Very high cycle fatigue testing of concrete using ultrasonic cycling

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The ultrasonic fatigue testing method has been further developed to perform cyclic compression tests with concrete. Cylindrical specimens vibrate in resonance at a frequency of approximately 20 kHz with superimposed compressive static loads. The high testing frequency allows time-saving investigations in the very high cycle fatigue regime. Fatigue tests were carried out on “Concrete 1” (compressive strength $f_c = 80$ MPa) and “Concrete 2” ($f_c = 107$ MPa) under purely compressive loading conditions. Experiments at maximum compressive stresses of 0.44 $f_c$ (Concrete 1) and 0.38 $f_c$ (Concrete 2) delivered specimen failures above $10^9$ cycles, indicating that no fatigue limit exists for concrete below one billion load cycles. Resonance frequency, power required to resonate the specimen and second order harmonics of the vibration are used to monitor fatigue damage in situ. Specimens were scanned by X-ray computed tomography prior to and after testing. Fatigue cracks were produced by ultrasonic cycling in the very high cycle fatigue regime at interfaces of grains as well as in cement. The possibilities as well as limitations of ultrasonic fatigue testing of concrete are discussed.

Concrete is the most widely used building material since it is versatile, durable and features excellent compressive strength. Although primarily used in statically loaded constructions, it is increasingly used in dynamically loaded structures. Gravitational and acceleration forces of motor vehicles on pavements and bridges, engine vibrations applying forces on fundamentals, forces caused by gusts of wind or periodic impact forces of sea waves impose numerous repetitive loads on concrete structures. These cyclic loads can lead to fatigue damage although all loads are well below the static strength of the material [1-4]. The highest number of load cycles occur in concrete bridges [5], wind turbines [6] and offshore structures [2], where 100 million load cycles or more can be accumulated during the planned technical lifetime. Thorough understanding of the fatigue behavior of concrete in the long lifetime regime is therefore required.

Experimental determination of the fatigue properties of concrete in the regime of $10^8$ cycles is very time consuming. Testing one single concrete sample at a typical testing frequency of 10 Hz takes about four months, and several tests are required for a statistically reliable set of data. Due to very long testing times needed, fatigue data of concrete are available solely below approximately $10^7$ cycles [7] to failure and fatigue limits are defined using $2 \times 10^6$ cycles for reference [8]. Until now, the very high cycle fatigue properties have only been theoretically approached [9]. The only way to investigate fatigue lifetimes of $10^8$ or even $10^9$ cycles within reasonable testing times is to increase the testing frequency.

Ultrasonic fatigue testing is a well-known and frequently applied technique to study the high cycle fatigue (HCF) and very high cycle fatigue (VHCF) properties of materials. Numerous investigations have been performed using this technique as it has already been used since 60 years for fatigue investigations, mainly of metallic materials. Specimens are stimulated to resonate vibrations at approximately 20 kHz cycling frequency rather than being stressed by external forces. The high testing frequency allows performing experiments in the regime of $10^8$ cycles within several hours or one day instead of months. Therefore, the further development of the ultrasonic fatigue testing technique for fatigue testing of concrete is of great scientific as well as practical interest. A recent description of the capabilities as well as limitations of ultrasonic fatigue testing can be found in [10].

In the present work, the ultrasonic fatigue testing technique is used for the first time for fatigue testing of concrete. Concrete is subjected to cyclic compression loading in service, whereas ultrasonic fatigue tests have been performed under cyclic tension-compression or cyclic tension until now. A method to perform cyclic compression ultrasonic experiments has been developed to study the cyclic strength of two concretes with different static strength. The evolution of fatigue damage in concrete is monitored by analyzing the vibration properties of the specimen. Fatigue damage produced in the VHCF regime is demonstrated comparing X-ray tomography figures of virgin and fatigued specimens.
Specimens are stimulated to resonance vibrations in ultrasonic fatigue testing rather than being stressed by external forces. Both ends of the specimen oscillate in opposite directions, forming a vibration node in the center. There, the cyclic strain amplitude reaches its maximum and can cause fatigue damage, i.e., the initiation of cracks and their propagation to fracture. Cycling frequency is around 20 kHz, which leads to a drastic reduction of testing time compared with conventional fatigue testing procedures. Ultrasonic fatigue testing procedures have already been developed, e.g., studying lifetimes, crack initiation and propagation under fully reversed loading conditions or with tensile mean loads, testing with constant or variable amplitude, in different environments and temperatures, as well as testing under cyclic torsion loading. Function principles as well as a summary of different experimental setups are described in a recent review article [10].

