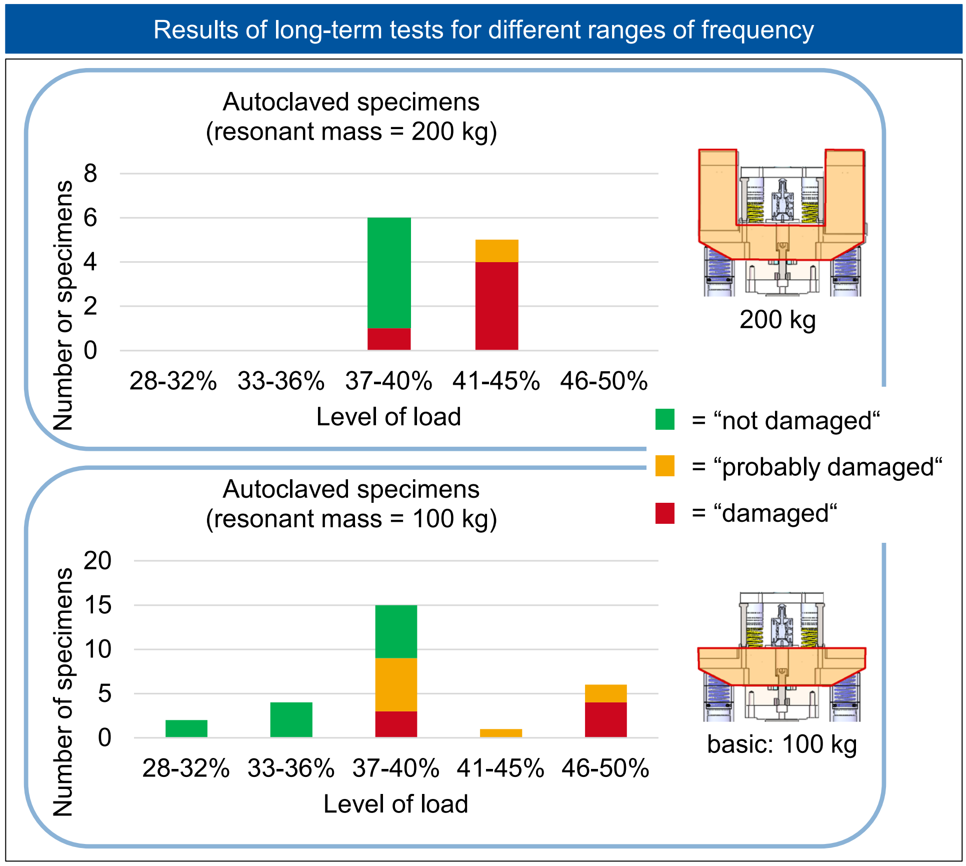


Fig. 8 Results of long-term tests for different configurations of parameters for autoclaved specimens

tests with autoclaved UHPC specimens as well as the method to evaluate the test results is explained. Autoclaved UHPC specimens were tested with different ranges of frequency and dynamic loads of 37% up to 50% of the static centric tensile strength and the results were evaluated—also considering tests with specimens with a post-treatment of L7. The results show, that the limiting load for alternating loads in a high-frequency range of autoclaved UHPC specimens is close to 40% of the static centric tensile strength. Hence, neither the two different high-frequency ranges nor the autoclaving process seem to significantly affect the limit for alternating loads on UHPC known from researches with low-level frequency ranges and previous investigations on the test bench (see [11, 12]). However, to stay on the safe side when using UHPC for machine tools, a maximum limit of 36% of the static centric tensile strength should be considered.

Future research should issue the further improvement of the automatic test regulation to achieve a faster regulation with less tolerance in the applied load. Additionally, further post-treatments should be investigated regarding their influence on the limiting value for alternating loads in a high-frequency range on specimens of cement concrete. Apart from that, the limiting load should be localized in more detail and for other material compositions as well, to compare the suitability for applications with loads in a high-frequency range. Another important point is to transfer the results of this article to the application of UHPC in real parts of machine tools, where they are exposed to alternating loads with high frequencies in multiple directions and not only in a single one as it is the case in the test bench.

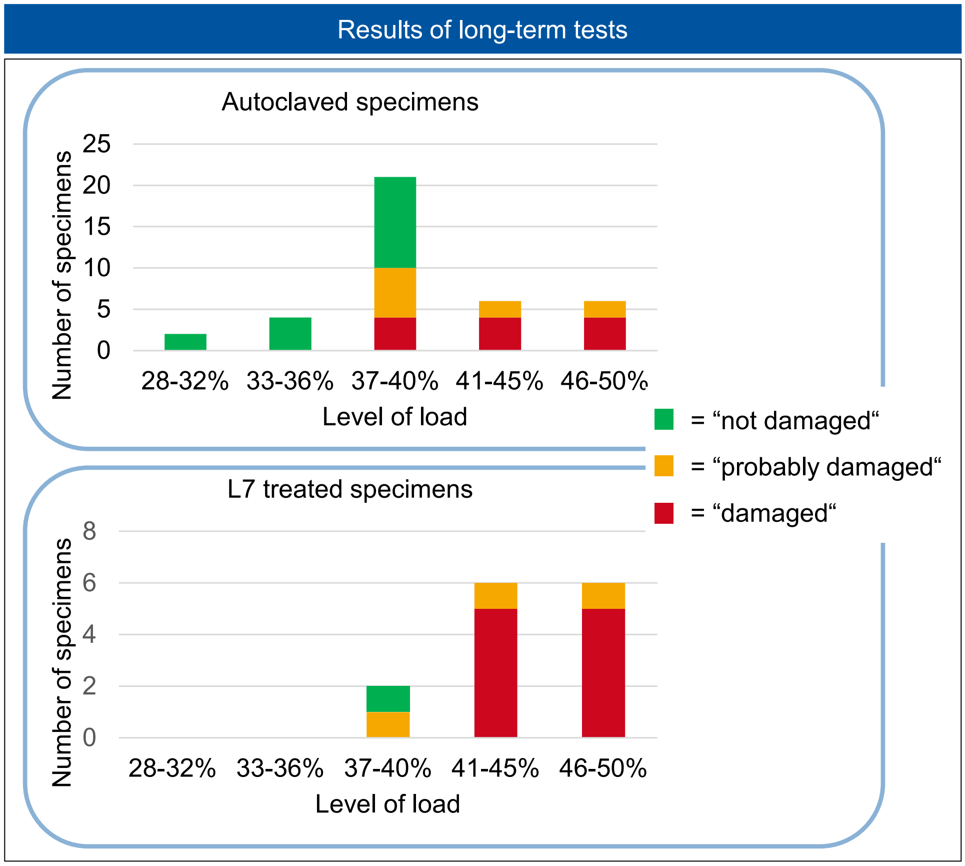


Fig. 9 Results of long-term tests for different post-treatments of specimens

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by CK-M and MK. The first draft of the manuscript was written by CK-M and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Availability of Data and Material The test specimens were provided by Ibac and the data of the static tensile testing are stored by Ibac. The data of the vibration tests are stored by WZL.

Code Availability The programs for running the test bench were set up in LabView (by National Instruments). The programs for the evaluation of the test results were set up in Matlab (by MathWorks). The programs are stored by the WZL.

Declarations

Conflict of interest Not applicable.

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