

# Non-destructive testing in civil engineering: A memorandum for teaching at German-speaking universities

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## Abstract

This contribution summarizes actual developments and draft fundamental teaching topics in the field of non-destructive testing in civil engineering (NDT-CE). It is based on the first memorandum on teaching and research in the field of NDT-CE at German speaking universities [1] and provides an overview of the academic education and highlights possible focuses, especially in teaching but also takes into account noteworthy developments and topics in research in the field of NDT-CE.

Suggestions are given for the development and advancement of the teaching curricula in regards to a comprehensive and sound professional education of students in civil engineering and adjacent disciplines.

**Keywords:** curriculum; core competencies; teaching concept; university, teacher memorandum; non-destructive testing in civil engineering; NDT-CE

## 1 Introduction

### 1.1 Motivation

Currently, most of the academic institutes at various departments in German-speaking countries teach individual NDT methods with rather varying weight and depth in different courses and formats. Apart from faculties of civil and environmental engineering, faculties teaching subjects of non-destructive testing include architecture, mechanical engineering, geosciences (in particular geophysics), physics, electrical engineering and medical engineering. There are also connections with mathematics, information technology, and chemistry so that nearly all fields of engineering and sciences somehow treat subjects of non-destructive testing or are connected to NDT.

This often makes systematic education at universities in the field of NDT difficult. The focus is left to the university professors and lecturers who see a need for teaching this subject. In particular at German universities, there is a great affinity in materials and engineering sciences to integrate NDT teaching content - for example in exercises. However, with a few exceptions, a discipline-wide or faculty-wide system of NDT training is seldom encountered, and inter-faculty training does not take place. The following paragraphs aim to enable a more systematic integration of NDT teaching content.

## 1.2 Core competencies

Non-destructive testing in civil engineering (NDT-CE) is an interdisciplinary field in the best sense of the word [2, 3] that is embedded in the process of building maintenance as part of a material spanning building diagnostics respectively inspection [4, 5] (fig. 2).



**Figure 1:** Building diagnostics within the building maintenance process [1]

This means that proper teaching in this field is only possible if the subject is embedded in the curriculum and competencies from related disciplines such as materials science, physics, mathematics, chemistry, electrical engineering, computer science or architecture have been acquired beforehand.

Important core competencies of non-destructive testing include:

### **Material and structural competence**

- Expertise in structural design, service life, rehabilitation/repair and building materials
- Understanding of external influences on materials and associated material deterioration processes

### **Measuring technology**

- Selection of measuring devices, measurement principles and methods; performing of measurements; design to NDT-CE; system theory and measurement chain

### **Sensor technology**

- Selection of sensors
- Operation of sensors
- Calibration and reliability



### **Data processing**

- Reliable data handling and storage also of large amounts of data ("big data")
- Generic filtering and data analysis techniques
- Specific signal analysis (feature extraction)
- Statistics
- Use of (micro) computers

### **Data interpretation**

- Error analysis, precision, and accuracy; Validation
- Probability of detection; effect of defects
- Simulation and modelling

## **2 Teaching non-destructive testing**

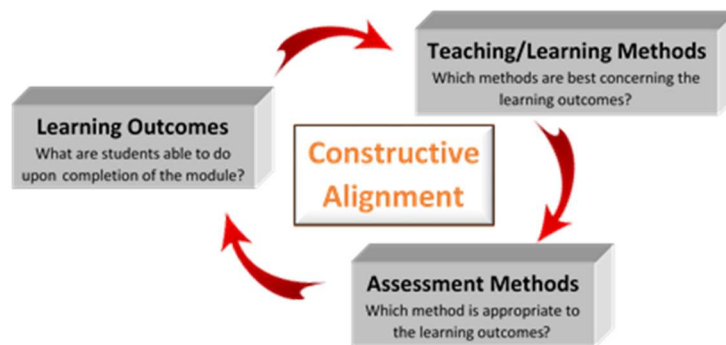
### **2.1 Suitable teaching formats**

Since teaching in Europe was transformed during the past decade by the so-called Bologna process towards a modular, several teaching formats offer themselves for integrating NDT-CE elements [6, 7]. Apart from the classical lecture, these include central, and tutor-guided exercises as well as practical activities and seminars. If only limited time resources are available, there are also block events such as block exercises available. A teaching module may consist of one of these formats or combine several of them. Ideally, lectures as a central opportunity for acquiring knowledge are complemented by central exercises where solutions (measurements) are presented and understood. In tutor-guided exercises, the students, supported by the tutor, develop solutions independently and design measuring tasks, perform them, and finally evaluate them. Seminars may help to become acquainted with new solutions (measuring methods) or to gain an overview of current developments. In practical exercises, the students can apply the methods learned under realistic conditions in a dedicated manner. As part of practical exercises, it is advisable to prepare test specimens with defined inhomogeneities or anomalies for different tasks. These test specimens can be used by many students over long periods and thus keep the consumption of resources to a minimum. The choice of teaching formats to be used depends highly on the available resources (supervisors, tutors, rooms and laboratories, time, measuring devices, etc.). Exercises guided by tutors and practical work in laboratories or (in case these resources are not available) central exercises are in any case an important element in teaching non-destructive testing. NDT-CE (like measurement technologies in general) needs practice and can only be understood if measurements are carried out and evaluated independently.