Concrete is subjected to compression loading in most actual applications. Therefore, the practical interest lies mainly in the fatigue properties under cyclic compression loading. Ultrasonic fatigue tests under cyclic compression loading with the entire load cycle at compression stresses have not been performed before. This testing technique was developed for the present investigation of concrete.

The setup used for cyclic compression testing of concrete is shown in Figure 1a, consisting of electronic equipment and a hydraulic load frame. The electronic equipment (see Figure 1a, left side) is the same as previously used in numerous ultrasonic fatigue studies and it is comprehensively described in [10]. No adaptations of the electronic equipment were necessary for fatigue testing of concrete.

The electronic components comprise the ultrasonic test generator, ultrasonic power amplifiers, strain gauge conditioners and an oscilloscope. Ultrasonic test generator determines and controls the vibration amplitude of the specimen. Since strain amplitudes in the center of the specimen and vibration amplitudes at antinodes are proportional, selecting the magnitude of the vibration amplitude determines the strain in the center of the specimen. The vibration amplitude at an antinode is measured with a vibration gauge and is controlled by comparing the signal of the vibration gauge and the preselected amplitude. The difference is processed in a closed-loop control allowing for an agreement between preselected and actual amplitude of 1%. Loading of the specimen is not continuous but in a pulse-pause sequence. Pulse length (typically 200 ms) and pause length (typically 2000 to 5000 ms) are chosen appropriately to avoid excessive heating of the specimens. Additionally, the ultrasonic test generator controls the excitation frequency. Internal damage as the result of fatigue testing causes a decrease of the resonance frequency of the specimens. Frequency control serves to keep the excitation frequency at the actual resonance frequency with an accuracy of 1 Hz. The electric power signal to drive the experiments is provided by ultrasonic amplifiers. The maximum output power of the used testing system is 600 W. Strain gauge conditioners serve to measure strain amplitudes and an oscilloscope is used to display various signals, such as vibration signal, strain measurement signals and power signals.

The hydraulic load frame (see Figure 1a, right side) serves to mount the ultrasonic load train and to superimpose static compression forces on the high frequency resonance vibration of the concrete specimen. All components of the load train, including the specimen, are designed to resonate close to 19.4 kHz. Each component shows maximum displacement amplitude (vibration antinode) at its ends and zero displacement (vibration node) in its center. The load train consists of an ultrasonic converter that generates high frequency axial vibrations. It is attached to a cylindrical rod with a length of half the resonance wavelength. The node in its center serves to mount the load train into the hydraulic load frame. An ultrasonic horn is attached to this cylindrical rod and serves to increase the vibration amplitude. A vibration gauge measures the vibration amplitude at the lower end of the ultrasonic horn.

The load train close to the specimen is shown in more detail in Figure 1b. Two nozzles are visible on both sides of the concrete specimen, which serve for cooling with pressurized air. Maximum surface temperature of the specimen was 30 °C. Two strain gauges are attached to the specimen in the center region to measure static and cyclic strains. Extension rods are connected to the specimen at both ends. The upper extension rod serves to displace the concrete specimen from the vibration gauge. In case of catastrophic failure, fragments of a fractured specimen may otherwise damage the gauge. Static compression forces are introduced in the center of the lower extension rod. At this vibration node, the rod features a convexity. A slide bearing serves to introduce the compression force avoiding the superposition of undesirable bending moments.

Distribution of strain and displacement amplitude along the length of the specimen and the upper and lower extension rod are shown in Figure 1c. The length of both extension rods and the specimen is half the resonance wavelength. Vibration antinodes at the ends and nodes with maximum strain amplitudes in the center of each component are visible.

