7.3 Modelling of aged reinforced concrete structures for design extension conditions (CONFIT)

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Abstract

The CONFIT project uses a multi-disciplinary approach to investigate the various physical and chemical degradation mechanisms and how they affect the mechanical load bearing capacity of concrete in long term operation. Reinforced concrete structures are, indeed, of safety relevance in nuclear power plants due to the containment function of the reactor building and load bearing functions of the control building and shielding functions of specific concrete structures.

During the project, it was investigated how various external chemical and physical stressors affect the mechanical concrete properties as a material (Ferreira, M. and Fülöp, L., 2020) and in particular how corrosion of the reinforcement affects the load bearing capacity of a concrete structure (Calonius, et al., 2023b) and how this can be numerically simulated (Calonius, et al. 2021). For the simulation of full-scale loading scenarios on reinforced concrete structures involving physically, chemically or mechanically deteriorated concrete, specific material models for concrete were developed during the project. One of the advantages of such advanced concrete models is the ability to respond to anisotropic behaviour, which is inherent in damaged concrete (Vilppo, et al., 2021).

Since the calibration of the model parameters requires measurements of anisotropy in concrete under controlled multiaxial loading, a specific method using ultrasonic wave velocity measurement was developed (Calonius et al., 2022c). This method enables the computation of the damaged stiffness matrix components from the ultrasonic pressure and shear wave velocity measurements on the concrete sample in different directions.

As a result, the project has generated important findings in the domain of nuclear safety, some of which present novelty value of academic importance.

Introduction

The protective walls, containment and civil structures of Nuclear Power Plants (NPPs) are mainly reinforced concrete (RC) structures. Long term operation of NPPs requires structural integrity assessment of aged concrete structures in YVL design extension conditions (DEC) e.g. external hazards like earthquakes and wide body aircraft crashes. These DEC have been introduced recently in NPP design in Finland. The DEC loads are considerably higher than the earlier design basis loads (DBL).

There is a need for a more universal material model which is more firmly based on physical phenomena and adequate for different types of loading cases, e.g. soft/hard impacts, earthquakes and resulting vibrations. Ageing of concrete has not been previously taken into account in DEC assessment. The material study including ageing and degradation mechanisms involves collaboration between structural analysis and concrete material experts at VTT. The material model development involves collaboration with Tampere University (TUNI).

Material model development (shown in Figure 1) is a trial and error process, which aims at finding the most appropriate mathematical description, such that the response of the model matches the response obtained from a number of experimental stress-strain situations. Due to the challenges that arise in the calibration of the material model against appropriate test results, it is of paramount importance to conduct proper validation simulations. In these small-scale validation simulations, the experimental test setup is modelled as accurately as possible using finite elements, and the measured macroscopic quantities are then compared to the simulated ones. In order to rule out artefacts due to discretization, a sensitivity study on the element mesh size has to be performed.

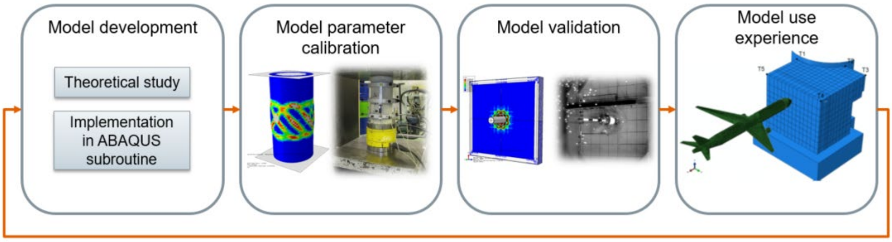


Figure 1. Concrete material model development chart.

The goal of the project is to develop understanding of the material modelling of concrete in the nonlinear domain by improving the use of existing material models, developing new material models and using calibration tests to stand at the basis of the development. Relatively new concrete material testing and measurement methods, such as DIC and ultrasonic methods, have also been further developed in the project. Methods and modelling techniques developed and validated here can directly be applied in safety assessment and design analyses of aged reinforced structures of NPPs under design extension conditions.