### **2.2 Constructive Alignment**

If, when designing NDT-CE courses, one does not assume which course content is to be imparted, but rather which competencies the students should acquire, the concept of constructive alignment helps [8]. Figure 2 illustrates the relationship between the acquisition of skills, teaching formats, and examination methods.

This approach focuses on the acquisition of competencies: defining the learning objectives of the students. The answer to this question determines the examination methods and eventually which teaching format or formats are selected that are most likely to ensure successful learning. About the competencies that can be acquired in NDT-CE courses, refer to subsection 1.2 of this memorandum.



**Figure 2:** Constructive alignment concept in order to define the appropriate examination procedure and teaching formats based on the learning objectives [9]

### 2.3 Supporting elements in teaching

In addition to classical supporting materials and methods (such as lecture notes, homework, literature reviews, and group works), digitization offers several more or less new methods which may be useful also in teaching/learning NDT-CE.

Lectures can be provided as Massive Open Online Courses (MOOCS) or eLearning modules (fig. 3). This has the advantage that expensive or immobile NDT-CE processes can be integrated and time-consuming measurements can be displayed in a compressed manner.



**Figure 3:** Educational video of TU Munich demonstrating infrared thermography measurements [1]

Other electronic aids are wikis for homework, peer instruction systems like Pingo [10] for lectures, and electronic learning platforms (e.g., Moodle) for preparing and reviewing lectures as well as semester resources [9]. Figure 4 shows an example of a pingo inquiry for a thermography lecture. Using the single or multiple-choice method, questions can be answered anonymously during the lecture, which enables teachers and students to immediately check the learning and teaching success. The questions maybe asked multiple times to compare the development of competencies of the same group or of different groups.

It is also possible to record descriptions of different applications of NDT-CE-devices in videos and made them available to students as a first step in the form of eLearning modules.

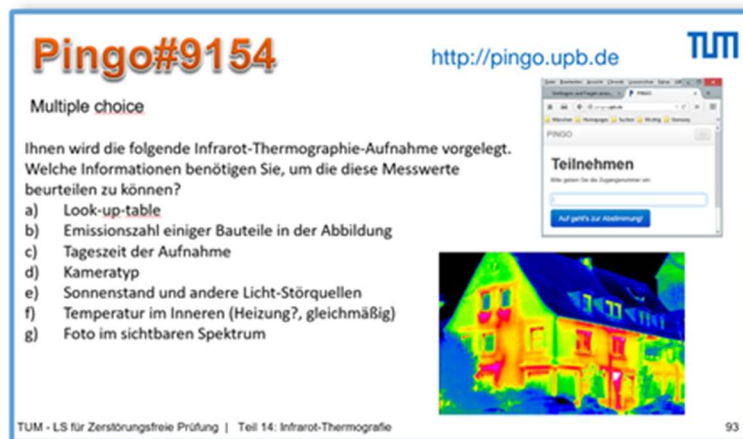


Figure 4: Example of a multiple-choice question using the PINGO system [1]

## 2.4 Practical work in laboratories and tutor-guided exercises

Practical work in laboratories and tutor-guided exercises represent a central element of NDT-CE courses. They can be easily combined with other teaching formats such as lectures and enable students to design and carry out measurements themselves and to evaluate and interpret the recorded data (fig. 5). Since it can take a long time, such kind of exercises should be prepared with great care. It is a good idea to hand out exercise sheets or tutorials for preparation and to keep measurement protocols for the individual tasks. Attention should also be paid to any necessary compliance with safety measures (safety briefings).



Figure 5: Student's exercises with infrared thermography applied to a car hood out of CFRC (© TU Munich) [1]

## 3 Curriculum

### 3.1 Boundary conditions

The selection of the course content and competencies to be taught to the students depends on many boundary conditions. A selection has to primarily correspond to the overarching teaching objective of the course, but also take into account the following other boundary conditions:



- Position in the curriculum (Bachelor or Master)
- Time contingent in weekly semester hours
- Modular capability
- Educational background of the students
- Learning objective
- Number of students
- Available resources such as tutors, assistants, measuring devices, computers, test specimens, etc.

Since most teaching formats (in particular exercises) are resource-intensive, sufficient financial resources are a basic requirement for successful teaching.