The wavelength of the longitudinal sound wave in the specimen and the extension rods is determined by the speed of sound, $c_{\text{sound}}$, and the vibration frequency, $f$. The speed of sound $c_{\text{sound}}$ of a sound wave traveling in a rod featuring a constant cross section is determined by the density of the material, $\rho$, and the modulus of elasticity, $E$, according to Equation (1):

$$c_{\text{sound}} = \frac{E}{\sqrt{\rho}}$$

(1)

The wavelength, $\lambda$, is determined by the vibration frequency and the velocity of sound according to Equation (2).
FATIGUE TESTING

The extension rods are made of the titanium alloy Ti6A14 V. This material has a density of 4430 kg m⁻³ and a Young's modulus of 114 GPa. At a frequency of 19.4 kHz, half the wavelength is 131 mm, which is the length of both extension rods.

Materials and specimens

Two concretes are tested in the present investigation, a normal strength concrete used in railway sleepers (Concrete 1) and a high strength concrete used in offshore structures (Concrete 2). Compositions and mechanical properties are summarized in Table 1. The specimens were taken from structural components. They were drilled in a cylindrical shape featuring a diameter of 21 mm and subsequently polished.

Figure 2 shows a specimen that is used in the ultrasonic compression fatigue tests. A concrete cylinder is visible with an aluminum thread on one side and an aluminum disk on the other side. Thread and disk were bonded to the concrete cylinder using epoxy with the specimen mounted in order to ensure good alignment. The epoxy was cured at a temperature of approximately 40 °C. Besides the benefits for the alignment of the specimen, the epoxy also serves to obtain a good sound transfer into the concrete. The thickness of the aluminum disk was varied in order to fine-tune the resonance frequency of the specimen.

Prior to fatigue testing, the following calibration procedure is performed in order to determine cyclic loads, i.e., corresponding strain in the specimen, by means of strain gauge measurements. Two strain gauges of 20 mm length were attached in the center of the specimen on opposite sides, as shown in Figure 2. Static compression forces are applied to the specimen with the hydraulic load frame and the resulting strains in the specimen are measured. This delivers the correlation between strain reading and compression stress. Then, the correlation between vibration and strain amplitudes is measured in order to determine the proportionality factor between ultrasonic vibration amplitude and stress amplitude. The proportionality can be quickly established for each specimen. It should be noted that it is not necessary to know the stiffness or the Young’s modulus of the concrete since the strain gauges serve as sensors whose sensitivity is determined by a static compression test. This is an advantage of the calibration method, since stiffness of concrete may vary from specimen to specimen even for the same concrete mixture.

<table>
<thead>
<tr>
<th>(d_s) (mm)</th>
<th>Cement content (kg m⁻³)</th>
<th>w/b</th>
<th>(E_c) (GPa)</th>
<th>(f_r) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete 1</td>
<td>16</td>
<td>330</td>
<td>0.48</td>
<td>37.0</td>
</tr>
<tr>
<td>Concrete 2</td>
<td>8</td>
<td>370</td>
<td>0.37</td>
<td>48.5</td>
</tr>
</tbody>
</table>

Table 1: Concrete compositions and mechanical properties. Concrete 1 is taken from railway sleepers and Concrete 2 from offshore wind turbine foundations

Monitoring of fatigue damage and failure criteria

Failure of a specimen can be easily detected in tension-compression or tension-ultrasonic fatigue tests. Fatigue lifetime can be specified as the number of cycles until the specimen fractures. However, this definition for failure is not applicable to ultrasonic cyclic compression testing of concrete.

Fatigue damage in concrete is the formation of new cracks and the growth of preexisting cracks. Cracks increase the compliance and deteriorate the vibration properties of concrete specimens. Since ultrasonic tests are displacement controlled and displacement and strain amplitudes are proportional, strain amplitudes are kept constant during the tests. However, stress amplitudes decrease as the compliance of the specimen increases (and the stiffness decreases) due to the formation and growth of cracks. This is the reason why concrete specimens could not be fractured in the present investigation, although fatigue cracks were initiated. A different failure criterion aside from specimen rupture is necessary to specify lifetimes in ultrasonic compression fatigue tests of concrete.