Impact simulation with Abaqus FE code

The Concrete Damaged Plasticity (CDP) model available in Abaqus finite element software has been implemented based on a theory developed in (Lubliner, et al., 1989) for monotonic loading cases and later enhanced in (Lee & Fenves, 1998) to encompass static cyclic behaviour. In order to extend the CDP model to dynamic behaviour, it is necessary to introduce rate dependency of concrete in the material model parameters. Based on the assumption that concrete compression strength increases with hydrostatic pressure, and that concrete tensile strength increases with strain rate, a VSDFLD Abaqus user subroutine has been written. This user-extended CDP model is described in (Fedoroff, et al., 2019). In addition to confinement pressure dependency of compressive strength and rate dependency of tensile strength, in hard missile impact simulations it is necessary to formulate an algorithm for element removal as a mean to materialize fragmentation of concrete during the impact process. The element removal algorithm is described in (Fedoroff & Calonius, 2020) and it is validated against experimental hard missile impact benchmark tests. The core of the work done for the implementation of the user-extended CDP model has been conducted in SAFIR2018 ERNEST project. Figure 2 shows an example where concrete confinement, shear cone formation and finally fragmentation of concrete can be observed.

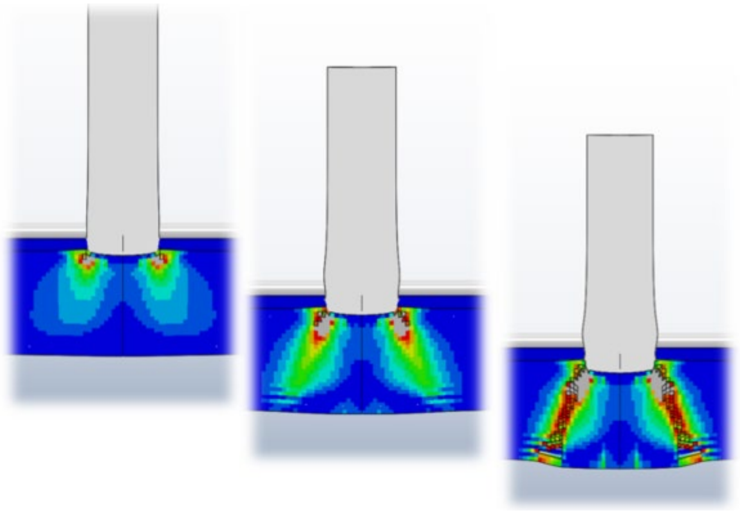


Figure 2. Example of hard missile impact simulation.

The focus was set on material model parameter calibration as described in (Calonius, et al., 2019). The proposed strategy for the material model parameter calibration is based on an iterative process where various concrete material tests (uniaxial compression, three point bending, split-tensile test, etc.) are simulated. At the end of each iteration, the model parameters are updated in order to obtain, on the next iteration a stress-strain curve that matches the experimental one. The CDP model parameters are generated using an Excel-VBA script by entering values for Eurocode material parameters (such as stiffness modulus, compressive strength, tensile strength, fracture energy, etc.) as well as values for confinement pressure and strain rate dependencies.

In addition to the development and validation of the user-extended CDP model, some novel non-destructive concrete testing methods were evaluated (Calonius, et al., 2021). Digital Image Correlation (DIC) was tested in a concrete cube compressive test and compared to strain gauge measurement results, Figure 3, and to Abaqus simulation results using the CDP material model, Figure 4.

