NONDESTRUCTIVE EVALUATION, SENSORS, AND DIAGNOSTICS

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Introduction

Engineering evaluation of existing structures requires a fundamental knowledge of the materials involved, as-built condition, construction quality, and the extent of any deterioration or distress. For many years the traditional approach to obtaining such information was through destructive probes and removal of materials for laboratory testing. The development of nondestructive evaluation (NDE) methods have changed the way engineers approach structural condition assessment projects. A wide range of nondestructive and in situ diagnostics are not only available to the practicing preservation engineer, but are becoming a common component of structural evaluation projects.

Preservation engineers must have a basic understanding of diagnostic techniques and the ability to not only recommend complementary test methods but also interpret basic test results. Engineers that are able to apply NDE methods to preservation projects analyze and design with confidence, thereby ensuring life safety and serviceability objectives are met while at the same time minimizing the necessary level of intervention.

Coursework on nondestructive evaluation and diagnostic methods is an essential component of a preservation engineering curriculum. A semester-type course on nondestructive evaluation and in situ diagnostics would be best approached as a combination of lecture and laboratory sessions to provide students with hands-on experience. An undergraduate-level course could concentrate on providing a general understanding of different test methods, with advanced topics and analytical methods taught at the graduate level.

Current State of Knowledge

In recent years the engineering community has seen NDE move from the research arena into general practice, and it is becoming commonplace to require use of NDE technology on projects involving historic structures.

Nondestructive evaluation and in situ diagnostics in common usage can be categorized as follows.

- Mechanical Methods. Measuring basic material response, mechanical methods may include rebound hardness, probe penetration, pullout tests, and drilling techniques. Results of mechanical tests are loosely correlated with material mechanical properties such as strength and stiffness, and are best used as comparative measures rather than direct indicators of material properties.

- In Situ Tests. A potential subset of mechanical methods, in situ tests provide a direct measure of material strength and stiffness properties. For example, concrete and masonry may be evaluated using a borehole dilatometer. Unique to masonry are flatjack methods, used to evaluate the state of existing compressive stress in a wall system as well as masonry compression behavior. In situ shear and flexural bond tests are also available to evaluate masonry properties.
- Electrical Methods. Embedded metals may be identified using any number of commercially available eddy-current devices. Electrical resistance testing is sometimes used to obtain information on material continuity, the presence of internal voids, and moisture content. Capacitance-based moisture meters are also available for measuring moisture content in timber, concrete, and masonry. Half-cell potential and linear polarization resistance tests are used for diagnosing corrosion activity in concrete and masonry structures.
- Infrared Thermography. Variations in heat radiation measured at the surface of a structural element can be measured with infrared film or, more commonly, recorded as digital images using infrared cameras. In a state of heat flux, differences in surface temperature will exist in the vicinity of materials with different densities, heat capacities, and/or thermal conductivities. Infrared images are commonly used to indicate variations in moisture content, subsurface anomalies such as voids, near-surface cracks, or incipient spalls, and features hidden by surface plaster or frescoes, such as blocked openings or previous repairs.

- Microwave Radar. Often termed ground penetrating radar (GPR) or surface-penetrating radar (SPR), microwave radar techniques are becoming increasingly common for evaluating concrete, masonry, and timber structures. GPR is useful for locating internal anomalies such as metals, voids, deteriorated zones, and areas of high moisture content.
- Stress Wave Propagation. Ultrasonic pulse velocity has been used for several decades to evaluate general soundness of construction materials, including metals, concrete, timber, and masonry. Highly attenuative materials common to historic construction are often better evaluated using low frequency mechanical pulse techniques. Impact-echo is used to detect the depth of delaminations, spalls, and cracks within a section.
- Nuclear/X-Ray. Measurement of soil density using nuclear methods has been common to the construction industry for several decades. Other methods, such as the neutron probe, have been used in a few instances to evaluate historic materials. Somewhat more common is the use of x-ray techniques to evaluate internal construction including deterioration or decay. Low-power sources used in x-radioscopy provide a real-time method to evaluate low density materials such as timber; higher power x-ray sources and radiography methods are required to evaluate concrete and masonry sections.
- Analytical Methods. Advanced analytical approaches may use data sets from many of the nondestructive techniques discussed above to extend the usefulness of NDE. Examples of analytical methodologies include evaluation of stress wave data in the frequency domain, used in impact-echo and modal response