An increase in number and length of fatigue cracks in the concrete specimens leads to changes of their resonating properties: an increase of compliance, an increase of damping resulting in an increase of power necessary to drive the vibration, and the generation of second order harmonics of the sound wave traveling through the specimen. These changes of physical properties can be detected, quantitatively determined and used as a measure for the progress of fatigue damage in the concrete specimen as described in the following:

The resonance frequency of the specimen is used as a measure for the compliance of the specimen. As compliance increases, the resonance frequency of the specimen and thus the resonance frequency of the whole resonating load train decreases. By monitoring the resonance frequency and comparing it to the initial resonance frequency with the virgin specimen mounted in the load train, the evolution of fatigue damage can be visualized. Furthermore, the resonance frequency serves as a criterion for failure of the specimen. If the resonance frequency has dropped 150 Hz from the initial resonance frequency at the beginning of the experiment, it is assumed that the specimen has failed.

Damping of the material due to the formation of cracks increases the ultrasonic power necessary to resonate the specimen. The vibration amplitude increases up to the selected vibration amplitude at the beginning of a pulse. After the end of the pulse, the vibration amplitude decreases. The increase of the vibration amplitude to the chosen value is the slower and the decay after the end of the pulse is the faster, the greater the damping of the specimen [11]. In the present work, the increase of the vibration amplitude at the beginning of a pulse is used as a second criterion to specify the fatigue lifetime. If 85% of the vibration amplitude is not reached within 100 ms, the experiment is stopped and it is assumed that the specimen has failed.

Fatigue cracks cause damping and reflections of sound waves that are traveling through the specimen. As a consequence, second and higher order harmonics of the sound wave are generated. Nonlinear propagation behavior of ultrasonic waves can be exploited in order to assess fatigue damage in progress [12, 13]. The displacement signal from the vibration gauge is analyzed...
and subsequently processed using fast Fourier transform algorithm [14]. The nonlinearity parameter, β, is derived from the amplitude of the fundamental vibration, \( u_0 \), and the amplitude of the second order harmonic, \( u_1 \), and the length of the specimen, \( L \), according to Equation (3):

\[
\beta = \frac{u_1}{u_0^2} \frac{4L}{\pi^2}
\]

(3)

Vibration properties of the virgin specimens may be different, i.e., even the untested specimen might exhibit a certain nonlinearity. Therefore, the change of the nonlinearity parameter rather than its absolute value is evaluated. The relative nonlinearity parameter \( \beta_{\text{rel}} \) is the ratio of the current nonlinearity parameter \( \beta \), measured continuously during the experiment and the nonlinearity parameter \( \beta_0 \), measured at the beginning of the experiment for the virgin specimen.

\[
\beta_{\text{rel}} = \frac{\beta}{\beta_0}
\]

(4)

Observation of the relative nonlinearity parameter is a third method to monitor the progress of fatigue damage in the concrete specimens in situ. However, the parameter was not used as failure criterion in the present work. Experience and knowledge about the vibration properties of the testing material are needed to interpret the nonlinearity parameter correctly. Since these are the first experiments with concrete and the first under cyclic compression, we solely monitored and stored this parameter for later investigations.

### Results

The results of ultrasonic cyclic compression fatigue tests of two types of concrete are shown in Figure 3. The tests were performed under purely compressive loading conditions. The ordinate shows the maximum compressive stress of a load cycle normalized with the respective compressive strength \( f_c \) of the concrete. The abscissa in logarithmic scale shows the fatigue lifetimes using the criteria for failure as detailed above. One specimen did not fail within \( 2 \times 10^9 \) loading cycles, which is marked with an arrow. Testing environment was laboratory air at a temperature of 20 °C to 23 °C and a relative humidity of 50 %. In order to avoid excessive self-heating of the specimens, dynamic loads were applied intermittently. With pulse lengths of 200 ms and pause lengths in the range of 2000 to 5000 ms, the effective cycling frequency was in the range of 750 to 1700 Hz.

The following tests were performed with Concrete 1: one test with a maximum compression stress \( S_{\text{max}} = 0.56 f_c \), one test with \( S_{\text{max}} = 0.50 f_c \), and two tests with a maximum compression stress of 0.44 \( f_c \). The minimum compression stress of a load cycle was 0.06 \( f_c \) in all four tests. The following tests were performed with Concrete 2: three tests with a maximum compression stress of \( S_{\text{max}} = 0.43 f_c \) and two tests with \( S_{\text{max}} = 0.38 f_c \). All five tests with Concrete 2 were carried out with a minimum stress of 0.04 \( f_c \).

