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ABSTRACT:

Student learning is enhanced through physical demonstrations and laboratory experiments. Such activities are a successful tool to facilitate retention of knowledge and increase student involvement in construction and physical testing. Students who experience laboratories have a clearer understanding of masonry construction and applying the fundamental concepts of masonry design. Furthermore, they are better equipped to troubleshoot and work with existing masonry because they are familiar with current field test methods. This paper covers the development of classroom activities for masonry construction, masonry testing and state-of-the art masonry field evaluation. The *primary objective* was to provide materials for masonry laboratory activities that can be easily incorporated into the curriculum at other institutions. This work developed a series of two masonry modules focusing on masonry construction and masonry testing. These modules include six masonry laboratories presented to introduce real world construction and field testing into classrooms. One unique feature of each laboratory is a demonstration of the experiment with sample data that students can use to create a "virtual" laboratory experience. Masonry instructors may enhance a curriculum through physically replicating the laboratory experiments if facilities and time permit, or through using the virtual aspect of the laboratory modules to model laboratory activities.

A *secondary objective* reviewed existing nondestructive test and evaluation methods (NDT and NDE). These nondestructive testing techniques are a viable alternative used to evaluate the condition and strength of existing structures instead of limiting use or causing destruction of the buildings. A case study was carried out where an array of nondestructive techniques were implemented in a forensic analysis of a set of concrete masonry structures. Along with the case study, independent research on a number of techniques was performed. These state-of-the art techniques were incorporated into the *primary objective* in the form of a new masonry laboratory.

Enhancement of masonry curriculums through virtual laboratory experiments

By
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Dedicated to

Jeanne Anne Coombs

Whose life and passing will never be forgotten…

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1.1 Statement of Problem

Students learn in a multitude of different ways. In the classroom, variety is essential to provide a well balanced curriculum applicable to all students' learning styles. One way to expand the types of teaching beyond the auditory and visual learning of the classroom is to include tactile/kinesthetic learning through laboratory sessions. Although student learning can be enhanced through laboratory sessions and physical demonstrations, these sessions and demonstrations frequently require time-consuming preparation and consequently are difficult to incorporate and complete within a 50-minute class period (Boggs 2006). Furthermore, laboratory sessions and physical demonstrations require space and equipment not readily available at all universities. While there are many civil and architectural engineering programs offering some masonry instruction, not all are equipped with the laboratory facilities to offer students full scale hands-on construction and testing experiences.

As laboratory activities are a successful tool to facilitate retention of knowledge and increase student involvement in construction and physical testing, the University of Wyoming has developed a supplement to hands on laboratory experience for its masonry course. The University of Wyoming's masonry course provides its students with a unique opportunity to experience the basics of building and testing of masonry and seeks to provide those students without access to laboratory facilities a way of vicariously experiencing the knowledge gained through these laboratory sessions electronically in a virtual laboratory. The virtual laboratory will be implemented online as well as provided in CD format.

Most students prepare for laboratory one day, carry it out the next and do not revisit it until final exam time where they try to recall what exactly they did and what they were looking for in the laboratory. Frequently, students find it hard to recall everything that is needed for an exam from only the laboratory handout and their laboratory write-up that might have originally only received a sub par score. (Boggs 2006) By virtue of a virtual laboratory, the laboratory procedure can be reviewed at any time throughout the semester, including the night before the final. With access to all the procedures visually and textually, correct sample results and sample write-ups, a student can have access to all the information needed to become knowledgeable about the laboratory. The virtual laboratory is always available to brush up on any of the concepts, or review ideas ensuring that a full understanding is available at any time. Thus, not only are virtual laboratories a way for students to experience and gain this knowledge initially, but also a way to make this knowledge available and accessible at any time throughout their course work, and ultimately in practice.

1.2 Purpose

The *primary objective* of this work was to provide instructional materials for masonry laboratory activities that can be easily incorporated into the curriculums at educational institutions. This incorporation can be accomplished through physically replicating the laboratory experiment at institutions where space, time and resources permit or through using the virtual aspect of the laboratory modules on-line or on CD. The material will be accessible through The Masonry Society (TMS) or Rocky Mountain

Masonry Institute (RMMI) website and on CD format for distribution at activities such as the University Professors' Masonry Workshop offered through TMS.

1.3 Virtual Laboratories

Virtual laboratories progress with technology. In today's networking age, it is increasingly easier to share information, whether it is from a piece of test equipment to a computer across the room or from two people on opposite sides of the world. With software, such as Labview, scientific test equipment can be linked to a computer from which it can be controlled and data management becomes trivial. Networking can ultimately allow the testing equipment to be remotely run from anywhere, opening up new doors to extend the laboratory experience to distance learning programs. Unfortunately, the laboratories set up for the masonry course do not lend themselves well to remote equipment control. Not all virtual laboratories require remote control of the testing equipment, many use a combination of text, audio, pictures, and video to simulate the laboratory experience.

Virtual laboratories are very versatile and can fit almost any academic program. There is heated debate, however, as to whether or not a virtual laboratory can adequately take the place of a traditional laboratory. The University of Wyoming does not suggest replacing existing traditional laboratories, but rather wants to augment every masonry student's ability to obtain knowledge. For those students who already take part in traditional masonry laboratories, the virtual laboratory can be used to assist and add to the experiences, not replace them. The virtual laboratory would also allow for students who miss the laboratories to vicariously make them up. For students without access to traditional masonry laboratories in their course, the virtual laboratories would enable them to add a laboratory component to their curriculum. By doing so, every masonry student can gain something from the introduction of a virtual laboratory in their curriculum.

The virtual laboratories will follow the format of traditional laboratories as they are taught in the University of Wyoming's CE-4280 and ARE-4280 Reinforced Masonry Design courses. Laboratories will be built on an interactive foundation allowing students to explore and learn within each laboratory at their own pace. Each laboratory will include the laboratory procedure, results, example solutions and literature expanding on the concepts illustrated in each laboratory. The information will be presented in the form of text, pictures, drawings, diagrams, video and simulation to encompass all students' styles of learning. The goal of the laboratory development is to replicate the experience of the actual laboratory with multimedia, ultimately imparting the same knowledge as the traditional laboratory with the potential for improved retention and understanding from its constant availability. This approach intends to give students a better conceptual understanding of the material allowing them to apply it to future educational instruction and testing as well as to their future.

The University of Wyoming currently has six laboratories for their masonry course which are divided into two modules:

Module A – Masonry construction

Laboratory 1 - Construction of masonry walls and prisms including mixing and testing mortar.

Laboratory 2 – Construction of masonry arches.

Module B – Masonry testing

Laboratory 3 – Evaluation of bond strength of masonry prisms using bond wrench testing and modulus of rupture testing.

Laboratory 4 – Evaluation of compressive strength of masonry units and masonry prisms.

Laboratory 5 – Testing of student-fabricated masonry arches and development of final report.

Laboratory 6 – Nondestructive evaluation of masonry

Module A's laboratory goals are to impart to students the basics of masonry construction. These characteristics include, but are not limited to, masonry's modularity, orientations, mortar mixing, construction and design processes. Module B's laboratory goals include familiarization with masonry testing and its material characteristics. These physical properties of masonry include tensile and compressive strengths and their corresponding masonry behavior.

1.4 Nondestructive Evaluation

Nondestructive evaluation is an excellent example of a constantly progressing new technology where improved techniques become available both for data acquisition and data processing. Engineers in the workplace need to continually learn about state-of-the art methods in testing and design. With this progression, nondestructive evaluation (NDE) has increasingly become a major part of masonry field work. As many of the United States' historical masonry buildings are aging and will require maintenance or repair, NDE is a viable alternative to evaluate their condition and strength instead of using techniques which would limit their use or cause destruction of the buildings. NDE is also used to evaluate structures of questionable structural stability, to survey buildings for legal proceedings, to monitor and carryout preventative maintenance, and other applications. NDE provides insight into the inner condition of masonry. Unfortunately, NDE uses expensive and specialized equipment; therefore, actual hands-on practice by students is even more limited in this laboratory than in other laboratories. In virtual laboratories, students will be shown the basics of NDE of masonry with observation, radar, infrared imaging, rebar location with pachometers or cover meters, flat jack testing, and impact echo.

Due to the required equipment and expertise, this laboratory lends itself particularly well to the virtual laboratory, where the concepts can be illustrated equally as well virtually as it is traditionally. Students can easily observe how these tests are run, results from the tests, and how the results from the equipment are analyzed and processed to evaluate the integrity of the masonry. Many of these tests are not solely used for the evaluation of masonry; these evaluation techniques are also used to evaluate structural concrete, metals, and composites. This makes knowledge of these tests very versatile, as it can be applied to many of the materials and structures confronting an engineer. Scientific literature on the concepts of techniques and uses of nondestructive evaluation equipment will be included in the virtual laboratory to give the student the resources to learn more.

2 Literature Review: Education

The manner in which we learn has been studied at length throughout history. It has been shown that individuals have different styles of learning. Each student retains knowledge best through their preferred style, but students have no control over an instructor's teaching methods and style. Lowman (1995) discussed intellectual excitement and interpersonal rapport as two dimensions essential to effective teaching. Intellectual excitement describes a teacher's intellectual relationship with the material and its teaching: expertise, excitement, understanding, organization, clarity, and presentation. A teacher's interpersonal rapport describes the personal interactions with students and their lives: concern, care, encouragement, accommodations, and help. Both dimensions are equally important and must be implemented together to achieve exemplary teaching and reach full teaching potential. Laboratories, both traditional and virtual, generally promote intellectual excitement and provide an opportunity for developing personal rapport.

Students whose preferred learning method matches the professor's teaching style will do much better than those that do not correlate. This can be seen in classes where students become bored and inattentive, both of which lead to poor performance throughout the course. Felder and Silverman (1998) provided the table of learning styles with corresponding teaching methods below.

Table 1: Learning and Teaching Style Correlations

Dimensions of Learning and Teaching Styles			
Preferred learning Style		Corresponding Teaching Style	
Perception	Sensory	Content	Concrete
	Intuitive		Abstract
Input	Visual	Presentation	Visual
	Auditory		Verbal
Organization	Inductive	Organization	Inductive
	Deductive		Deductive
Processing	Active	Student participation	Active
	Reflective		Passive
Understanding	Sequential	Perspective	Sequential
	Global		Global

Each student's different learning style corresponds to the teaching style from which they will best learn. In engineering education, most students' learning and professors' teaching styles do not match. Most students are "visual, sensing, inductive, and active [learners], and some of the most creative students are global [learners]; [however] most engineering education is auditory, abstract (intuitive), deductive, passive, and sequential." (Felder and Silverman 1998) This disparity in learning and teaching styles leaves many potential engineers struggling and sometimes failing.

It is shown that most students benefit from the addition of laboratory or hands on sessions during their education. The laboratory environment is shown to cater better to engineering students than lecture alone. By combining lecture and laboratory, a greater base of student's learning styles are covered yielding better class participation and performance. Unfortunately, laboratory experiments have been de-emphasized in many curriculums due to a number of reasons: cost of equipment, faculty time, equipment upkeep, and low expectations of students running expensive and fragile equipment accurately. Laboratories provide discovery learning present in no other part of education. (MacKenzie 1988)

Currently, science education is lacking laboratory emphasis. Schools are not providing basic science classes. They are pushing the boundaries of the definition of science and teaching music and health in place of physics and chemistry. Laboratories currently rush students through a predetermined laboratory which emphasizes write ups and data evaluation, not data acquisition or the scientific process of experimenting. (MacKenzie 1988) Virtual laboratories, through ease of use and implementation, can help bring back true scientific experimenting to the classroom.

How does a virtual laboratory fit into today's educational system? Virtual laboratories can be included in situations where laboratories are too dangerous or difficult to carry out in a classroom environment due to facility or time constraints. They can also be carried out at each student's own pace, allowing them to revisit the laboratory and continue or brush up on the concepts learned. Virtual laboratories have been considered as an addition to existing laboratory experiences as well as the sole "laboratory" experience and both offer benefits to the traditional laboratory experience of most science and engineering programs.