techniques; combined time and frequency domain analyses using the wavelet method, to measure stress wave dispersion in building materials; and tomographic analysis, used to back-calculate the velocity distribution throughout a section, thus locating anomalies in 2-D or 3-D space.

- Monitoring. Sensors to measure movement (tilt, displacement, strain) and environmental conditions (temperature, humidity, wind speed and direction) are often used to track long-term building response.

Applications of nondestructive methods towards evaluation of building materials are discussed in thousands of industry publications, including two texts on concrete evaluation, by Bungey (1982), and Malhotra and Carino (1990), nondestructive evaluation of timber, by Pellerin and Ross (2002), and applications for evaluating masonry by Suprenant and Schuller (1994). Standardized methodologies for some NDE approaches exist within the ASTM and RILEM systems, and several NDE techniques are discussed in ASCE 11-90 (1990), which includes NDE in their structural condition assessment guideline. Reference to NDE methods is less common in building codes and code-type documents. The International Existing Building Code (2007) and its predecessor the Uniform Code for Building Conservation (1997) mention only rudimentary shear and anchor bolt test methods for evaluating seismic resistance of historic masonry. More recently, publication of ASCE 41-06 (2006) includes a fairly comprehensive listing of major NDE techniques available for evaluating historic building materials, including recommendations for planning an engineering evaluation program.

Research Needs and Potential Funding Sources

It is clear that many NDE techniques are available to practicing engineers, and there are a wide range of publications describing the methods and potential applications. Much work remains, however, to develop applications better-suited to evaluation of historic building materials, and to educate design professionals on the proper application of NDE methods.

Significant funds are required to develop NDE methodologies. Nondestructive methods often involve emerging technologies and substantial investment in hardware and analytical development. Considering the large investment required, and the relatively minor potential for economic return, researchers often turn to federal funding sources to develop new techniques or adapt existing technology. Potential federal funding sources include the National Science Foundation and the National Center for Preservation Technology and Training (NCPTT). Equipment and software development may also be possible through the Small Business Innovative Research (SBIR) program, which is available through many federal agencies, aimed specifically at high risk technologies with a moderate return potential. Minor funding may also be available through private corporations with a vested interest in product development.

Without listing specific research topics, I can define several general directions for future NDE research.

1. Technology transfer. Most NDE techniques were originally developed by other industries, such as the medical or aerospace fields. Existing technology

should be sought out and modified as necessary for evaluation of historic building materials.

2. Historic construction material characterization. Many nondestructive methods have been developed or adapted for use with modern construction materials, and the response of historic materials to nondestructive evaluation can be very different. Use of classic NDE techniques for evaluation of historic materials is often unknown or untested. Basic research is needed, for example, to identify dielectric constants of typical historic materials, to be used for microwave radar evaluation. Dielectric characterizations would include the effect of salts and varying moisture content on the materials' ability to store and transmit electromagnetic energy.
3. Real-time imaging. Improved post-processing and development of expert systems are needed to simplify interpretation of NDE results. Real-time imaging would permit evaluation of historic sections in the field.
4. Non-contact methods. Many NDE techniques require sensors to contact the structure. Critical historic materials may be damaged by even casual contact; non-contact methods would simplify access requirements and also prevent or minimize damage to sensitive surfaces.
5. Global evaluation approaches. Many NDE techniques are highly localized in nature, requiring a database established by a series of point-by-point measurements. Automated techniques and global scanning methods would be especially useful for evaluating historic structures, which often involve materials and structural components from many different periods.