### ***3.2 Subdivision of the course content***

Courses on non-destructive testing can follow either a more method-oriented or a more application-oriented system. No clear recommendation can be given as to which system should be given preference. There are several arguments in favour of both systems. Ultimately, the external circumstances (curriculum, courses, etc.) will have a major influence on the decision. In case the classes are offered in a single course, there are few reasons why NDT-CE should not be taught with the application-oriented approach. In case classes are offered in several courses or even across several departments, they may focus on the fundamentals and thus on the methods.

It is also advisable to subdivide the teaching content of non-destructive testing into subject areas, which can, however, also be mixed or combined. NDT-CE methods can be used both in the construction phase (for example in quality assurance), but also in the operating phase for inspection or damage analysis. The area of condition monitoring, which is often described with the term structural health monitoring (SHM), is also becoming increasingly important. If one considers a procedural division of the teaching content, for example for a lecture (as described in the following section), then a (process-related) subdivision can be executed into

- a) physical-mathematical basics,
- b) measurement concept or setup and sensor technology,
- c) fields of application and practice examples
- d) bibliography.

A brief historical development overview of the method as well as a summary of its possible applications and limitations complements this subdivision. In contrast to industrial teaching formats, care must be taken in higher education that the basic theoretical training enables students to understand the basic physical principles of a procedure.

### ***3.3 Exemplary curricula for NDT-CE-lectures***

In table 1 two exemplary curricula are presented which can be used for reference purposes - one for the procedure-based, the other for the application-oriented approach.

Exemplary curriculum (EC) 1 shows the procedure-based structure of an NDT-CE course with 3-5 weekly lecturing hours (45 min) for a master's degree. However, the compilation only shows a selection of the most important methods. Individual topics probably have to be merged, as a one-semester course usually only has 14 to 16 individual teaching events.

In comparison, a more application-oriented structure can be set up analogous to exemplary curriculum (EC) 2. It gives some examples of important or typical applications of NDT-CE methods in civil engineering with a strong focus on cementitious elements or structures.

**Table 1:** Exemplary curricula (EC)

<b>EC 1 - Procedural</b>	<b>EC 2 - Application oriented</b>
<p><i>A) Fundamentals</i></p> <ol style="list-style-type: none"> <li>1. Introduction to and motivation for NDT-CE</li> <li>2. Test concepts, signals, systems, filters, time series, measurement accuracy, determination of measurement uncertainty</li> <li>3. Fields, waves, particles, radiation in the context of material specifics</li> <li>4. Measurement technology, sensors, signal recording, data processing, evaluation, damage mapping</li> </ol> <p><i>B) Inspection methods</i></p> <ol style="list-style-type: none"> <li>5. NDT-CE techniques in quality control of materials and in component design</li> <li>6. Visual inspection + hand-held and minimally invasive methods (rebound hammer, endoscopy, inductive and capacitive procedures, moisture measurements, etc.)</li> <li>7. Ultrasound</li> <li>8. Impact echo</li> <li>9. RADAR and microwaves</li> <li>10. Eddy current and magnetic flux</li> <li>11. Infrared thermography</li> <li>12. Radiography and computed tomography</li> <li>13. Half-cell potential methods and electrical resistance measurements</li> <li>14. Laser breakdown spectroscopy (LIBS) and other spectroscopic methods</li> <li>15. Typical areas of application</li> </ol> <p><i>C) Structural health monitoring methods</i></p> <ol style="list-style-type: none"> <li>16. Passive and active permanent monitoring procedures for structures (ultrasound, fibre optics, strain gauges, etc.)</li> <li>17. Vibration analysis</li> <li>18. Acoustic emission analysis</li> <li>19. Wireless sensors and sensor networks</li> </ol>	<p><i>A) Fundamentals</i></p> <ol style="list-style-type: none"> <li>1. Introduction to and motivation for NDT-CE</li> <li>2. Test concepts, signals, systems, filters, time series, measurement accuracy, determination of measurement uncertainty</li> <li>3. Measurement technology, sensors, signal recording, data processing, evaluation, damage mapping</li> </ol> <p><i>B) Quality control of building materials</i></p> <ol style="list-style-type: none"> <li>4. Quality &amp; production control</li> <li>5. Evaluation/classification of building materials</li> </ol> <p><i>C) Inspection methods used for the assessment of building components</i></p> <ol style="list-style-type: none"> <li>6. Material tests like compressive or tensile strength tests</li> <li>7. Measurement of geometric parameters (cross sections, concrete cover, etc.)</li> <li>8. Assessment of usability</li> <li>9. Specific object properties (seals, coatings, geometries, types of reinforcement, etc.)</li> </ol> <p><i>D) Inspection methods for existing structures</i></p> <ol style="list-style-type: none"> <li>10. Corrosion detection</li> <li>11. Detection of cracks, cavities, and delaminations as well as determination of thickness</li> <li>12. Determination of porosity and analysis of building materials</li> <li>13. Structural stability and residual service life analysis</li> <li>14. Detection of thermal bridges and differential pressure or airtightness tests using infrared thermography</li> <li>15. Test methods for different building materials (wood, steel, stone, glass, composites)</li> <li>16. Typical applications, i.e., for moisture detection</li> </ol> <p><i>E) Monitoring of</i></p> <ol style="list-style-type: none"> <li>17. Bridges with wired/wireless sensors</li> <li>18. Wind turbines</li> <li>19. Cultural heritage structures</li> </ol>