Moure et al. (2004) evaluated the effects of using a virtual laboratory in conjunction with a traditional laboratory versus the traditional laboratory alone. They show virtual laboratories bridge the gap between the theoretical teaching and the actual laboratory. In electrical engineering, mistakes in the actual laboratory while trying to go directly from classroom theory to practice result in broken components, poor circuit board building and misused equipment. By allowing students to practice on a virtual laboratory, mistakes can be made with little consequence. This practice gives students a chance to learn the techniques, processes and ask questions, enabling them to more easily relate the theoretical lecture material to the practice of hands on laboratories. To test their hypothesis Moure et al. (2004) had 12 students do an electrical circuit laboratory, half with no virtual practice and half with virtual practice. All those with no virtual laboratory made a variety of mistakes in the build while all those exposed to the virtual laboratory made theirs the same way and did not have any errors in the build. In the laboratory, a circuit error was designed into the circuit to give students an opportunity to diagnose malfunctioning circuitry. Those students who used the virtual laboratory were able to diagnose the built-in flaw in the circuit system 60% faster than those who did not participate in the virtual laboratory. As a consequence of this experiment, the virtual laboratories were adopted as a permanent component in the curriculum to increase learning, knowledge, and decrease the broken equipment and laboratory costs due to mistakes. (Moure et al. 2004)

Many virtual laboratories exist in the health sciences and life sciences (Akpan et al. 2000; Boggs 2006; Huang 2003, 2004). This thesis focuses on a particular virtual laboratory developed and implemented at the University of Wyoming by Christi Boggs and Rachel Watson. Boggs developed and evaluated a virtual laboratory system for a microbiology class at the University of Wyoming. The virtual laboratory was developed with the intent of supplementing the traditional laboratory. The virtual laboratory creates better options for instructors and students to deal with missing laboratories without requiring tedious and time-consuming preparations. In this application, some laboratories require live organisms which have a very limited useful life span and could have been cultivated for months before hand to be ready for a specific laboratory day. The development of the virtual laboratories can, therefore, be used not only to supplement the traditional laboratories but also as a stand-alone make up laboratory.

During the study, Boggs designed and implemented the virtual laboratory system online utilizing text, pictures, drawings, diagrams, video and simulation. The laboratories were built using multimedia taken during previous laboratory sessions and during some specific sessions whose sole purpose was to provide multimedia for the virtual laboratories.

Boggs also created a feedback system to monitor the student's response to the laboratories as well as the overall usage of the online laboratories. Throughout one of her focus groups or semester implementations of the virtual laboratory (fall 2005), 73 students were actively enrolled in the sections of the microbiology laboratory where the instructors introduced the virtual laboratories as a reference tool in the class resources. However, all students enrolled in a microbiology laboratory section had access to the virtual laboratories regardless of whether or not their instructor utilized them as a class resource. As they were not required to do so, few students used the virtual laboratories to prepare for the actual laboratories. But those that did use the virtual laboratories responded very positively to the preparedness they had experienced in the traditional laboratory due to carrying out the virtual laboratory. Often those that tried the virtual laboratory once ended up using it for the remainder of the semester to prepare for all laboratories. Although the virtual laboratory was available for the duration of the semester, the majority of its use was at the end of the semester right before the laboratory practical exam. During this time period, web page counter logs displayed over a hundred users and thousands of page hits, showing that even with no incentive to use the virtual laboratories, students found it very helpful in reviewing the laboratories at later dates. The data showed that students who were not enrolled in the sections using the virtual laboratories as a resource were also using the virtual laboratories.

Boggs monitored not only usage, but also received feedback in the form of an optional survey. The survey utilized a Likert scale for testing the effectiveness of the virtual laboratories and getting a student profile. In Boggs' survey, the Likert scale scores ranged from 1 for "strongly disagree" to 5 for "strongly agree". In Boggs' fall 2005 focus group, 75% of the enrolled students took the optional questionnaire. When asked if the virtual laboratory helped prepare them for the laboratory practical exam, the average response was 4.22, or in between agree and strongly agree. Also, when asked if the virtual laboratories should be continued in future classes, the average response was 4.65, showing overwhelming student support for the usefulness and effectiveness of the virtual laboratories. Faculty were also polled informally about the virtual laboratories and responded positively to their use in supplementing the traditional laboratories. Boggs concluded that the virtual laboratory was an effective tool to augment and improve traditional laboratories as well as provide flexibility for students who are not able to attend the traditional laboratory.

Van Poppel et al. (2004) also compared a traditional laboratory to a virtual laboratory as well as both forms used in conjunction. The gas turbine engine is a common power plant in many military applications such as tanks, helicopters, and ship propulsion and the incorporation of this laboratory into the thermodynamics class is essential to the learning and retention of knowledge for use in the future military officer's career. The gas turbine laboratory at the United States Military Academy (USMA) was damaged and in a state of disrepair after an unusually intense summer weather season. To facilitate the laboratory during the down time, the professors developed a virtual laboratory which simulated the traditional laboratory and provided close to the same learning experience to students.

The virtual laboratory starts with a video introduction to familiarize students with the gas turbine engine, its components and instrumentation. After watching the introduction video, students were quizzed on the material. In laboratory groups of 3-4, students are shown another video of the actual engine during startup, the engine under different load and power conditions, and during shutdown. Students are shown the instrumentation, the dynamometer, torque, and engine speed at four key points in the operating range of the engine. After observing and collecting data from the instrumentation at these four points, the students carry out the rest of the laboratory in the same manner as if they had just completed the data compilation from a traditional laboratory. Students use the raw data to carry out theoretical and actual performance calculations and create a laboratory report.

Approximately 60 students used only the virtual laboratory for their thermodynamics course. Both the instructors and students agreed that the virtual laboratories were beneficial and helped augment the class lecture and theory. Twelve students participated in both the virtual laboratory and the traditional laboratory. These twelve students concluded each form of the laboratory contained strengths and weaknesses. The virtual pre-laboratory work and introduction was better than that of the traditional laboratory. The actual data gathering and physical presence in the traditional laboratory was superior. Overall the professors and students concluded that the "virtual laboratory assets used in conjunction with real laboratory equipment may be an ideal compromise for programs that maintain both types of laboratory assets." (Van Poppel et al. 2004)

The virtual laboratories have a high up front cost but little or no reoccurring costs. Generation of the virtual laboratory, which included video footage of the laboratory, video editing, and running all calculations as students would, required over 60 hours of professors' time, and over $1300 dollars in video equipment and editing costs. A virtual laboratory, however, is a one-time cost. The upkeep of a traditional laboratory is reoccurring with laboratory equipment maintenance, laboratory personnel, and material needs. Overall, the professors concluded that all schools, even those with laboratory facilities, should "maintain a virtual laboratory as a ready and easily implemented contingency in case of mechanical or other difficulty. For schools that do not maintain a … laboratory, the option of a virtual laboratory could be a viable alternative laboratory experience to reinforce … fundamentals." (Van Poppel et al. 2004)

Rak et al. (2006) and Steidley and Bachnak (2005) discussed the increasing possibilities of a true virtual laboratory, one that is carried out completely virtually through the use of networking or other control system and where the laboratory process is actually carried out remotely. Sites with remote control systems have been funded through the National Science Foundation (NSF) and the Network for Earthquake Engineering Simulation (NEES) programs. With today's upgrades in technology, laboratory equipment is becoming integrated into computer systems which can control equipment operation and monitor data acquisition. Programs such as Matlab and Labview are capable of connecting to, and communicating with, ever updating testing equipment. This connectivity provides an interface to remotely control equipment and manage data from miles away. Utilizing this technology allows students taking remote classes to conduct laboratories individually, without any special laboratory facilities locally available. Some required features are a login process which can, (1) limit the use to only students who are "qualified" to conduct the experiments, and (2) to allow only one user at a time to remotely control the equipment. One controlling user is a must to achieve efficient and productive results and safeguard the condition of the equipment. In the future many distance learning programs will be able to upgrade their courses to include a laboratory session in addition to the lecture component. The University of Wyoming's masonry laboratories are currently not capable of remote control; therefore their virtual laboratories do not use this remote testing option.

3 Development of Virtual Laboratories

The development of the University of Wyoming's virtual laboratories utilized a variety of tools to facilitate the use of different presentation methods. Three important software programs in the development of the laboratories included Macromedia's Dreamweaver 8, Adobe's Premier 2.0, and Macromedia's Flash 8. In the development, Macromedia's Dreamweaver 8 was used to build web pages while Adobe's Premier 2.0 and Macromedia's Flash 8 were used to provide the web pages with animations, movie clips and other graphics.

As a starting point, a "homepage" was developed (Figure 1). The homepage was used as a template for all other pages, which followed its basic format and setup. From this homepage, all other laboratories and resources would be linked. Each laboratory includes a thorough description of the laboratory, sample data where applicable, a sample laboratory handout, a sample laboratory report, photographs of the laboratory being carried out, and if possible, a video of the laboratory experiment being carried out. (Figure 2, Figure 3 and Figure 4)

Video and picture media were captured for use during actual laboratories carried out during the fall 2005 and fall 2006 semesters and for individual laboratory test runs set up and run by graduate students and under-graduate assistants. During the building of the virtual laboratory, all pictures and videos were edited and condensed to provide concise media which emphasized the key components of the laboratory. This was done through the capabilities of Adobe's Photoshop for photos and Macromedia's Flash 8 and Adobe's Premier 2.0 for video.

Combining all the components of the laboratories was time consuming, involving the gathering, organizing and processing of a wide range of information. The costly setup, both monetarily and time wise, is normal for the development of a virtual laboratory.

The reader is encouraged at this point to review the enclosed supplemental CD for a preview of the construction and testing procedures.

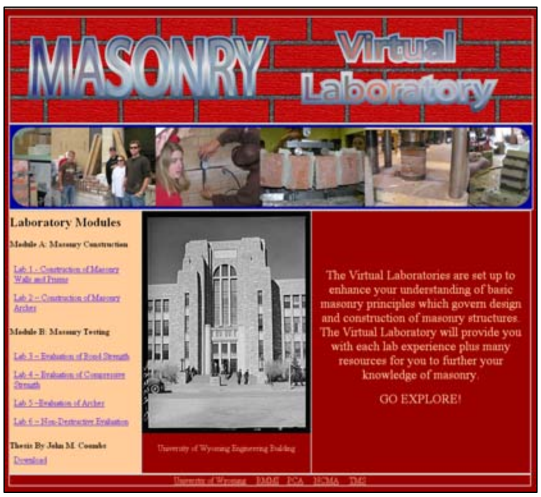

Figure 1: Virtual Laboratory home page.

Figure 2: Characteristic photograph page.

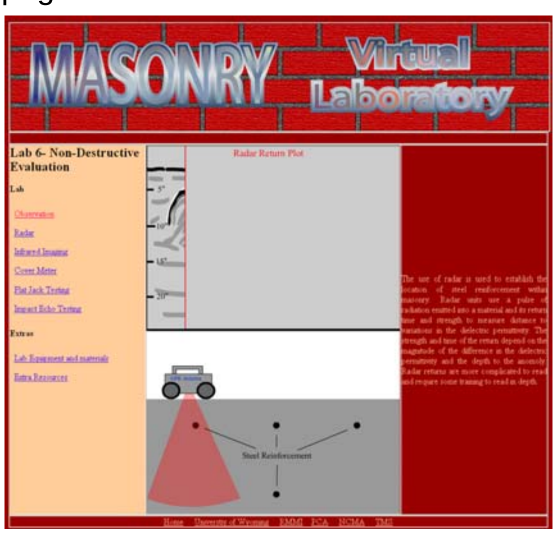

Figure 3: Animations used to illustrate difficult concepts and ideas.

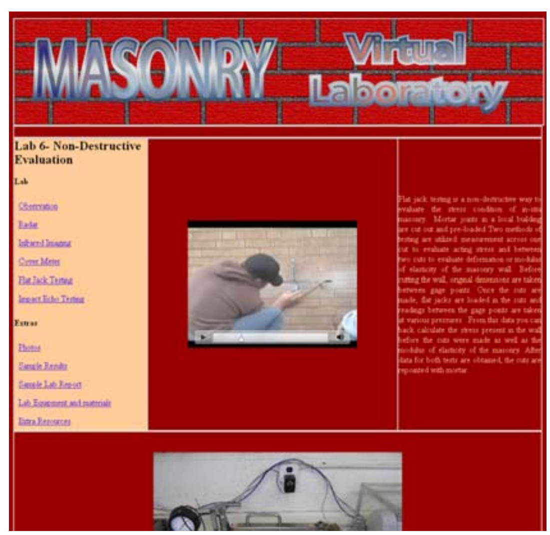

Figure 4: Video used to present the laboratory procedures and ideas.

Laboratories

The masonry course taught at the University of Wyoming includes two modules broken into six laboratories, each offering hands-on experience to students in a variety of masonry principles. The two modules consist of masonry construction and masonry testing. The laboratories are broken down to include mortar mixing, prism assembly, basic wall construction, arch construction, prism testing, and nondestructive evaluation techniques. Each virtual laboratory module contains an introduction and background information on the topic and real world applications that masonry professors may use to introduce the topic. Video demonstrations in digital format are available to easily incorporate the laboratory experience into a normal class lecture. In each laboratory module, where feasible, results are available for introduction and practice data analysis. The video demonstrations cover the laboratory and information on the test setup and correct test procedures. This allows students the opportunity to see what can affect the data and outcome of an experiment as well as the knowledge of how the test is run, its inherent shortcomings and what to expect from each test. Additional supporting material for the instructor for each laboratory module may also include: material lists, sources for equipment and materials, drawings for test equipment, literature review, laboratory instructions, video with demonstration test, and examples of sample laboratory reports for students and professors to review.