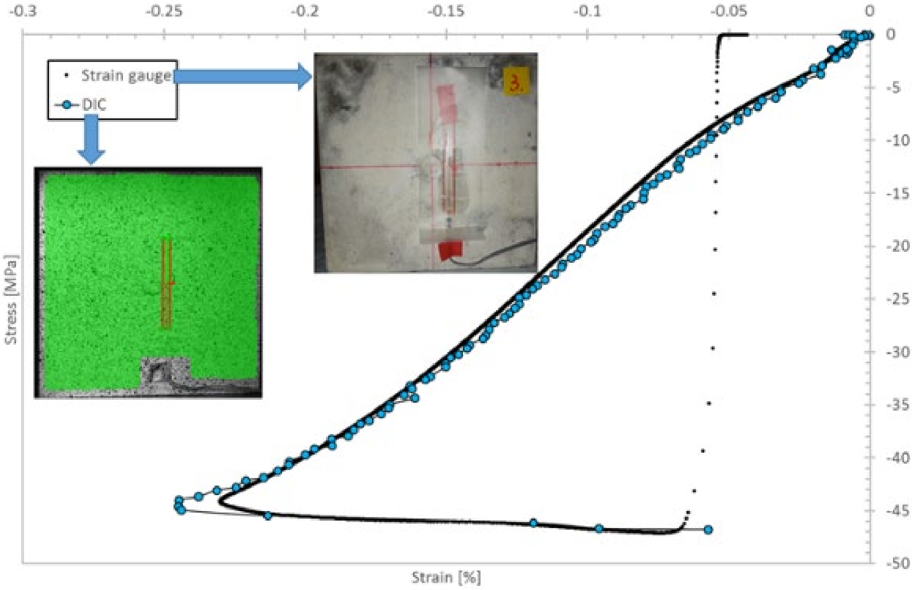
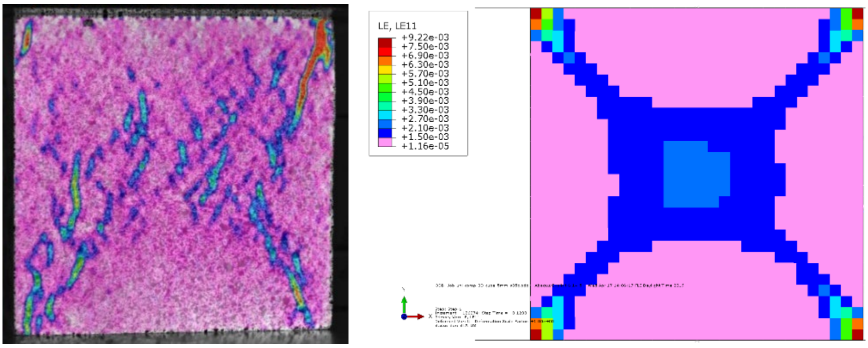


Figure 3. Comparison of vertical strain measurement results with a strain gauge and Digital Image Correlation.



(a) DIC strain field

(b) Abaqus CDP simulation strain field

Figure 4. Comparison of strain fields DIC vs. simulation.

Understanding the effect of ageing and deterioration of reinforced concrete

Reinforced concrete structures used in NPPs are used for varying applications and environments. The long-term reliability of NPP safety-related concrete structures depends on the ability of these structures to withstand the time-dependent deterioration. Experience has shown that concrete is a durable material. However, faulty design, use of unsuitable materials, improper workmanship, exposure to aggressive environments, excessive structural loads, accident conditions and a combination of the above factors can compromise its performance. Many factors complicate the contribution of ageing effects to the residual life of the NPP safety-related concrete structures. Uncertainties arise due to differences in design codes and standards for components of different ages and lack of past measurements and records. During the exploitation phase, detection, inspection, surveillance, and maintenance methods or programs may be inadequate. In addition, there may be limitations in the applicability of time-dependent models for quantifying the contribution of ageing to concrete structures (Naus et al., 1996).

Concrete long-term reliability can be improved by limiting the exposure of the concrete structures to deteriorating effects, and by periodic inspection and maintenance procedures. The ageing research of concrete structures is to not only identify and mitigate the time-dependent deterioration mechanism on concrete, but also understand the implication for structural performance and characterise this performance in material models.

A degradation factor, or stressor, can be defined as an agent or stimulus resulting from construction or pre-operation and operation conditions that can result in the ageing process and failure of the structure. Different materials within the concrete structure are affected by different types of stressors (USNRC, 2013).

The implications of material ageing for structural performance assessment and especially for numerical modelling of reinforced concrete structures have been studied. The four main constituents of reinforced concrete (concrete, mild steel reinforcement, prestressing steel and steel liner) and their likely stressors, degradation mechanisms, potential failure modes, and in-service inspection methods have been reviewed (Ferreira & Fülöp, 2020).

The study provides a review of the current state of understanding of the effect of stressors on the material and mechanical properties that are currently used in concrete modelling. Focus has been on mechanical properties of concrete as a function of the "loading" conditions. The sources of the formulas are design codes, most prominently the fib Model Code (2010) and to a much lesser degree Eurocode 2 and the research literature. Generally, it is concluded that models exist for estimating the effect of aging and deterioration on a large number of mechanical properties (e.g. compressive strength, tensile strength, modulus of elasticity, etc.). Hence, the use of "as-new" properties for estimating performance of existing NPP structures should be critically revised. Aged concrete and its respective time-dependent properties should be considered in performance estimation for NPPs to accidental loads or DEC conditions.