6. Field evaluation of salts, stains, and biological deposits.
7. Guideline development. Development of guides for NDE use and code-type language must be continued, to provide engineers with methodologies and evaluation systems that can be applied to structural condition assessment.

Essential Competencies

A primary goal of a college-level NDE course would be to provide a working knowledge of NDE methods. Potential learning objectives follow.

- An understanding of different NDE methodologies that are available, including applications for material evaluation, conditions under which methods provide useful information, and the limitations of each technique.
- Basic theory behind different methods should be taught to provide general knowledge of the function of different NDE techniques. Theory lectures would include discussion of the property measured directly by each method, and how those measures are correlated to parameters of interest.
- Persons completing a course on NDE should be able to recommend tests and combinations of tests to diagnose certain conditions, and be able to use combined methods to verify results.
- Interpretation of test results. These skills may range from rudimentary evaluation to advanced analysis.
- A working knowledge of statistical methods. Students should be able to apply statistical techniques towards choosing test locations, analyzing results, and recommending design values. Statistical knowledge could range from basic

methods such as calculation of mean, standard deviation, and coefficient of variation values, to advanced techniques such as q- and f-tests and curve fitting.

- Finally, hands-on experience is necessary. Some NDE methods are user dependent and the various techniques lend themselves towards a laboratory or field component. Equipment could be used to evaluate simple conditions as part of the curriculum.

Experiential Learning Opportunities

No formal internship or scholarship program is known; any such opportunities would have to come through individual efforts with private corporations. It may be difficult to establish a meaningful internship program, considering the relatively small number of firms using NDE for evaluating historic construction and the advanced level of experience required for some NDE methodologies.

Curriculum

A semester-long curriculum for teaching NDE applications with historic structures is not known to exist. Short NDE course modules are thought to exist at only a handful of universities throughout the country. Existing courses or course components are taught at the University of Wyoming (www.masonrysociety.org/Masonry%20Lab/Home.html), the Massachusetts Institute of Technology and Colorado State University. Other college level courses undoubtedly exist and should be identified.

Another educational resource is the Association for Preservation Technology (APT). APT first developed an engineering diagnostics workshop in 2004 as a 2-day course discussing NDE applications for evaluation of historic concrete, timber, and masonry. The curriculum includes classroom lectures and hands-on exposure to several of the more commonly-used NDE techniques. The workshop has been held 3 times, in Galveston, Texas, Charleston, South Carolina, and Fredrick, Maryland. Future workshops are planned, with partial funding support provided by NCPTT. The course notebook includes PowerPoint lectures and reference materials.

A course on NDE applications for evaluating historic structures would be of interest to most engineers studying preservation principles. The curriculum would be best established as a combination of background theory, learned through lectures, and laboratory sessions, to provide hands-on experience.

Prerequisites would be an understanding of historic materials and their deterioration processes, historic building systems, and historic construction methods. It would be useful for students to have a working knowledge of these topics to facilitate planning and interpretation tasks. Basic mathematical skills are required for many methods as well, including the ability to conduct simple statistical analyses.

Developing or even providing an NDE course could pose problems for smaller educational institutions. Many types of NDE equipment is prohibitively expensive, and it may require upwards of $100,000 to assemble a set of NDE hardware suitable for educational purposes. Technology changes rapidly and the need to update NDE equipment would pose a continual funding challenge. Many devices can be rented, however, for short-term usage. X-ray and nuclear methods also present safety issues for use in crowded buildings; special state or federal certification is often required to use these types of equipment. Finally, a high level of experience is necessary to gather useful data and interpret results of some NDE techniques. Diagnostics coursework would be best taught by faculty with several years' NDE experience.

An undergraduate level course could be developed to provide basic, yet critical, information as well as hands-on experience. Advanced coursework at the graduate level may include more detailed study of new technology and in depth experience with more complex approaches such as ultrasonics, microwave radar, and infrared thermography. Advanced analytical methods could also be incorporated into a graduate level course, to include topics such as FFT analysis of transient stress waves, modal analysis of structural response, and tomographic analysis.

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