The modules and individual laboratories are broken down as follows (same as in introduction):

Module A – Masonry construction

Laboratory 1 - Construction of masonry walls and prisms including mixing and testing mortar.

Laboratory 2 – Construction of masonry arches.

Module B – Masonry testing

Laboratory 3 – Evaluation of bond strength of masonry prisms using bond wrench testing and modulus of rupture testing.

Laboratory 4 – Evaluation of compressive strength of masonry units and masonry prisms.

Laboratory 5 – Testing of student fabricated masonry arches and development of final report.

Laboratory 6 – Nondestructive evaluation of masonry

3.1 Module A: Masonry Construction

The masonry construction module of the laboratory sessions is instrumental in the teaching of masonry design. In construction, each material used has its advantages and disadvantages. Construction, and its practices, is also a major factor in the overall properties of the masonry system. By taking part in construction with a building material that will be used in design, students gain some first-hand knowledge of its construction methods, its strengths, its unique features and shortcomings.

In masonry, some key characteristics are demonstrated in a short introductory construction session. These two laboratories are designed to familiarize students with these characteristics of working with masonry. The biggest concept in masonry design and construction for the future designers to grasp is modularity. Masonry units are modular or built to a nominal standard size. A masonry unit can be combined in one orientation to match the dimensions of another orientation. When designing masonry, an engineer should make all dimensions fit an integer number of brick in any orientation used.

By understanding the material and its characteristics, a designer can produce a design that more efficiently uses materials and labor. This concept is called design constructibility. Designing with constructibility in mind will make the contractor's job easier, yielding a better product in less time with less errors, revisions and corrections made on site and ultimately a more cost effective product.

3.1.1 Laboratory 1- Basic Construction Techniques

The objectives of this laboratory session are to familiarize students with basic masonry tasks including laying brick and mortar mixing and testing. In the design, construction, and use of masonry structures, each involved party desires different properties from the mortar. The engineers design with physical properties of compressive strength and bond strength. Masons during construction desire a mortar that is workable making their job easier. Finally the user desires a mortar that is durable and requires little or no maintenance. Unfortunately, there is no perfect mortar type that can accomplish all these properties and emphasizing one most often detracts from the other properties. Therefore, great care must be used in deciding which mortar to specify.

Masonry mortar is divided into three cementitious systems: portland cement-lime, masonry cement, and mortar cement. The first is mixed using both portland cement and lime while the latter two are pre-mixed blends of cementitious materials and plasticizing materials to enhance workability. Masonry mortar is further broken down into five different types corresponding to different compressive strengths. The types from strongest to weakest are M, S, N O, and K. Most often types S and N are used as they provide a good compromise of strength and workability.

During this laboratory, students mix mortar using two of the three cementitious systems found in masonry: portland cement-lime and masonry cement. Mixing both systems illustrates the ease of proportioning with pre-mixed masonry cement and its increased workability due to its admixtures and plasticizers. When a mortar is specified in design, it can be specified by proportion or by property. Most often specification by proportion is used to avoid strength testing requirements to verify that the actual mortar strength meets the specified strength. Students perform the batching and mixing of different mortars, prior to measuring the corresponding flow rate and entrained air content.

Workability of mortar is its ease of use measured by the flow. The standard flow test uses a standard conical frustum of mortar with a diameter of four inches (Figure 5 and Figure 6). The conical frustum mortar sample is placed on a flow table and dropped 25 times. As the mortar is dropped, it spreads out on the flow table (Figure 7). Flow numerically compares the final diameter of the mortar sample to the initial diameter. Flow is defined as the increase in diameter divided by the original diameter multiplied by 100. Laboratory mixed mortar, where conditions are more controlled, should have a flow of approximately 110. In the field, mortar is usually mixed to a flow of about 130-150. As mortar sits, its flow decreases. To maintain workability, the mortar is re-tempered by adding water. Mortar should only be re-tempered for the first two and a half hours, after this time, a new batch should be mixed.

Figure 5: Mortar flow table with mortar mold in place.

Figure 6: Mortar flow table with mortar mold removed.

Figure 7: Mortar flow table after being dropped 25 times.

Figure 8: Mortar air entrainment measure by pressure method.

Entrained air content is measured by a pressure meter method (Figure 8). Air content in mortar affects both the compressive strength and bond strength of the mortar. Limits imposed on the percent air by volume of mortar are a max of 12% for portland cement-lime mortars and 18% for masonry cement mortars.

Once the mortar is mixed and verified to be within limits on flow and entrained air, it is used to construct six unit stack bond masonry prisms (Figure 9). In the construction of the prisms, a jig is used to ensure the specimens are plumb. Each student group constructs two prisms, one using a portland cement-lime mortar

(PCL) and the other using a pre-mixed masonry cement (MC). These masonry prisms are later tested as part of Module B.

With the remaining mortar, students practice basic brick laying techniques by constructing a mock masonry wall. (Figure 10) The mock wall gives each student the opportunity to practice the art of laying brick and reinforces different bond patterns and unit orientations. The overall construction imparts the knowledge of experience to the future engineers, providing a better basis for designing with constructibility in mind.

Figure 9: Masonry prism construction.

Figure 10: Mock masonry wall construction and brick laying familiarization.

This laboratory was evaluated by a focus group of seven students who accessed and explored this portion of the virtual laboratory. They answered a worksheet as a simulated in class assignment and filled out a survey. The focus group included students in Criminal Science, Range Ecology and Watershed Management and Civil and Architectural Engineering majors, from sophomore through graduate level and varying computer skills. Correctly completed worksheets indicate an understanding of the presented material. All students responded positively to the virtual laboratory, its implementation and use as a class resource. In the survey, which utilized a Likert scale as well as short answer questions, students thought that the virtual laboratory was an effective resource and should be implemented. One student expressed that "the virtual lab presented the hands-on lab well, but I would rather see the virtual lab before I did the hands-on lab," precisely the way it will be implemented in the future at the University of Wyoming. All responses were positive on the virtual laboratory reinforcing its development and implementation.

Virtual Laboratory inclusions:

a. Lab 1: Masonry Familiarization
   i. Mock Masonry Wall
      1. Text
      2. Pictures
   ii. Initial Rate of Absorption
      1. Text
      2. Animation
   iii. Mortar Mixing
      1. Text
      2. Video
   iv. Mortar Workability
      1. Text
      2. Video
   v. Mortar Air Content
      1. Text
      2. Video
   vi. Prism Construction
      1. Text
      2. Video
   vii. Extras
      1. Lab Handout
      2. Sample Lab Report
      3. Photos
      4. Lab Equipment and Materials
      5. Extra Resources

3.1.2 Laboratory 2- Masonry Arch Construction

The objectives of this laboratory session are to provide students with an opportunity to design and build an atypical masonry structure. When combined with the corresponding testing laboratory, students get to practice a design, build and test process, rarely available in their normal course work. In this laboratory, the groups are given dimensional requirements through a box rule, to limit the size and shape of the arch, and fix material quantities. The box rule allows each group to come up with their own design ideas while still allowing for a single test setup to test all groups' arches. Common arch designs include: single and double wythe, semi-circular, gothic, and primitive.

In this construction part of the laboratory, students submit a preliminary design of their arch indicating: dimensions, mortar type, materials needed for actual arch construction, construction plans for building and transporting the arch to the test location, and most importantly, a conjecture on possible failure modes and locations.

Students are allowed to amend their construction plans and design throughout the construction process. This section of the laboratory practices and reinforces the basic brick laying techniques introduced in the first construction laboratory (Figure 11).

The arch construction teaches future engineers a valuable lesson in construction: the need for change. The changes each group experiences in their design and construction plans for their arches reflect the on-site changes that will confront them in future practice. These future engineers will learn that change is a part of improving and facilitating construction and not a criticism to their engineering skill.

Figure 11: Masonry arch construction

Virtual Laboratory inclusions:

b. Lab 2: Arch Design and Construction
    i. Masonry Arch Construction
        1. Text
        2. Diagrams
    ii. Extras
        1. Lab Handout
        2. Sample Lab Report
        3. Photos
        4. Lab Equipment and Materials

3.2 Module B: Masonry Testing

The second module in the masonry laboratory sessions is the testing of masonry. This module is extremely important to the student's understanding of masonry. Through testing of the masonry, students expand their knowledge of the characteristics of masonry behavior allowing them to design it more expertly in the future. Seeing the testing method also introduces students to methods by which they can monitor the quality and check the properties of the construction of their design.

In the testing module, students test the bond strength of masonry systems in the form of prisms in two different methods, modulus of rupture and bond wrench testing. Students will also test the compressive strength of the system as well, noticing how the different components of the masonry system work together and contribute to the characteristics of the overall system.

Another key component to the testing module will be the introduction to nondestructive evaluation. As time goes on, structures degrade and age. These changes require a constant retrofit and repair process. To facilitate this process in the most economical method, nondestructive evaluation (NDE) is used. NDE allows the user to evaluate the current condition of structures including strength and actual constructed state. NDE will become a crucial part of any engineer's future as more and more buildings become structurally questionable and need retrofit or repair.

3.2.1 Laboratory 3- Bond Strength

Masonry units and masonry mortars combine to form masonry systems. These masonry systems perform both structural resistance and weather resistance for a structure. Bond strength between mortar and masonry unit is a significant factor in the performance of a masonry system. Mortar bond is divided into two main characteristics: extent of bond and bond strength. The extent of the bond is the degree of contact the mortar makes with the unit, while bond strength is the strength of the adhesion between the mortar and unit. In both cases, a chemical and mechanical bond can occur. Strong bond strength does not necessarily mean good water resistance and vice versa. The bond between mortar and unit is vital to predict cracking making it important for students to understand.

Five main factors affecting the bond strength of masonry systems are: mortar properties, type of masonry unit, techniques used to fabricate masonry assemblies, specimen conditioning between fabrication and testing, and the testing procedure (PCA 1994b). Each factor has been shown to affect the bond strength in specific controlled tests and some factors yield a general relationship for these controlled tests. It is important to notice that these relationships are achieved under very controlled conditions, which do not directly model the complex relationships between these factors or additional factors in field construction. Hedstom et al. (1991) tested twelve different combinations of portland cement-lime mortars in multiple laboratory facilities maintaining strict procedure and showed no consistent correlations and therefore no real conclusions. Sharon L. Wood (1995), after testing more than 500 joints of various unit-mortar combinations, came to the conclusion that bond strength is an elusive property based on the complex interaction of both mortar and unit as well as construction techniques. The variability in these and others results showed that the coefficient of variations (around 20%) seen in masonry testing require over 15 joints to be tested to achieve a 90% confidence in being within 10% of the mean bond strength value (Wood 1995). Ghosh (1991), whose test provided the basis for lowering the allowable stress for flexural masonry elements in the Uniform Building Code and ACI standard 530 in 1988, came to the same conclusions. (Ghosh 1991)

> "Perhaps the most significant finding that can be gleaned from a review of the numerous investigations with respect to bond strength is the observation that it is a combined property of the mortar and the unit together. It cannot be accurately predicted from individual characteristics of the component materials." (PCA 1994b)

Formal bond strength testing has been recorded since 1932 when a modulus of rupture test was conducted with three point bending. Soon afterward, a cantilever test method was introduced. Both tests were valid but produced very different results. (PCA 1994a) The first ASTM standard adopted for testing the bond strength between masonry unit and mortar was Test Method C 321, entitled "Standard Test Method for Bond Strength of Chemical Resistant Mortars." ASTM C 321 was adopted in 1954 and used a crossed brick specimen to provide direct tensile forces in the mortar-unit interface. (Figure 12) Through the years, as new methods and ideologies were introduced, new ASTM's were developed and adopted. The most accurate model of actual in place

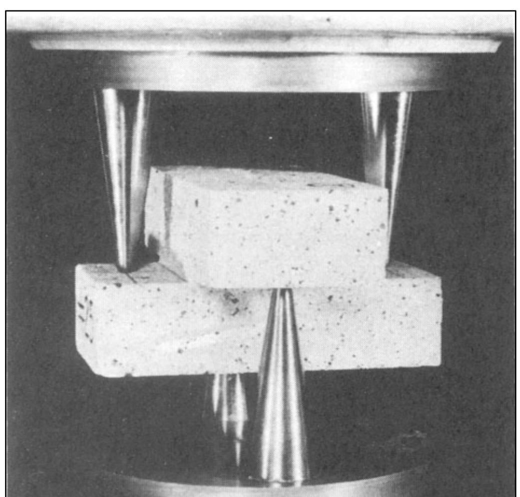

Figure 12: ASTM C 321's crossed brick specimen in special loading apparatus.

masonry in service is by ASTM E 72 which tests a four foot wide wall which is as tall as the typical wall height of the building it models and subjects it to either two point loading or a uniform loading apparatus to failure. While ASTM E 72 most accurately models masonry in service, its cost and difficulty in assembling and testing of the specimens makes it impractical to most needing to conduct bond strength testing. (PCA 1994a)

Khalaf (2005) proposed a new test method to evaluate bond strength. The proposed method uses a specimen of two bricks bonded together in a staggered method to replicate a running bond, which is more common in actual construction than stacked bond. (Figure 13) Both a linear stress distribution (Equation 1) and a parabolic stress distribution (Equation 2) can be used to predict the stresses in the joint at failure.