Artificial ageing of reinforced concrete slabs for impact testing

Mechanical properties of concrete have a paramount influence on the behaviour of reinforced concrete structures under impact and impulsive loadings like aircraft crashes and blasts. These properties depend on the strain rate as well as phenomena related to ageing of concrete. Experimental tests are needed to characterize concrete as material in different stages of ageing as well as to study the behaviour of structures cast with this concrete under impact loading. The ultimate goal of this research is to define the effect of corrosion of bending reinforcement and minor degradation of surface concrete to the impact resistance of a reinforced concrete wall. To achieve the degradation of reinforcement and concrete, the slabs are artificially aged before impact testing. NDE is needed to assess the level of damage to the reinforcement inside the concrete slabs. The impact tests will be conducted in future.

Two slabs to be tested are 250 mm thick and reinforced with 10 mm reinforcement bars with spacing of 90 mm in both directions and on both surfaces. A projectile weighing approx. 47.5 kg will be shot at it with impact velocity of either around 100 m/s or around 135 m/s. The exact impact velocity will be fixed after the used batch of concrete has been tested for compressions strength. The goal is to reach a ballistic limit (i.e. the projectile will perforate the slab with minimal residual velocity). The reference test cases with undamaged slabs are the punching tests conducted in OECD IRIS_2012 benchmark and some punching tests in IMPACT projects.

The concrete slabs were exposed to accelerated ageing by use of impressed current. For that purpose, to establish an electrical field, a counter electrode mesh out of stainless steel was placed on the top surface of the slabs. Since it was not embedded in the concrete slab, it needed to be placed in an electrolyte solution. A pool was prepared by fastening wooden beams on the concrete surface and sealing the joints, see Figure 5. Sodium chloride was dissolved in the water and the pool was covered with plastic sheets to prevent intensive evaporation.

Taking into account the top layer reinforcement steel surface area and assuming an estimated average current level for a duration of 11 months, the calculated total mass loss of reinforcing steel can be calculated and average uniform corrosion rates derived. The uniform corrosion rates are roughly in the range of 1–2mm of decrease of reinforcing bar diameter. Due to the nature of chloride-induced corrosion in concrete and the observation of high levels of gas production on the counter electrode surface during the impressed current feed the actual corrosion is most likely local type corrosion and the impressed current feed has not entirely been causing the dissolution of iron and production of corrosion products. Therefore the actual corrosion rate is difficult to predict based on the impressed current feed values. Locally there can be significant damage but in other locations it is possible that the reinforcing bars show zero or a negligible amount of corrosion.

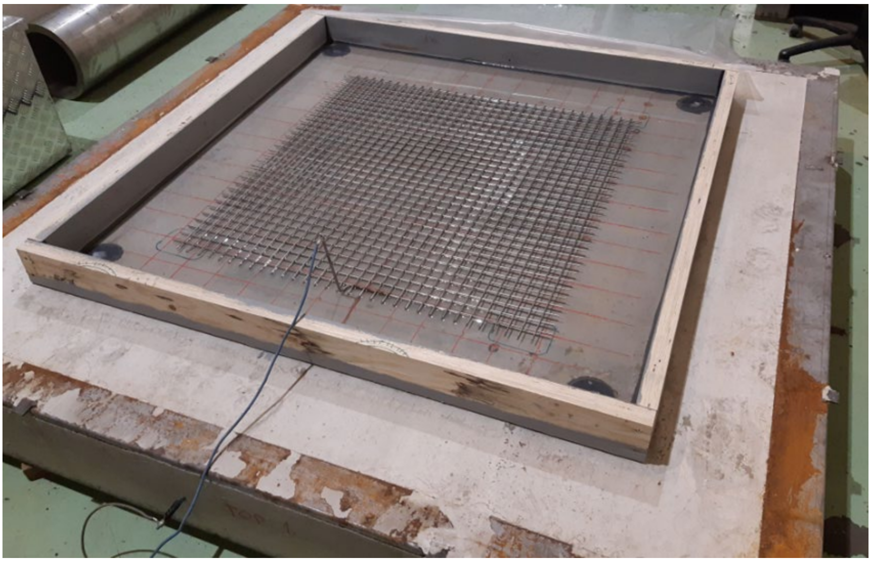


Figure 5. One of the slabs exposed to impressed current.