These examples can and shall be adapted by the teacher according to the teaching and competence goals. In particular, section E in exemplary curriculum 2 only contains methods respective examples for applications of structural health monitoring procedures, which can be replaced by your own examples. If the course is less time-consuming, entire areas of application (e.g., monitoring) can be omitted, but this must be indicated in the module description so that a later employer can correctly assess the skills acquired. There is also the option of moving individual content from a lecture to exercises, which is useful for both fundamentals and applications.

### **3.4 Exemplary content for exercises**

Exercises aim to present or develop possible solutions (or in the case of NDT-CE methods: measurements). This can be achieved, for instance, in central exercises by demonstrating measurement methods. Small and portable test devices exist e.g., for ultrasound, thermography, eddy current, and vibration analysis or for specific applications like concrete coverage determination. These may also be connected to presentation technology (projector) so that a larger number of students can follow the measurements and the evaluation. Tutor-guided exercises and practical work are generally preferable, as they allow the independent development of NDT-CE test results and thus improve the motivation of the students. It is useful to offer exercises to accompany the lecture and to hand out exercise sheets with tasks. Measurements can be performed on test specimens with a known structure. Table 2 contains some examples of exercise content that is suitable for training master students in civil engineering.

**Table 2:** Exemplary content for NDT-CE exercises

<ol style="list-style-type: none"><li>1. Visual inspection of voids and cavities by means of (video) endoscopy</li><li>2. Investigation of concrete walls regarding reinforcement and moisture by means of magnetic and capacitive induction as well as resistance measurements</li><li>3. Prestressing steel tendon detection by means of GPR measurements</li><li>4. Determination of transit time and modulus of elasticity in different materials by means of ultrasound including for initial quality control</li><li>5. Detection and localization of defects in reference specimen by means of ultrasound and GPR</li><li>6. Corrosion detection in reinforced concrete by means of half-cell potential</li><li>7. Determination of the heat flow in components by means of infrared thermography</li><li>8. Crack detection in reinforcing steel by means of eddy current</li><li>9. Vibration analysis and modulus of elasticity determination of test specimen by means of vibration and modal analysis</li><li>10. Acoustic emission analysis including 3D localization in concrete structures</li><li>11. Monitoring of structural elements by means of sensor networks (temperature, moisture, expansion, vibrations)</li></ol>
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By means of exercises students not only learn to use sensors and measuring devices but also which components of the measuring chain influence the measurement (coupling, cables, A/D-transformation). They also learn to take a critical approach to measure data, analyse measurement errors, determine their dimensions and present them. The measurement results should then be interpreted in collaboration with the teacher and at the end, an “ideal solution” should be presented. Alternatively, if there is sufficient time, tasks for students can be defined





as laboratory work in which students find solutions by working either in small groups or independently.

#### **4 Summary and prospects**

The demand for non-destructive testing methods in civil engineering is growing. In addition, recalculation regulations, durability requirements, and digitalization/BIM provide further fields of application. This means that the approach to the education of civil engineers has to change, and corresponding subjects have to be integrated into the curricula at universities. Some fundamentals and applications can already be incorporated into bachelor's degree programs. The master's program should ideally contain at least one lecture with, ideally, at least 3 lecturing hours (3x45 min) per week and at least one exercise with 1 exercise hour (45 min) per week. Additional courses such as seminars, practical activities as well as excursions, and expert lectures are desirable. Higher education differs from industry-related education usually by providing a deeper understanding of theoretical knowledge, which enable students to understand the methods irrespective of their application. This includes competencies in measurement technology, sensor technology, data processing, and analysis as well as data interpretation. The individual topics should be carefully compiled in the curriculum and sensibly integrated into the course objectives. A link to related subjects such as building surveying structural subjects can be achieved, for example, employing a practical project dealing with existing buildings/structures.

Two exemplary curricula are recommended, which enable a more method-oriented or more application-oriented course structure. Focal points can be set individually. A supplement to the teaching content of existing courses regarding NDT-CE is important for comprehensive preparation of the students in the rapidly changing civil engineering sector where abilities in using and understanding NDT-CE techniques is a necessity.

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