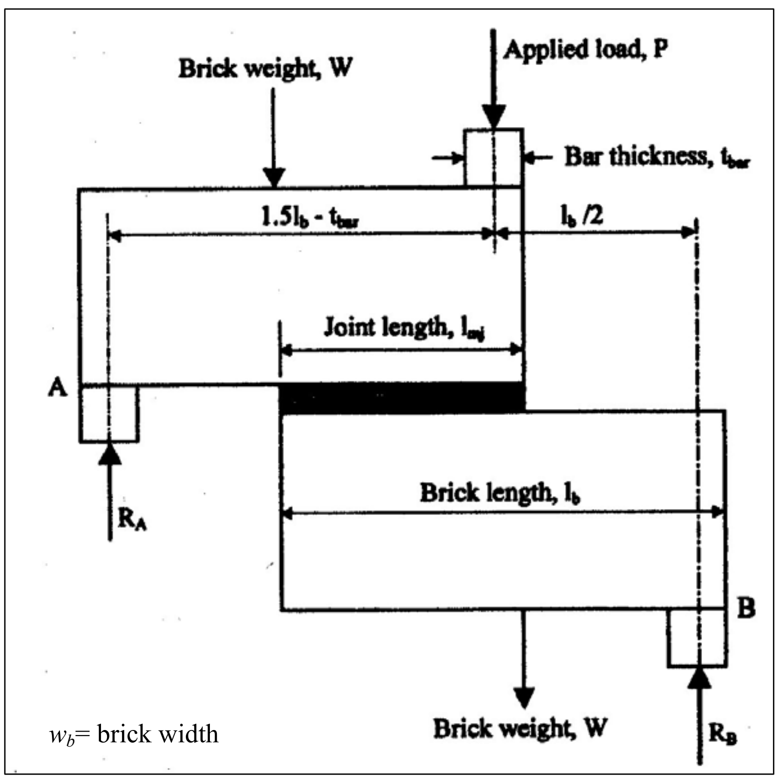

Figure 13: Khalaf's proposed Z brick orientation for bond strength testing. (Khalaf 2005)

$$f_{fb} = \frac{(0.5l_b^2 - l_b t_{bar} + 0.5t_{bar}^2)P + (0.75l_b^2 - 1.25l_b t_{bar} + 0.5t_{bar}^2)W}{(0.333l_{mj}^2 w_b)(1.5l_b - t_{bar})} \quad \textbf{[1]}$$

$$f_{fb} = \frac{(0.5l_b^2 - l_b t_{bar} + 0.5t_{bar}^2)P + (0.75l_b^2 - 1.25l_b t_{bar} + 0.5t_{bar}^2)W}{(0.42l_{mj}^2 w_b)(1.5l_b - t_{bar})} \quad \textbf{[2]}$$

The parabolic model yielded lower bond strengths from the test results and could be used to design conservatively. In Khalaf's study, mortars with compressive strengths ranging from 7.8 to 22.2 MPa (1100 to 3200 psi) were tested having bond strength ranging from 0.35 to 0.43 MPa (51 to 62 psi). It is interesting to note that the highest compressive mortar strength is three times that of the lowest yet the highest bond strength is only 1.25 times the lowest. Khalaf's test specimens failed the majority of the time in the upper mortar unit interface. This was possibly due to the effect of gravity, but because of this regularity along with a consistent failure plane, a lower coefficient of variation than most other masonry bond strength tests was achieved.

The two most used methods, which have comparable results, are ASTM C 1072 and ASTM E 518. (Figure 14 and Figure 15) ASTM C 1072 is the most recent test and is entitled "Standard Method for Measurement of Masonry Flexural Bond Strength." "In this test, a masonry assembly is subjected to a cantilevered load, which "wrenches" the top brick from the rest of the assembly held beneath a vise," hence the term "bond wrench" testing. ASTM E 518, entitled "Standard Test Method for Flexural Bond Strength of Masonry," uses a stacked bond masonry prism tested as a simple beam in two point loading or uniform loading. ASTM C 1072 is the most commonly used bond strength test due to its ability to test every joint in a masonry prism, not just the middle joint as in ASTM E 518. It is easy to both fabricate specimens for and conduct the testing of both these tests, which has led to their widespread use and their use in this laboratory. (PCA 1994a)

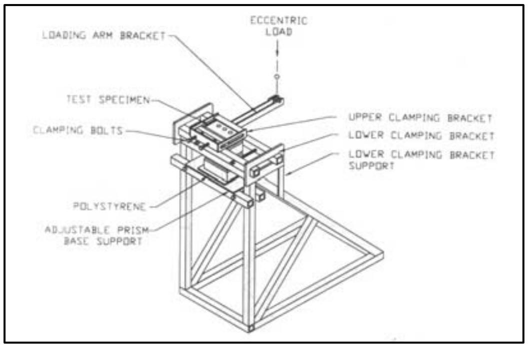

Figure 14: ASTM C 1072 test setup (ASTM)

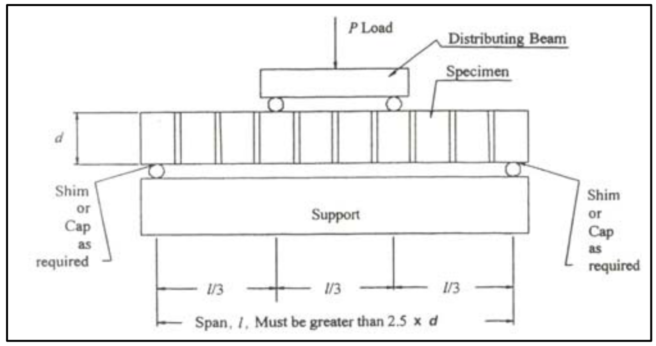

Figure 15: ASTM E 518 test setup (ASTM)

> "It is recognized throughout the testing community that masonry assembly testing does not precisely duplicate construction practices, exposure, and loading. It is more difficult to build assemblies for testing than to build a masonry element. Assembly test procedures generally isolate single joints to measure failure, whereas building elements distribute loads over larger areas. Conditions differ between laboratory or field exposure of assemblies compared to in-place exposure of masonry elements. As a result, variability associated with assembly testing is generally higher than that obtained from wall segment tests such as ASTM E 72. However, correlation between assembly testing and wall segment testing can be established through parallel testing under controlled conditions." (PCA 1994a)

As shown by numerous tests, one of the most important physical properties of masonry in design is the bond strength. Bond strength dictates the maximum tensile stress a masonry system can sustain and most often controls the design. The bond between the unit and mortar also contributes to the water integrity of the wall and thus serviceability and durability. Achieving a working understanding of this very complex property and what affects it is crucial to masonry design.

The objective of this laboratory is to explore different methods of experimentally determining the flexural bond strength between masonry units and mortar while also observing the effect of mortar type on bond strength. Students test the bond strength between the mortar and unit in the prisms constructed in Laboratory One using both a modulus of rupture beam test (similar to ASTM E 518) and a bond-wrench test (ASTM C

1072). Students first test the prisms in flexure as a beam subject to four-point bending to provide a constant zone of maximum moment, see Figure 16 and Figure 17 and Equations 3 and 4 for a sample test setup. This test usually splits the six-unit prism into two, three-unit prisms. Each three-unit prism is then tested in the bond wrench tester, which also creates a moment to break the bond between masonry and mortar, see Figure 18 and Equations 5-9. During both tests, each group records their data. At the end of the laboratory session, the class reconvenes and compiles all the groups' data for a more statistically reliable evaluation of the bond strength of different mortars. In evaluating the data, students deduce the tensile bond strength of different mortars from each test method and compare them to those values given in the masonry code. Students also calculate the experimental coefficients of variation for each mortar type. Sample results shown in Table 2, Table 3, Table 4, and Table 5 indicate coefficients of variation between 17 and 32%, normal for laboratory testing of masonry. (Ghosh 1991; Hedstrom 1991; Wood 1995) In the provided sample results notice that portland cement lime mortar is usually stronger than masonry cement.

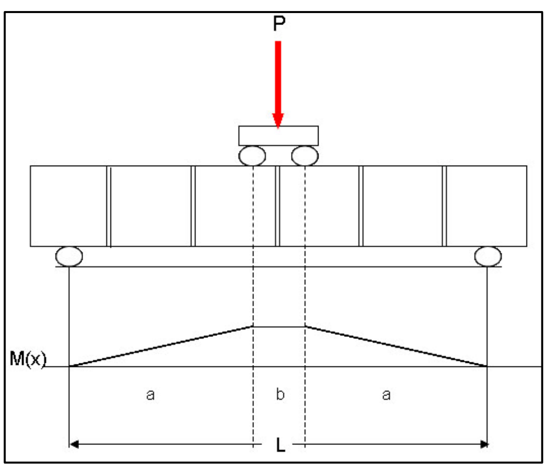

Figure 16: University of Wyoming's modulus of rupture bond strength testing (similar to ASTM E 518) test setup.

Figure 17: Modulus of rupture test equipment with specimen ready for testing.

$$M_{midspan} = \frac{P}{2}a \qquad [3]$$

$$\sigma = \frac{Mc}{I} \qquad [4]$$

Table 2: Fall 2005's masonry modulus of rupture test results

Group	Load lbs (N)	Stress psi (kPa)	Group	Load lbs (N)	Stress psi (kPa)
PCL 1	381 (1700)	61 (420)	MC 1	207 (921)	33 (230)
PCL 2	486 (2160)	78 (540)	MC 2	246 (1090)	40 (270)
PCL 3	321 (1430)	52 (360)	MC 3	341 (1520)	55 (380)
PCL 4	531 (2360)	85 (590)	MC 4	324 (1440)	52 (360)
Average	430 (1910)	69 (480)	Average	278 (1240)	45 (310)
COV		22%	COV		23%
Note: a=5.375 in (137 mm), I=30.27 in^4 (12.60 $x10^6$ mm^4) and c=1.81 in (46.0 mm)					

Table 3: Spring 2007's masonry modulus of rupture test results

Group	Load lbs (N)	Stress psi (kPa)	Group	Load lbs (N)	Stress psi (kPa)
PCL 1	663 (2950)	104 (719)	MC 1	472 (2100)	74 (510)
PCL 2	499 (2220)	78 (540)	MC 2	525 (2340)	83 (570)
PCL 3	540 (2400)	85 (590)	MC 3	466 (2070)	73 (510)
PCL 4	354 (1580)	56 (380)	MC 4	426 (1900)	67 (460)
PCL 5	497 (2210)	78 (540)	MC 5	641 (2850)	101 (695)
			MC 6	513 (2280)	81 (560)
Average	511 (2270)	80 (550)	Average	507 (2260)	80 (550)
COV		22%	COV		15%
Note: a=5.25 in (133 mm), I=30.27 in^4 ($12.60x10^6$ mm^4) and c=1.81 in (46.0 mm)					

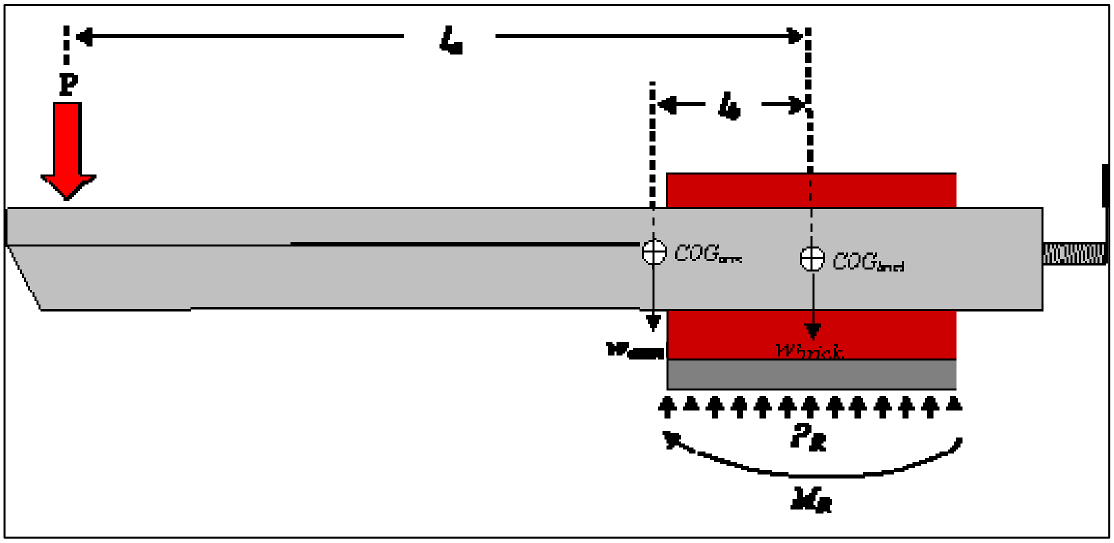

Figure 18: Free body diagram of bond wrench test specimen.