Before, during and after the end of the impressed current feed non-destructive electrochemical measurements were conducted by half-cell potential mapping and measurements of the electrical resistivity of the concrete. The results of these measurements show clearly that the conditions for active corrosion during the impressed current feed prevailed. They indicate as well that there are local differences of the extent of corrosion between both slabs, and on the investigated surfaces of each slab. The magnitude or extend of damage cannot be assessed without local removal of the concrete cover and inspection of the condition of the reinforcing bars (Calonius, et al., 2023b)

Development of tensorial damage material model

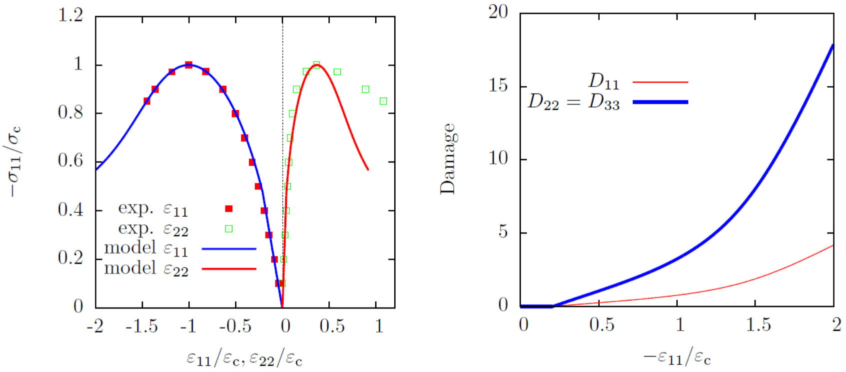
Modeling of concrete structures under extreme loadings as explosion and impact is challenging. Both the material and geometric non-linearities have to be considered in the modelling. The ultimate failure of structures can be described as a continuous process of damage initiation, propagation and fragmentation.

In the simulation, it is extremely important that the failure pattern during the damage evolution is correctly described by the model. That is not the case in classical continuum models – the models target on the modelling of ultimate stress state and often neglect the associated failure patterns. Brittle kind of materials like concrete, natural rocks and natural ice tend to fail by axial splitting along the direction of uniaxial loading. As discussed by Schreyer (2007) the classical stress criteria do not have the flexibility to reflect the failure modes for various of stress states and “none predicts axial splitting”.

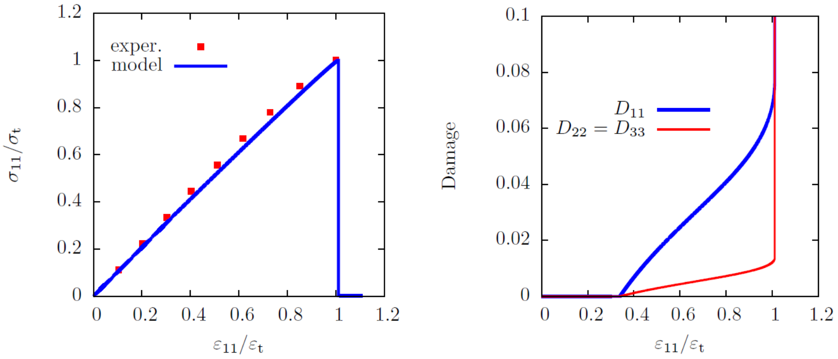
Formulation of the anisotropic tensorial damage model is done by specifying two potential functions, the specific Gibbs free energy and the dissipation potential. The isotropic potential functions are written in terms of invariants forming a functional, i.e. irreducible basis having two symmetric second-order tensor variables, namely the stress tensor and the damage tensor, which resembles the crack density tensor of Kachanov (1992). Therefore, the magnitude of the components of the damage tensor are not limited above, which makes numerical implementation somewhat simpler than using the standard definition of damage as a ratio of damaged to the undamaged area.