Lifetimes range from \( 10^6 \) to \( 10^9 \) loading cycles under the tested loading conditions. Failures could be detected above \( 10^7 \) cycles for both concretes. Fatigue data of Concrete 2 (which shows higher compressive strength than Concrete 1) are shifted towards lower values of \( S_{\text{max}} \) compared with Concrete 1. Neither Concrete 1 nor Concrete 2 shows a fatigue limit in the investigated regime. It should be noted that these are the first experimental investigations of concrete in the range of \( 10^9 \) cycles. It is therefore the first experimental proof that concrete does not show a fatigue limit, at least not below one billion cycles.

Figure 4 shows the evolution of resonance frequency \( f \) (in Hz) and the relative nonlinearity parameter \( \beta_{\text{rel}} \) (in dB) with the number of load cycles for a specimen of Concrete 1 that was loaded with 0.50 \( f_c \) and failed after \( 2.5 \times 10^8 \) load cycles. Starting with the first load cycles, \( f \) and \( \beta_{\text{rel}} \) show a decrease and increase, respectively, continuing steadily throughout the test. In the last cycles before the experiment was stopped, the resonance frequency and the relative nonlinearity parameter show a steeper progression. At the time of failure, the resonance frequency has dropped from 19 490 to 19 300 Hz and \( \beta_{\text{rel}} \) has increased to 4 dB.

X-ray computed tomography (CT) has been carried out on three specimens (two specimens of Concrete 1 and one specimen of Concrete 2) before and after ultrasonic fatigue testing to evaluate fatigue damage. Images have been generated in the axial and transversal plane, perpendicular to the long axis of the specimen. In a first step, the specimens were analyzed quantitatively in regard to shape and distribution of grains, size and number of pores as well as cracks present in the grain, cement and interface, respectively. Therefore, images in the axial plane corresponding to a distance of approximately 1 mm were used. In a second step, the initiation of new as...
well as the growth of preexisting cracks is qualitatively analyzed using images in the transversal plane corresponding to a distance of 6 mm.

Figure 5 shows the CT images of the cross section of a specimen made of Concrete 1 that failed after $2.5 \times 10^8$ loading cycles at $S_{\text{max}} = 0.50 f_c$. Two cracks that propagated along the interface between large grains and the cement are visible. Additionally, one crack, probably originating from a preexisting crack, runs through the grain as well as through the cement.

Figure 6 shows the CT images of the cross section of a specimen made of Concrete 1 that failed after $1.8 \times 10^9$ cycles at $S_{\text{max}} = 0.44 f_c$. Probably originating from a preexisting crack, a crack has grown through grains and cement, spalling a piece of grain at the surface of the specimen.

Figure 7 shows the CT images of the cross section of a specimen made of Concrete 2 that failed after $9.6 \times 10^7$ cycles at stress level $S_{\text{max}} = 0.43 f_c$. A crack, probably originating from the interface of grain and cement, runs through the cement.

**Discussion**

The CT images clearly show that fatigue damage can be produced by ultrasonic cyclic compression loading in the very high cycle regime. New cracks were initiated and existing cracks were prolonged due to the cyclic compression stresses with maximum at about half the compressive strength. Specimens are severely damaged when the above-described criterions to stop the tests are fulfilled. The criterions are therefore suitable to define failure.

Rupture of the specimen was not observed in ultrasonic tests. The initiation and growth of cracks progressively increase the compliance of the specimen, which reduces the cyclic stress in experiments where the displacement amplitude is kept constant. Additionally, the required power to drive the specimen increased and eventually would have reached the maximum power of the equipment. This points to an inherent difference between stress controlled and displacement controlled fatigue tests, where the latter results in prolonged lifetimes. It is possible to quantify the difference between the two methods by periodically measuring the stiffness/compliance of the specimens. Thereby, it is possible to correlate stress and displacement controlled tests.

Compared to specimen sizes used for conventional fatigue testing, the specimen diameter designed for ultrasonic fatigue testing is rather small. The gauge volume affects the distribution of existing flaws such as voids resulting from entrapped air. Furthermore, concrete as a quasi-brittle material features a localized zone of progressive material damage ahead of the crack tip called the fracture process zone,
its size is influenced by the specimen dimensions [15-17]. As a consequence, specimens with a diameter of 50 mm should be used in fatigue tests [9, 18].