$$P_R = P + w_{arm} + w_{brick} \quad \text{(resultant force)} \qquad [5]$$

$$M_R = P \cdot l_a + w_{arm} \cdot l_b \qquad [6]$$

$$\sigma_{axial} = \frac{P_R}{A} \qquad [7]$$

$$\sigma_{moment} = \frac{M_R \cdot c}{I} \qquad [8]$$

$$\sigma = \sigma_{axial} + \sigma_{moment} \qquad [9]$$

Table 4: Fall 2005's masonry bond wrench test results

Group	**Load lbs (N)**	**Stress psi (kPa)**	**Group**	**Load lbs (N)**	**Stress psi (kPa)**
PCL 1	100 (445)	81 (560)	MC 1	120 (534)	97 (670)
PCL 2	180 (801)	145 (1000)	MC 2	110 (489)	89 (610)
PCL 3	100 (445)	81 (560)	MC 3	180 (801)	145 (1000)
PCL 4	142 (632)	115 (790)	MC 4	210 (934)	169 (1170)
PCL 5	100 (445)	81 (560)	MC 5	110 (489)	89 (610)
Average	124 (553)	100 (690)	Average	146 (649)	118 (812)
COV		29%	COV		32%
Note: l_a=14 in (356 mm), l_b=2 in (51mm), w_{arm}=8.95 lb (4.06 kg), w_{brick}=3.6 lb (1.63 kg), I=30.27 in^4 (12.60x10^6 mm^4) and c=1.81 in (46.0 mm)					

Table 5: Spring 2007's bond wrench test results

Group	Load lbs (N)	Stress psi (kPa)	Group	Load lbs (N)	Stress psi (kPa)
PCL 1	175 (778)	141 (972)	MC 1	180 (801)	145 (1000)
PCL 2	200 (890)	161 (1110)	MC 2	140 (623)	113 (779)
PCL 3	150 (667)	121 (834)	MC 3	220 (979)	177 (1220)
PCL 4	190 (845)	153 (1060)	MC 4	190 (845)	153 (1060)
PCL 5	215 (956)	173 (1190)	MC 5	205 (912)	165 (1140)
PCL 6	220 (979)	177 (1220)	MC 6	200 (890)	161 (1110)
PCL 7	190 (845)	153 (1060)	MC 7	150 (667)	121 (834)
PCL 8	160 (712)	129 (889)	MC 8	200 (890)	161 (1110)
PCL 9	230 (1020)	185 (1280)	MC 9	200 (890)	161 (1110)
PCL 10	170 (756)	137 (944)	MC 10	170 (756)	137 (944)
PCL 11	180 (801)	145 (1000)	MC 11	180 (801)	145 (1000)
PCL 12	140 (623)	113 (779)	MC 12	110 (489)	89 (610)
PCL 13	260 (1160)	209 (1440)	MC 13	140 (623)	113 (779)
PCL 14	160 (712)	129 (889)	MC 14	190 (845)	153 (1060)
			MC 15	150 (667)	121 (834)
Average	189 (839)	158 (1090)	Average	175 (778)	141 (972)
COV		18%	COV		18%
Note: l_a=14 in (356 mm), l_b=2 in (51mm), w_{arm}=8.95 lb (4.06 kg), w_{brick}=3.6 lb (1.63 kg), I=30.27 in^4 (12.60x10^6 mm^4) and c=1.81 in (46.0 mm)					

This laboratory illustrates firsthand the variability of materials. In building codes this variability is expressed in both allowable stress design (ASD) and load and resistance factor design (LRFD) in the form of materials strength reductions. In the laboratory, the need for resistance factors is validated and students see the variations in strength both above and below the average values showing why nominal strength values are oriented around the lower bound of experimental data.

Virtual Laboratory inclusions:

c. Lab 3: Bond Strength Testing
    i. Four Point Bending Test
        1. Text
        2. Diagrams
        3. Video
        4. Equations
    ii. Bond Wrench Test
        1. Text
        2. Diagrams
        3. Animation
        4. Video
    iii. Extras
        1. Lab Handout
        2. Sample Results
        3. Sample Lab Report
        4. Photos
        5. Lab Equipment and Materials
        6. Extra Resources

3.2.2 Laboratory 4- Compressive Strength

Compression is masonry's forte, therefore making its test behavior essential to understanding masonry behavior. As with bond strength in masonry, many factors affect the compressive strength of masonry systems, or prisms in our case. Some of these factors include: unit geometry and bed area, prism height, strength of mortar, unit strength, end platen restraint, bond pattern and thickness of mortar joints (Drysdale et al. 1999; Atkinson 1991). Bed area, mortar strength and joint thickness all affect the behavior of the mortar when compressed and ultimately the cause of the tensile failure seen in masonry systems subject to compressive stresses. One of the biggest factors in compressive strength is the mortar strength. Using a disproportionately weak mortar decreases the overall compressive characteristics of the masonry system, while using an overly strong mortar yields no justifiable increase in strength. While each of these factors, like in bond strength, can be isolated in specific laboratory tests, they are very difficult to combine to quantify actual compressive strength of masonry systems which is why understanding the behavior of masonry components and masonry systems is vital to design practice. (Drysdale et al. 1999; Atkinson 1991)

Students determine the compressive strength of individual brick as well as of multiple unit prisms modeling a masonry system to once again grasp the key concept of how all the components of the masonry system interact and how those interactions affect the physical characteristics of the system as a whole. Next students test units both alone and in small prisms with mortar joints to show different modes of failure and the decreased compressive capacity of masonry systems compared to the compressive strength of both mortar and unit alone.

First students test a multi-unit prism in compression. This test yields a lower compressive strength than that of the unit yet a higher compressive strength than the mortar due to Poisson's effect. The Poisson's ratio of the mortar and the unit are different. The unit and mortar's dimensions perpendicular to the applied force change different amounts under equal stress. As the mortar is compressed vertically, it expands horizontally more than the unit. This results in a net tension in the brick perpendicular to the applied compressive force and a net compression in the mortar also perpendicular to the applied compressive force. (Figure 19) The compression present in the mortar acts as confinement and increases the compressive capacity of the otherwise weaker of the two materials. (Drysdale et al. 1999; PCA 1993) The induced tensile stresses in the unit cause cracking in tension down the center of the unit parallel to the applied compressive force as shown in Figure 20. (Hamid et al. 1987; Maurenbrecher 1985; Drysdale et al. 1999) This cracking occurs earlier than the true compressive strength of the unit alone yet higher than that of the mortar alone. (Drysdale et al. 1999)

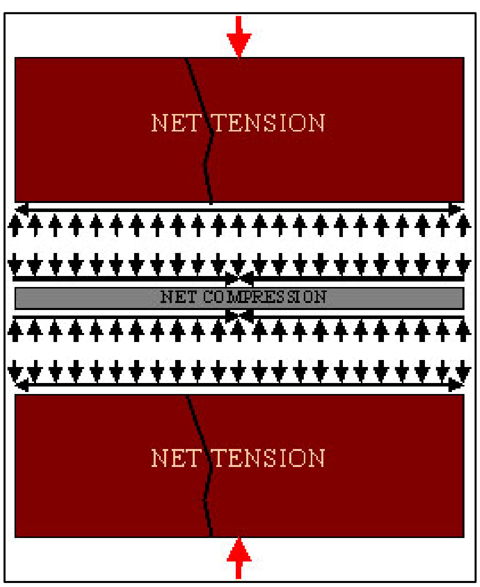

Figure 19: Free body diagram of compression induced tensile failure.

Figure 20: Compression failure of masonry prism due to induced tension.

After breaking the prisms with tensile stress yielded from applied compression, single units are tested alone subject to uni-axial compression. After obtaining the different test results, the class once again compiles all data for evaluation. Sample results in Table 6, show the strength differences between unit and mortar and the combined system. The results verify that the compressive strength of a masonry system is different than a single masonry unit. Students compare the experimentally obtained data to standard design values as given in the Masonry Standards Joint Committee (MSJC). As in the bond strength laboratory, students experience first-hand the variability of materials and the interaction of materials in a complex multiple material system.

Table 6: Spring 2007's Test Results

Group	**Load kips (kN)**	**Stress ksi (MPa)**	**Group**	**Load kips (kN)**	**Stress ksi (MPa)**
PCL 1	104 (463)	3.77 (26.0)	Brick 1	222 (988)	8.03 (55.4)
PCL 2	101 (449)	3.65 (25.2)	Brick 2	245 (1090)	8.85 (61.0)
MC 1	120 (534)	4.34 (29.9)	Brick 3	205 (913)	7.43 (51.2)
MC 2	93 (410)	3.36 (23.2)	Brick 4	168 (747)	6.08 (41.9)
MC 3	79 (350)	2.84 (19.6)	Brick 5	219 (972)	7.91 (54.5)
			Brick 6	279 (1240)	10.1 (69.5)
Average		3.59 (24.8)	Average		8.06 (55.6)
COV		15%	COV		17%
Note: Gross area of 3-5/8"x7-5/8" (92mm x 194mm)					

Virtual Laboratory inclusions:

d. Lab 4: Compressive Strength Testing
    i. Compressive Strength
        1. Text
        2. Diagram
        3. Video
    ii. Extras
        1. Lab Handout
        2. Sample Results
        3. Sample Lab Report
        4. Photos
        5. Lab Equipment and Materials
        6. Extra Resources

3.2.3 Laboratory 5- Masonry Arch Testing

The masonry arch testing allows students to finish their design, build and test process. Each group moves their arch into the test apparatus where it is loaded vertically to failure. (Figure 22 and Figure 21) A deflection and load report is provided to students for them to complete a written test report, which will include failure mode, strength to weight ratio, arch stiffness, and a comparison of actual behavior to expected behavior. A key component to this laboratory is it seeing different forms of failure and comparing them to their earlier conjectures. Students see where defects in workmanship or design may lead to failure and also see the behavioral characteristics of masonry systems. Students learn firsthand inherent difficulties in masonry design and in masonry construction, allowing them to design for such irregularities more adequately in the future.

In one particular case, an arch failed during transportation to the test site, but the segments were reassembled in the load frame and the test was performed as normal. Students were surprised to learn the arch pieces supported load even without bonding of all units. This further reinforced the concept that compression is masonry’s forte and the extensive use of arches in both past and present masonry construction have taken advantage of this characteristic.

Figure 22: Masonry arch in test frame.

Figure 21: Masonry arch exhibiting failure during testing.

Virtual Laboratory inclusions:

e. Lab 5: Arch Testing
    i. Arch Testing
        1. Text
        2. Video
    ii. Extras
        1. Lab Handout
        2. Sample Lab Report
        3. Photos

4 Laboratory 6- Nondestructive Evaluation

Nondestructive evaluation is becoming ever more important as we move into the future with better and more adequate designs to cope with Mother Nature's surprises and human progress. NDE is as vital to structures as x-rays and CAT scans are to doctors, enabling us to look inside without "cutting" and increasing risk. In the future, older buildings will need upgrade and retrofit, and historical buildings will need preservation. NDE allows each structure to be attended to specifically for its needs and requirements without compromising the structures aesthetics or current condition. NDE is a growing field with only unexplored potential. Future engineers will undoubtedly take part in some type of NDE in their careers. Knowing the different techniques available as well as the theory behind them, their capabilities and limitations will enable engineers and NDE specialists to work together more efficiently in acquiring the desired data and information. In this laboratory, nondestructive techniques of observation, radar, infrared imaging, cover meters, impact echo, and flat jack testing will be covered to give a good base of the most currently available and used NDE techniques. The accompanying media includes animations for both radar and impact echo to provide a general explanation without the corresponding complex mathematical relationships. Video demonstration is also used to introduce flat jack testing. An animation explores some of the possibilities of findings within a CMU wall using NDE techniques. Engineers will be exposed to these techniques more frequently in the future, making this background part of a life long learning process for engineers who undoubtedly will be exposed to a portion of NDE in their careers.