The specific Gibbs free energy is constructed to represent linear elastic solid in undamaged states. Furthermore, only linear terms of the damage tensor are retained, thus the “crack” interaction is not taken into account. Hardening and softening is modelled using a single internal variable. The dissipation potential is chosen in accordance to the famous Ottosen (1977) failure criterion, which captures the relevant features in concrete failure. The formulation is basically non-associated, however, the formulation follows closely the one for the standard dissipative solid. An additional convenient feature is that the material parameters of the model can be obtained in a closed form solution from standard material tests results: uniaxial compression/tension, equibiaxial compression and one extra point on the compressive meridian.

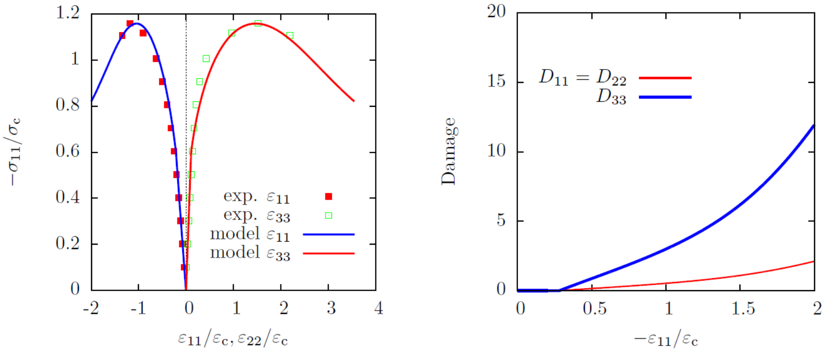
In Figure 6 the model predictions, stress-strain relations and damage evolutions, are shown in unconfined compression/tension and equibaxial compression (Vilppo, et al., 2021 and 2022). Correspondence to the well-known experimental results by Kupfer et al. (1969) is good. It can also be seen from the damage-strain curves that the model is able to capture the correct failure mode. The model has been implemented to Abaqus FE code. The calibration process of this model using cyclic compression tests and ultrasound NDE is described below.


Stress-strain relation in unconfined uniaxial compression

damage-strain relation in unconfined uniaxial compression


Stress-strain relation in unconfined uniaxial tension

damage-strain relation in unconfined uniaxial tension.


Stress-strain relation in equibiaxial compression

damage-strain relation behaviour in equibiaxial compression

Figure 6. Stress-strain relations and damage evolutions in different directions predicted by the model under different types of loading schemes.

Evaluation of anisotropic material parameters in damaged concrete using ultrasound velocity data

In this research, a novel method of evaluating material stiffness parameters using ultrasound measurements on compressively damaged concrete cube specimens has been carried out. The method consists in measuring the soundwave velocity in principal and diagonal directions, both with longitudinal and shear waves, and computing the stiffness tensor components as a function of the measured soundwave velocities. The results show the method is capable of producing stiffness degradation profiles comparable to the ones obtained from traditional means of measurement from stress-strain data (Calonius, et al., 2022c and 2023a).

Concrete cube samples of 200mm were cast using C40/50 ready mixed concrete with evaluated air content of 2.1% and maximum aggregate size of 8mm. The loading surfaces of the cubes were smoothed and parallelized with a diamond grinding apparatus prior to testing. Three standard compression tests with average concrete strength of f_{cm}=62.72MPa were carried out to identify the reference loading capacity of the concrete batch. The engineering strain measured between the loading plates and corresponding to the peak load had an average value of ε_{c1}=0.4383%. The experimental test setup consists of the following equipment:

- A hydraulic press suitable for uniaxial compression of concrete specimens and instrumented with a load cell for engineering stress measurement and two displacement sensors for engineering strain measurement between the loading plates in the loading direction.
- A digital image correlation (DIC) system, consisting of two cameras, computer hardware for data acquisition and software (LaVision StrainMaster) for data processing. The DIC data enables the computation of the strain tensor field at selected time frames from one of the free surfaces of the concrete cube.
- An ultrasonic measurement device (Proseq Pundit) with 54 kHz longitudinal wave transducers and 40 kHz shear wave transducers.