The main limiting factor for the specimen diameter is the maximum power output of the ultrasonic fatigue testing equipment. The testing volume and thus the necessary power to resonate the specimen increases with increasing cross-sectional area. Maximum power of 600 W was sufficient to test specimens with 21 mm diameter. The cross-sectional area of a specimen with a diameter of 50 mm is by a factor of 5.7 larger than the presently used specimen, and the ultrasonic power to test such a specimen is expected to increase by the same factor. Ultrasonic equipment used for welding typically has a maximum power of about 4000 W. No principal physical limitation exists to use such equipment although the necessary control electronics and computer systems need to be developed. It is therefore feasible to expand the presented ultrasonic compression fatigue testing method to specimens with a diameter of 50 mm.

The drastic increase of testing frequency is the main key to access the very high cycle fatigue regime. However, the high cycling frequency needs to be considered if measured cyclic properties are used for design purposes. Loading in actual structures occurs at much lower frequencies, and strain rate influences on fatigue lifetimes must be considered therefore. Fatigue lifetimes of concrete increase with increasing frequency [19-21]. This means that the cyclic strengths measured at ultrasonic frequency are non-conservative. It is necessary to consider the frequency influence and to determine a transfer function to appropriately scale the measured lifetimes to actual applications. Experiments at low and ultrasonic frequency in the range where conventional experiments as well as ultrasonic tests are applicable (i.e., in the regime of 10^6 cycles) could serve to quantify the effects of strain rate in the future.

An interesting result of the present tests is the higher relative fatigue strength of Concrete 1 compared with Concrete 2. If maximum compressive stresses of a load cycle are normalized with the compressive strength of the respective concrete, the concrete with the higher compression strength (Concrete 2) shows the lower cyclic strength. Fatigue life of high strength concrete decreases with increasing strength if presented relative to their compressive strengths [1]. A possible explanation is the more brittle structure of high strength concrete leading to higher crack growth rates [1].

Summarizing the results of the present work, an outstanding benefit of the newly developed ultrasonic compression fatigue testing technique of concrete is the possibility to experimentally approach fatigue damage produced in the regime of 10^6 load cycles. However, several tasks remain to be solved in the future: the measured fatigue lifetimes are prolonged in displacement controlled compared with stress controlled experiments, and this effect must be considered and quantified by periodic stiffness measurements. Larger specimen diameters with larger testing volumes should be used, which is possible by developing ultrasonic testing systems with increased output power. Finally, the frequency influence on fatigue lifetime of concrete must be considered.

### Conclusions and outlook

It is shown that cyclic compression fatigue tests of concrete can be performed using the ultrasonic fatigue testing technique. The concrete specimen is stimulated to resonance vibrations at a frequency of approximately 20 kHz with a static compression load superimposed. Intermittent loading avoids excessive heating of the specimen. Lifetime investigations in the very high cycle fatigue (VHCF) regime are feasible within acceptable testing times, which is of scientific as well as practical interest. The actually performed first investigation already answers some fundamental questions associated with cyclic compression ultrasonic testing of concrete:

- Concrete does not show a fatigue limit below one billion load cycles.
- Fatigue damage in concrete produced in the VHCF regime are interface cracks between large grains and cement, cracks in the cement and spalling at the surface.
- Initiation and growth of fatigue cracks cause an increase of the compliance of the specimen, an increase of damping and an increase of second order harmonics. These physical properties can be used to monitor the progress of fatigue damage in situ.
- Limits for the resonance frequency and the steepness of the increase of vibration amplitude at the beginning of a pulse were successfully used to specify the fatigue lifetime.
- Presenting lifetimes versus relative maximum stresses (i.e., S_{max}), normal strength concrete showed better cyclic properties than high strength concrete.

Further development, especially in two fields, is necessary to make the ultrasonic fatigue testing results of concrete applicable for practice.

- The diameter of the specimens should be larger than used in the present investigation. The maximum possible diameter of the concrete specimen is limited by the power of the used ultrasonic equipment. Increasing the power by a factor 6 is feasible and would similarly increase the possible cross-sectional area of the specimen.
- Fatigue properties of concrete are strain-rate sensitive. Increasing the testing frequency increases the measured fatigue lifetime. Comparative studies at conventional and ultrasonic frequency are necessary to determine transfer functions that make the results of ultrasonic tests applicable for practice.

### References

Abstract


Bibliography

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