4.1 Radar

Radar is used to determine the internal condition of materials. Radar, unlike many other nondestructive methods, can detect not only steel, but also plastics and other anomalies in a material. Radar used for civil engineering NDE differs from that used commercially mainly in the maritime and air industries. For civil engineering NDE purposes, ground-penetrating radar is used to evaluate structures, water tables, bedrock location, locate underground pipelines, and much more. Ground-penetrating radar (GPR) is made up of a control unit (computer) and an antenna. The frequency of radiation that the GPR antenna transmits is dependent on the depth of interest as shown in Table 7. (Geophysical Survey Systems, Inc. 2006)

Table 7: Radar frequency capabilities. (Geophysical Survey Systems, Inc. 2006)

Depth Range (approximate)	**Primary Antenna**	**Secondary Antenna**	**Appropriate Application**
0-1.5ft 0-0.5 m	1600 MHz	900 MHz	Structural Concrete, Roadways, Bridge Decks
0-3ft 0-1 m	900 MHz	400 MHz	Concrete, Shallow Soils, Archaeology
0-12ft 0-9 M	400 MHz	200 MHz	Shallow Geology, Utilities, UST's, Archaeology
0-25ft 0-9 m	200 MHz	100 MHz	Geology, Environmental, Utility, Archaeology
0-90ft 0-30 m	100 MHz	Sub-Echo 40	Geologic Profiling
Greater than 90 ft or 30 m	MLF (80, 40, 32,20, 16	20 m	Geologic Profiling

GPR uses a pulse of radiation energy emitted into a material along with the measured reflected return strength and return time to map the internal makeup of a material. Radar reflections are returned when the emitted pulse of radiation energy crosses boundaries of different dielectric permittivity. This difference in dielectric permittivity, or conductance, dictates the return strength. As the pulse passes from concrete to steel rebar, materials with very different dielectric permittivity, a strong return is yielded. The pulse, if not reflected, continues until it is attenuated in the medium. Steel is considered a perfect conductor and yields a good return and attenuates radar waves immediately, letting no waves continue. The radar's energy pulse is attenuated very quickly in all materials with high conductivity; making radar evaluation of water saturated materials or conductive materials useless.

Reading radar returns involves interpreting both the signal locations and strength. Many returns are yielded as the radar wave passes through a material. In a heterogeneous material like concrete, many returns are seen of weak strength as it passes through different aggregates and cementitious materials. Another weak signal can be produced by voids whose dielectric permittivity is only slightly lower than concrete's, making them difficult to identify. Strong returns are usually the items of interest on a radar return, indicating steel, water or bedrock. Because the GPR antenna energy pulse is emitted in a cone shape returns are in the form of upside down parabolas. The radiation energy at the leading edge of the emitted cone shows returns off an object sooner, but the object is perceived as being deeper. As the item of interest moves under the antenna, the distance to the return lessens, and as it passes behind the antenna, it appears deeper again, yielding the upside down parabola type return with the actual location at the apex of the parabola. In Figure 23, which is a scan of reinforced concrete, it can be seen that there are two rows of reinforcing steel, one at 5 in. and one at 11 in. as well as an area of concern in the integrity of the concrete in the lower right of the scan. By conducting multiple scans and combining them, an accurate plan of imbedded pipes, reinforcing steel, and voids can be obtained.

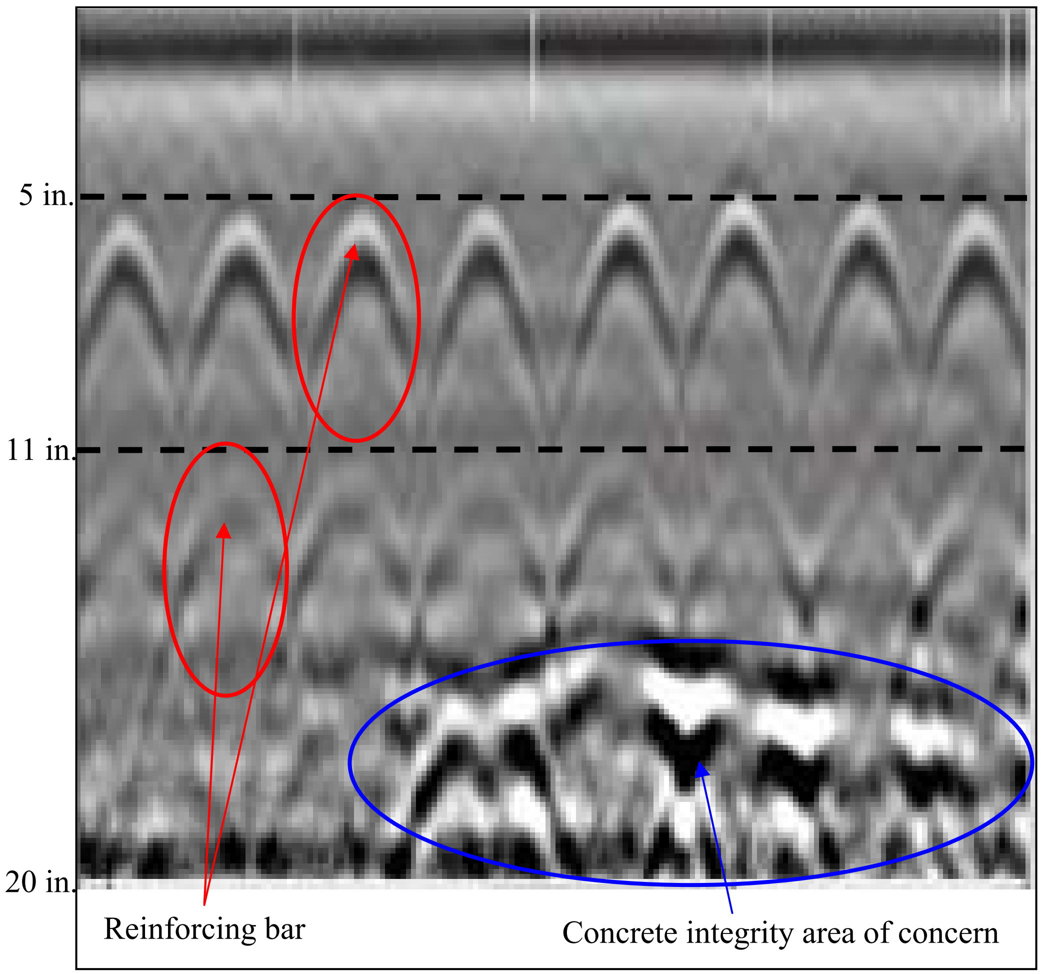

Figure 23: Characteristic radar return (Geophysical Survey Systems, Inc. 2006)

4.2 Infrared Imaging

Infrared imaging is a common technique used for NDE across a wide spectrum of materials and conditions. Infrared imaging of concrete and masonry structures evaluates the condition of the material; whether it is the location of grouted cells in concrete masonry walls, or locations of localized lamination flaws in reinforced concrete. Infrared thermography is not only used in civil engineering, but is very versatile and has been applied to many areas from in the medical field to measure of conductive heat loss of infants, to quality assurance of semiconductors, for determining when ink is dry in the printing industry, finding buried mine shafts, identifying canal seepage, and other civil engineering applications (Clark et al. 2003). In civil engineering, infrared thermography is used as a NDE method. Infrared thermography NDE is advantageous due to its non-contact nature which allows data to be taken remotely, minimizing impact on the structure or its use.

Infrared radiation cannot be seen by the human eye, but can be felt in the form of heat. All objects above zero degrees Kelvin emit infrared energy. The infrared energy emitted from an object is a function of its internal temperature, its emissivity, and the reflectivity of surrounding infrared energy. Infrared radiation makes up part of the electromagnetic spectrum and falls between visible light and radio waves with wave lengths ranging from 0.75 μm to 1 mm (Rigden 1996). The infrared region of the electromagnetic spectrum can be divided into four arbitrary sub-regions as follows: (Clark et al. 2003)

Table 8: Infrared radiation spectrum

Sub-Region	Wavelength (µm)
Near infrared	0.75-3
Middle infrared	3-6
Far infrared	6-15
Extreme	15-100

Wilhelm Wien showed that the maximum wave length intensity of the infrared radiation emitted by all objects is inversely proportional to its temperature as shown in Equation 10 where T is in K and λ_m is in µm.

$$\lambda_m = \frac{2898}{T} \quad \textbf{[10]}$$

With Equation 10, it can be easily shown most masonry and concrete being tested, probably at ambient temperature, emits maximum radiation intensity around 10 µm or in the far infrared region. This dictates an instrument, in our case a thermal camera, which is dedicated to long wavelength radiation frequencies to achieve adequate data resolution. A higher resolution camera is able to detect smaller temperature differences, showing more clearly the difference between areas of concern and areas of sound material. In reinforced concrete and masonry, the temperature gradient from sound material to questionable material can range from less than a degree Celsius to a couple of degrees Celsius. To achieve a good thermal image, a temperature difference is needed. In structures the easiest way to achieve this is with the radiation of the sun. Infrared imaging can be done passively by capturing the images shortly after they absorb solar radiation in the morning or shortly after they are shaded in the evening. This heat differential can also be mimicked by either cooling or heating one side of the wall. In the morning and evening, when the structure changes from having no solar radiation to being in direct solar radiation and vice versa, the anomalies in the material's ability to absorb the radiation is seen. As a CMU wall is hit with direct sunlight in the morning, the grouted cells remain cool much longer due to the increased mass which can absorb the solar radiation. At approximately 30 minutes after being in direct sunlight, the temperature differential between the two is of a magnitude that a thermal imaging device can easily differentiate between the two. The images of a two story CMU shear wall shown in Figure 24 were taken shortly after exposure to sunlight; notice the grouted cells are cooler. This corresponds to the vertical blue-green lines in each figure. The wider red-yellow areas indicate un-grouted cells. Likewise, the same process applies to reinforced concrete; where a lamination problem is present. This process is the same in the evening as the solar radiation disappears; the sound material will remain warm longer than the de-bonded or un-grouted region. In the laboratory, students will be shown how infrared imaging is used to help in the location of grouted and un-grouted cells in a CMU wall.

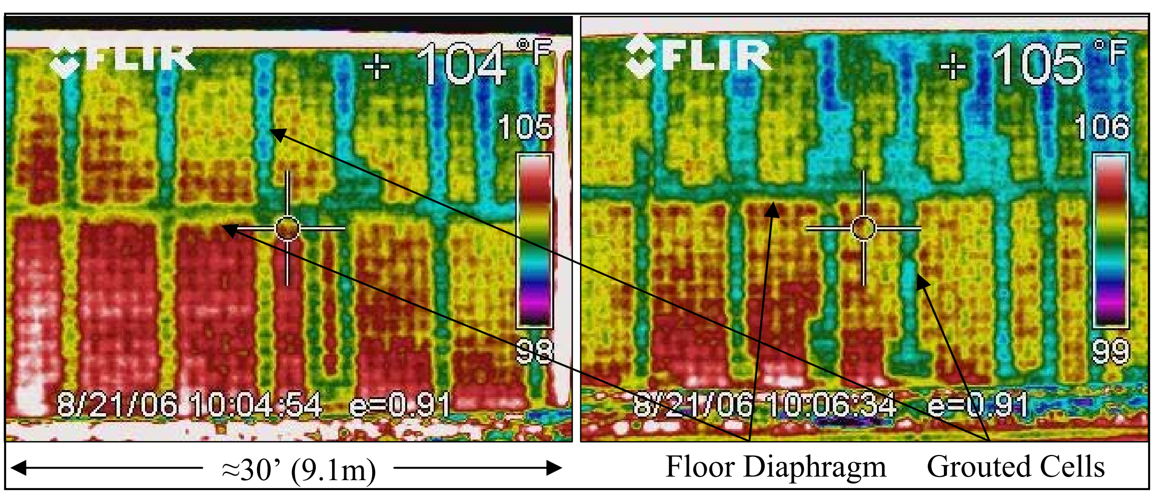

Figure 24: Characteristic infrared images of reinforced CMU wall, notice discontinuities in vertical grouting/reinforcing shown as the cooler regions.

4.3 Impact Echo

Impact-echo utilizes the propagation of impact induced sound wave stresses through concrete and masonry to measure material thickness and ultimately identify internal flaws. The stress waves propagate through the material, reflecting back from changes in medium as seen at internal flaws and at exterior surfaces. (Figure 25) Impact echo is currently being applied to the locating and quantifying of flaws such as cracks, delaminations, voids, honeycombing, and debonding present in all forms of concrete ranging from walls, pavement, decks, columns and beams (Sansalone and Streett 1997).