The pseudo-cyclic uniaxial compression tests were conducted on a total number of 18 concrete specimens with displacement control at a rate of 0.1 mm/min to obtain a controlled loading and unloading portion of the stress-strain curve. “Pseudo-cycle” is referred here to a loading pattern consisting of a single constant rate loading up to the target displacement value and a constant rate unloading down until the applied force is zero. Six target displacement values were chosen. For each target displacement three repetitions were carried out.

After the compressive tests, the concrete sample cubes are cut with a diamond saw along the edges to obtain a chamfered cube shape (see Figure 7). The ultrasound measurements are carried out by placing the emitter and receiver probes on opposite sides of the specimen along three principal directions and six diagonal directions. The first time arrival of the emitted signal is recorded by the ultrasound device as shown in Figure 7. For statistical significance, multiple time arrival and dimension readings are performed on each face of the chamfered cube. A stiffness degradation plot based on various measurements is shown in Figure 8.

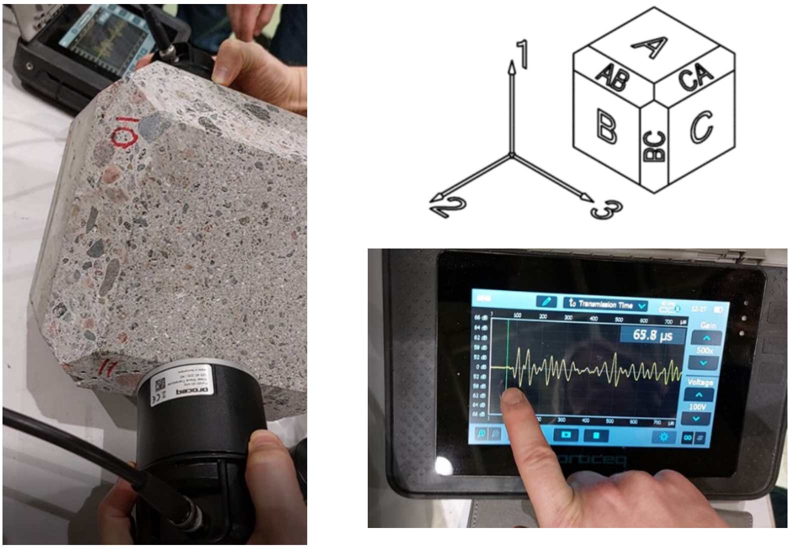


Figure 7. Views of a chamfered cube specimen and the first time arrival determination.

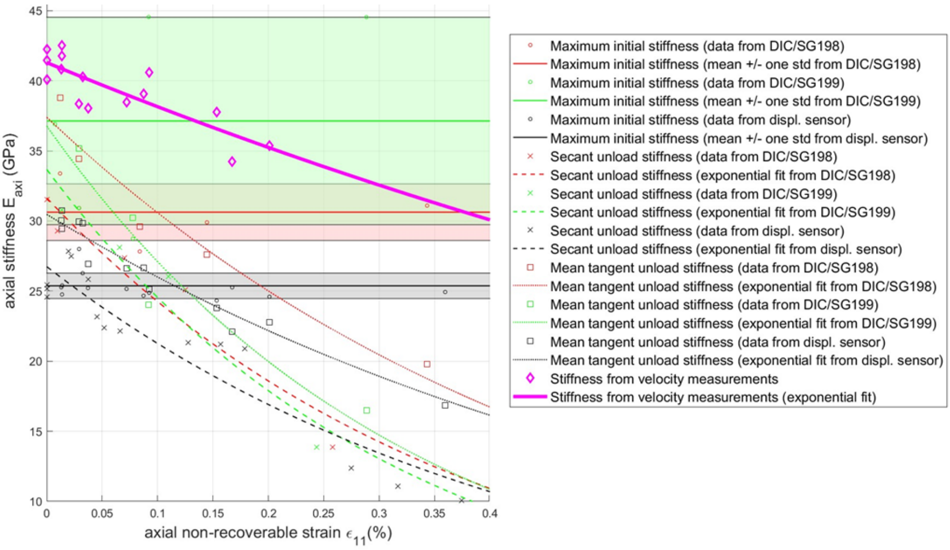


Figure 8. The plot shows: a) initial stiffness mean values from various data sources (solid horizontal lines), b) unload stiffness values as a function of non-recoverable strain from various data sources (dashed or dotted lines), and c) stiffness values from ultrasound velocity measurements (thick magenta line).

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