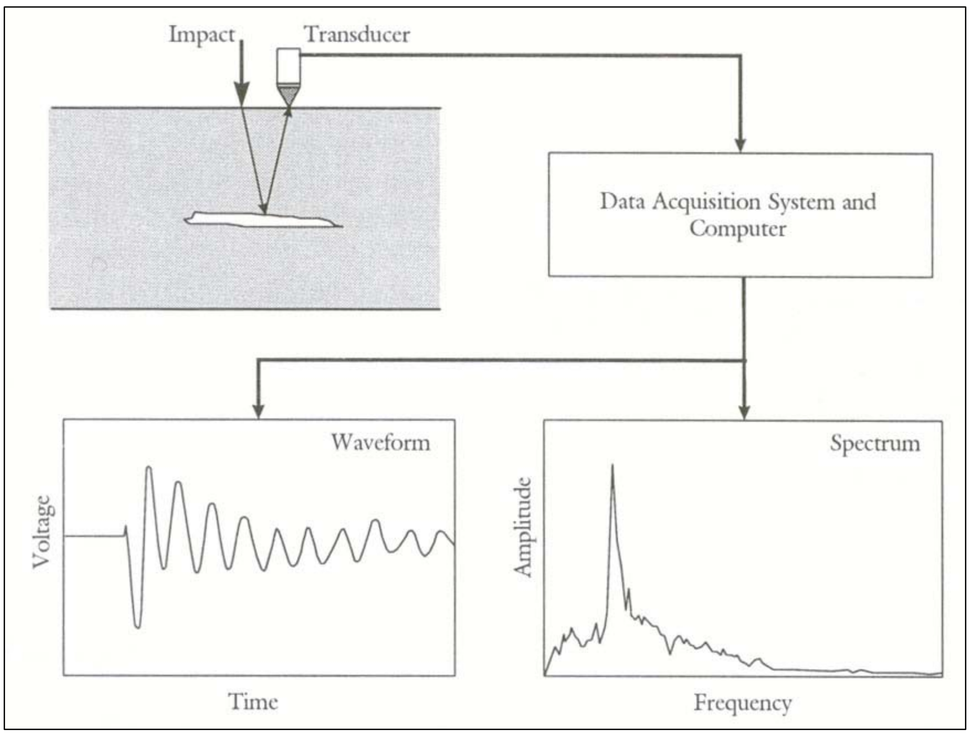

Figure 25: Basic impact-echo process (Sansalone and Streett 1997).

A version of pulse-echo technique has been utilized since the 1940's in materials such as steels and plastics. Concrete, unlike these materials, is non-homogeneous, or heterogeneous. Because concrete is heterogeneous, the pulses of energy or stress used in metals and plastics, 100 kHz or above, were attenuated quickly. To get equivalent data from concrete, a much lower frequency energy pulse was needed, one below 80 kHz. (Sansalone and Streett 1997)

Impact-echo testing relies mainly on the induced stresses. Stresses are induced through P-waves; those which wave amplitude is in the direction of wave propagation, yielding compressive and tensile forces in the medium. The speed of P-waves through a medium is dependent on the Young's modulus (*E*), the mass density (*ρ*), and Poissons ratio (*v*) given in the following equation:

$$C_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad \textbf{[11]}$$

Unfortunately, as the wave moves through concrete or masonry, there are many reflections and returns yielded in the voltage (displacement) versus time data, or wave form data. (Figure 26) The return data is complex and it is almost impossible to glean any pertinent information on locations of discontinuities in the material. To make this data easily readable and useful, the return wave form is transformed through the use of a Fast Fourier Transform (FFT). Once transformed, a plot of amplitude frequency spectra is shown. Points of interest on the spectra are shown as spikes or resonance. (Figure 26) The resonant frequency of the expected return is given as:

$$f = \frac{0.96C_p}{2T} \quad \textbf{[12]}$$

Where C_p is the P-wave speed in the medium and T is the expected thickness. This equation is also used as an approximate method to find the P-wave speed on a material of known thickness and to find the depth of voids once the P-wave speed has been established.

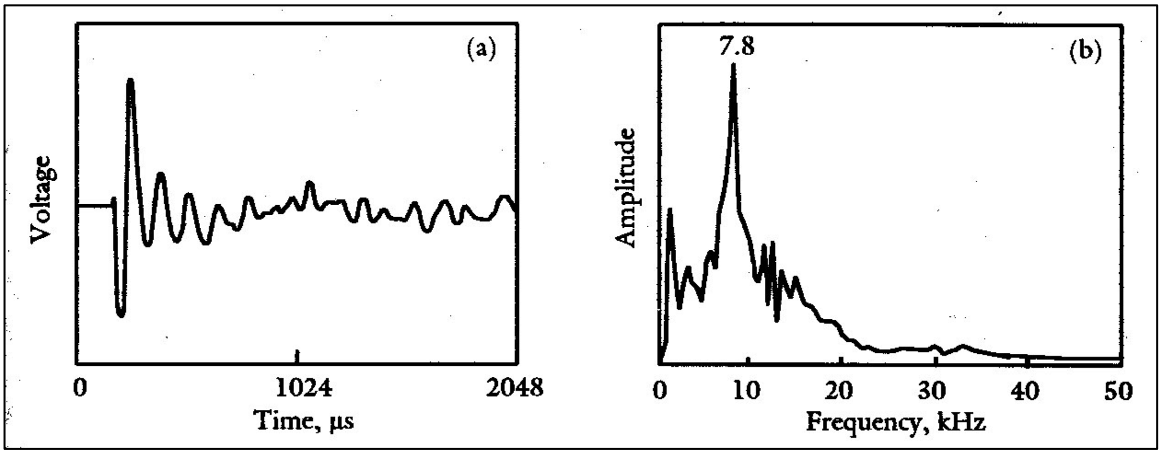

Figure 26: Complex return voltage (left) transformed to frequency domain (right) (Sansalone and Streett 1997).

The majority of impact-echo tests currently being carried out are on bridges to find delaminations, voids in post tensioning grouted ducts, and deck thicknesses. The return data in the form of spectra can become very complicated and difficult to read depending on a multitude of factors including but not limited to concrete make up, void size to depth ratio, impact frequency, void size and depth, and delamination vibration. A series of grouted CMU specimens were constructed including fully grouted, simulated voids, and un-grouted (Figure 27). These specimens were subject to impact-echo evaluation using an Olson Instruments Concrete Thickness Gauge 1T (CTG-1T). Frequency domain results for two specimens are shown in Figure 28. The left side indicates a thickness of 0.62’ (189 mm). The right side shows peak test results shifted to a thickness of 0.72’ (219 mm) as a result of multiple small voids. These results are similar to those of honeycombing of concrete which does not usually give a return off the voids, but only shows a shift in the resonant frequencies and magnitudes. (Figure 28) The results for the specimen with only one small spherical void yielded a return very similar to the fully grouted specimen. This illustrates the dependence of impact-echo on among other factors, the size and shape of the void. The specimens with large voids and un-grouted cells, created peak returns corresponding to the natural frequency of vibration of the concrete shell. Practice and an extensive knowledge of both material and impact echo technique are crucial to the understanding of the spectra returns.

Figure 27: Impact-echo specimens from left to right: solid, one small void, many small voids, one large void, and empty

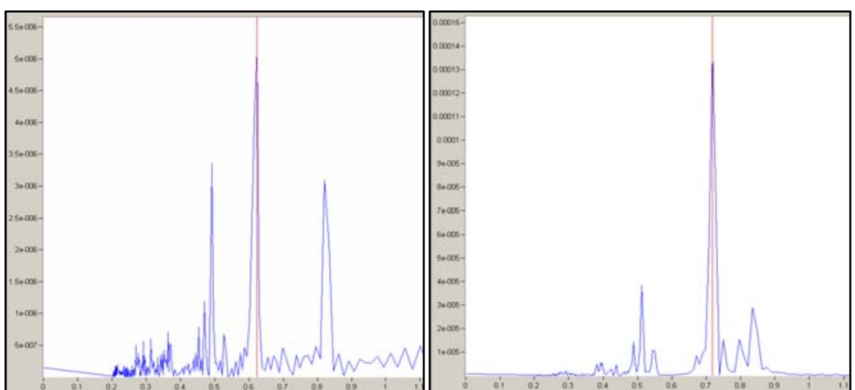

Figure 28: Impact-echo returns for sound cross section (left) and one with multiple simulated voids (right) notice the shift in return depths and magnitudes.

4.4 Flat Jack Testing

Flat jack testing is an invasive technique that allows the user to acquire the modulus of elasticity and to determine the in-situ stress present in a particular location. To carry out flat jack testing, mortar joints in the desired test location are removed. While this test is invasive, it is considered as a nondestructive evaluation method because it preserves the structure as a whole. The in-situ stress test requires the removal of one mortar joint while the modulus of elasticity test requires the removal of two mortar joints. Before the mortar joints are removed, initial gage points are fixed to the wall. One set spans the planned in-situ stress test joint to be removed and another set is placed between the two to be removed mortar joints for modulus of elasticity test. (Figure 29 and Figure 30) After initial distances between the gage points are recorded, the mortar joints are removed for about 18 in. Once the joints are removed, flat jacks (Figure 31) are slid into the open joints. The flat jacks can be stacked to fill thicker mortar joints. Once the flat jacks are installed, they are pressurized with liquid, usually oil or water, from a pump which reads out the pressure. (Figure 31) In the situ stress test, the jacks are pressurized until the initial gage reading is achieved. At this point, the pressure in the flat jack corresponds to the in-situ axial stress before the mortar was cut out. For the modulus of elasticity test, the jacks on either side of the gage points are pressurized simultaneously. The gage point distance is recorded at intervals throughout the pressurization through approximately 80% of the assumed compressive strength of the units. The strain change is calculated and the modulus of elasticity is the slope of the stress-strain relationship. After the test is completed, the jacks are de-pressurized and removed. Now the mortar joints are ready to be re-pointed, leaving the wall in its original condition.

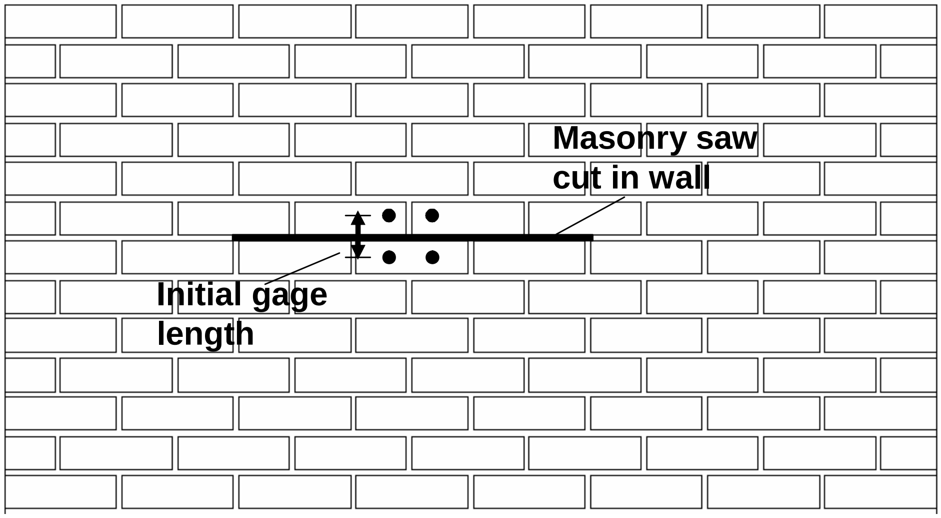

Figure 29: In-situ stress flat jack test setup.

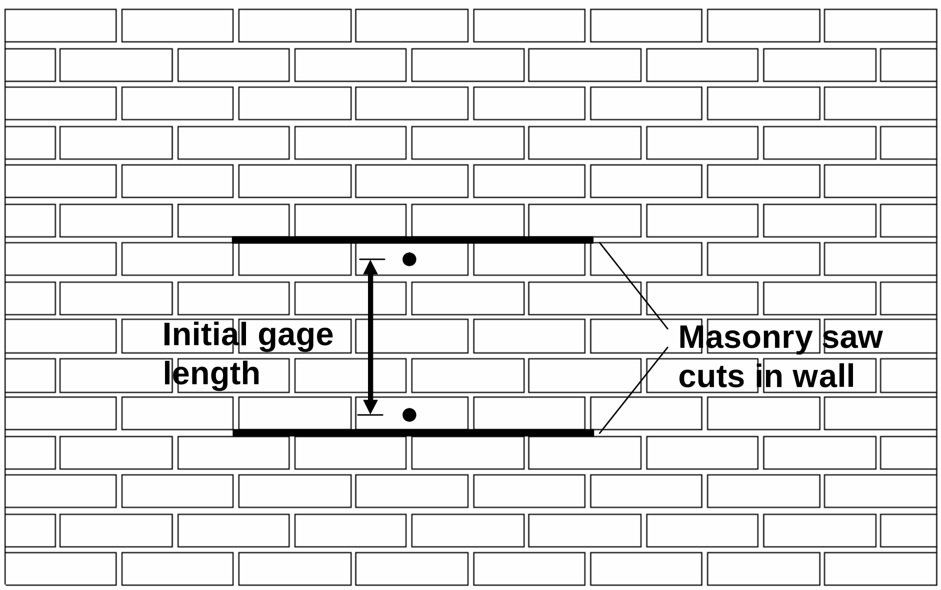

Figure 30: Modulus of elasticity flat jack test setup.

Figure 31: Flat jack test equipment: Pump (back), flat jack (front), and flat jack remover (middle and right).

In the laboratory, mortar joints in a local building will be cut out and pre-loaded to allow students to take measurements. Both methods of testing will be utilized: measurement across a cut to evaluate in-situ acting stress and between two cuts to evaluate the modulus of elasticity of the masonry. Before the wall is cut, the gage points and original dimensions between them will be recorded. When the students arrive, they will only have to load the flat jacks and take readings at various pressures. From this data they will back calculate the stress present in the wall before the cuts were made and the modulus of elasticity of the masonry. Sample data for the in-situ stress test and deformation test are shown in Figure 32 and Figure 33. In Figure 33 the experimental modulus of elasticity of 940,430 psi (6484 MPa) is very close to the MSJC code value of 1,050,000 psi (7239 MPa) for masonry with f'_m of 1500 psi (10.3 MPa) given by Equation 13. The lower experimental data may be due to deterioration of stiffness over time as the tested building is approaching the end of its life. After data is taken for both tests, students re-point the masonry, practicing techniques learned in Laboratory One and Two.

$$E_m = 700 \cdot f'_m \quad [13]$$

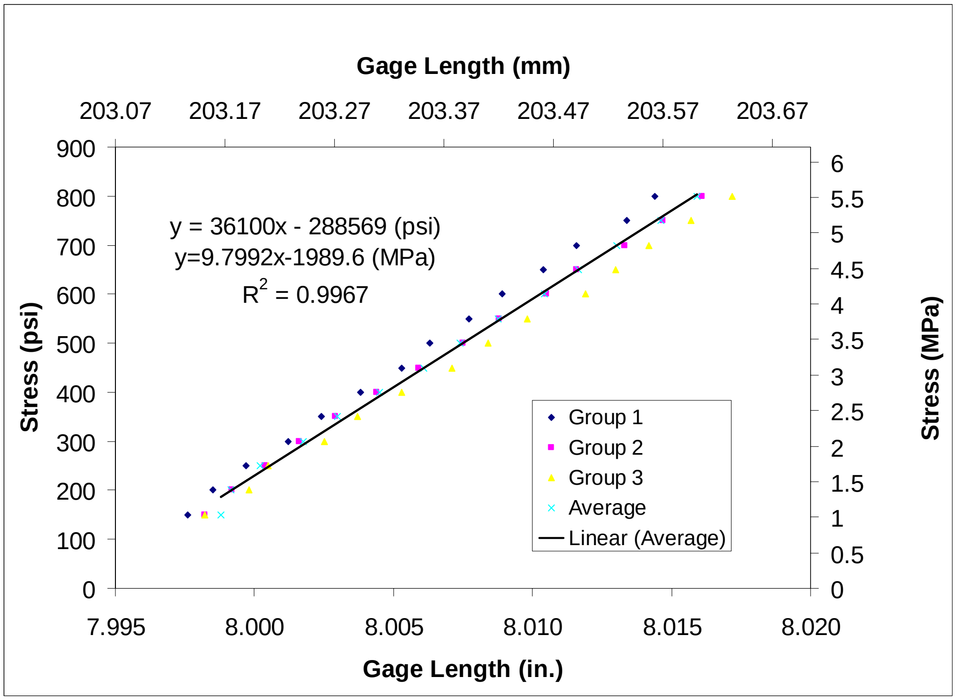

Figure 32: Sample in-situ stress gage measurements.

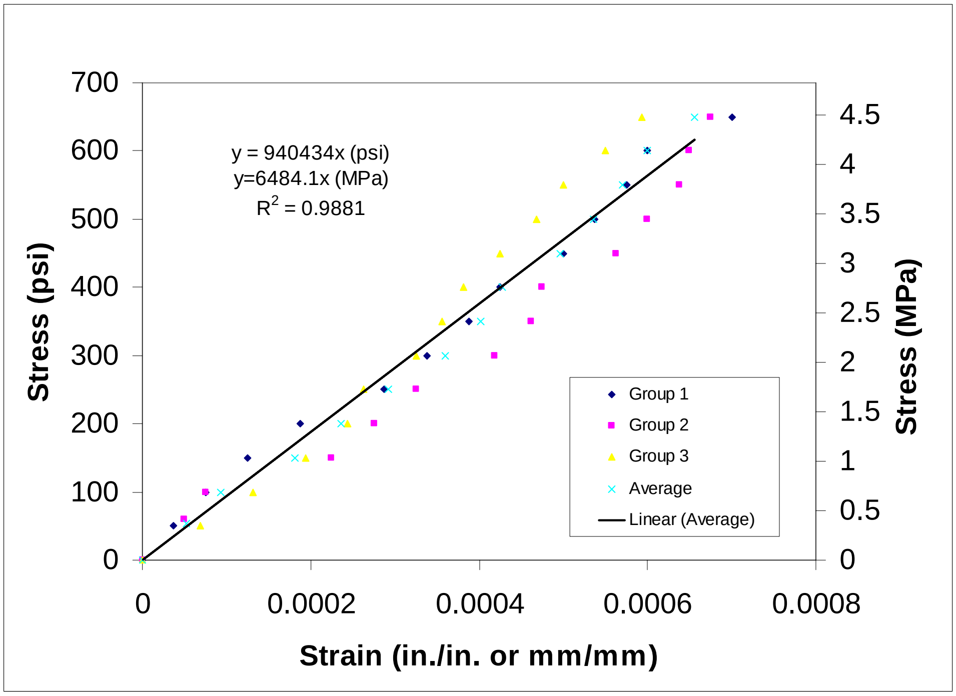

Figure 33: Sample modulus of elasticity test gage readings

4.5 Cover meter

A cover meter is often used to determine the location and the depth of a ferrous reinforcing bar in concrete and masonry. (Figure 34) A cover meter works on the principle that steel within the masonry and concrete will be affected by a magnetic field that is applied by the cover meter. When a magnetic field is forced through a magnetic material, it opposes this change with an eddy current, which produces its own magnetic field opposite in direction to the applied field. The strength of an eddy current and its corresponding opposing magnetic field depends on the magnetic properties of the material subject to the impressed magnetic field and the distance between the two. By assuming a set magnetic property for all steel reinforcing bars and using a given bar size, the cover meter can predict the depth and location of the reinforcing bar. The cover meter pulses its magnetic field and then measures the opposing magnetic field created by the eddy currents in the ferrous material, most likely reinforcing bar. By measuring the strength of the opposing magnetic field, using the given bar size and magnetic properties, the cover meter can calculate the distance to the reinforcing bars. To locate the bar position, the distance to the bar is minimized, indicating that the cover meter is directly over a piece of the reinforcing steel.

Figure 34: Cover meter made by PROCEQ (PROCEQ USA, Inc. 2003-2006)

4.6 Observation

The most important and often overlooked nondestructive evaluation technique is observation. During the life of a structure, visual inspection routinely carried out is crucial to the upkeep and repair of a facility. This is also known as preventative maintenance. Preventative maintenance helps to minimize large costly repairs in the future by carrying out economical and effective constant conservation of the material and structural integrity of the building. A more refined form of observation is by the use of auditory evaluation. While there are many machines available that use sound to test very accurately the properties of in-situ masonry, the human ear is adequate for some tests. The use of soundings are used to find locations of grouted and un-grouted cells in concrete masonry walls, areas of honeycombing and shallow delaminating in concrete structures. In masonry, a small hammer is used to tap on the units and differences in sound indicate different internal conditions. To sound bridges, a tester taps sections of the bridge in much the same way as in masonry testing, listening for sound anomalies. In bridges, to facilitate covering a larger area, chain is dragged over it to help identify problem areas that can then be investigated further in more detail.

In a future laboratory, students will visit a CMU wall to observe techniques for sounding and get a chance to practice it themselves. Sounding NDE requires a keen sense of hearing, often developed through experience, to differentiate areas of concern with non-issue areas. To a well trained ear, though, sounding can be very accurate. Students are also introduced to visual inspection and the role it plays in the routine maintenance. These two seemingly archaic techniques make up the majority of nondestructive evaluation present today.

4.7 Practice

During the summer of 2006, I spent three weeks in Texas with Atkinson Noland and Associates of Boulder, Colorado, carrying out nondestructive evaluation of masonry buildings that were involved in a legal proceeding. The purpose of the study was to find the actual constructed state of the masonry. With this forensic evaluation, the lawyer and their client would proceed as they saw fit. During our stay, we incorporated quite a few of the nondestructive techniques introduced in this laboratory. We used sounding, pachometers or cover meters, radar, infrared imaging and observation. (Figure 35 through Figure 38)

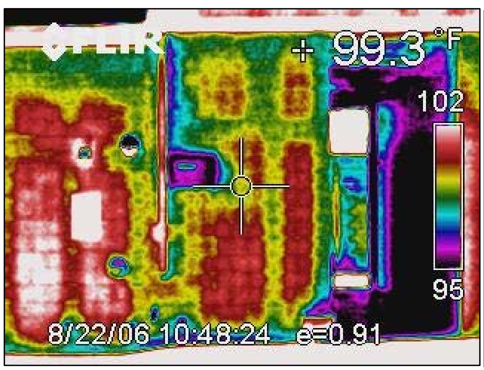

Figure 35: Infrared imaging of grout (cool) location in CMU wall.

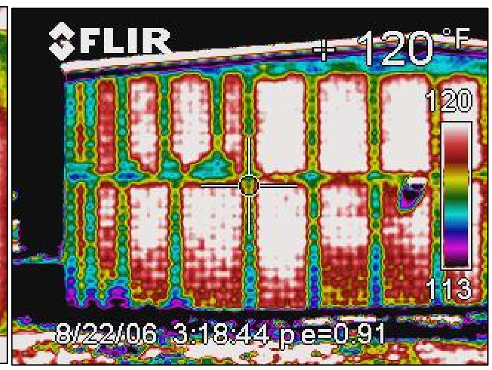

Figure 36: infrared imaging of grout (cool) location in CMU wall.

Figure 37: Locating steel reinforcement in CMU masonry wall with a cover meter.

Figure 38: Cooling system utilized in infrared imaging of interior walls.

All the masonry evaluated was reinforced concrete masonry. We mapped out the grouted and un-grouted cells with soundings backed up with infrared imaging. To obtain infrared data on interior walls, an industrial air conditioner was used to achieve the needed heat differential between the two sides of the masonry wall. (Figure 38) Cooling was the preferred method to create the heat flux through wall in Texas due to the outside ambient temperature of close to 100°F (38°C) and even higher inside ambient temperatures. We found the location and quantity of the reinforcing steel, both vertical bars and horizontal joint reinforcement, with cover meters backed up with radar. We also conducted a thorough visual inspection of the masonry noting the condition of cracking and deterioration. Visual inspection holes, or probes, were also drilled to verify certain locations and conditions. These probes validated the location of steel reinforcing bars, grouted cells, and voids. Along with the inspection holes, a number of cores were taken at representative locations to be used in evaluating the strength of the grout present. (Figure 39 and Figure 40)

Figure 39: Drilling core samples for visual inspection and strength testing.

Figure 40: Characteristic core sample.

All data collected was recorded both on paper and on the walls in chalk to be photographed, Figure 41. With close to two thousand each of infrared images and photos for record and hundreds of radar return files, careful organization was crucial to facilitate data compilation at a later date. Recorded data included: location code, reinforcing steel, voids, cracking and overall condition, and radar paths with their corresponding file numbers. Once all the data was gathered, it was compiled by Atkinson Noland and Associates giving a comprehensive current, as is constructed, condition of all the buildings. During our stay, we witnessed poorly carried out evaluation of another company carrying out the same basic mission for the other side of the lawsuit. Without the use of multiple techniques to achieve confident results, excessive invasive larger inspection holes were drilled. In one wall it was a 30'x30' (9.1m x 9.1m) section where every cell was drilled to verify internal condition, a task we covered accurately and easily with our well implemented NDE.

Figure 41: Data records on actual walls before being transcribed to paper.

Through the extensive testing of multiple buildings in different cities, a great deal can be learned about construction practice. In general, all buildings exhibited typical cracking, but nothing warranting any real concern on the structural integrity of the masonry. But after mapping out the as constructed state of the buildings, including all reinforcing steels and grouted cells, a general trend was present; as built plans do not agree with design plans. In construction, a constant need for change is present as work time and conditions dictate. An odd layout of steel reinforcement was observed, with vertical steel not lining up all the way up the structure or random placement and lengths of horizontal steel. These anomalies could possibly be due to reinforcing steel availability or possibly a lack of continuity in day to day construction. While this practice is in no way condoned, it is important for an engineer to note the standards of construction where his design will be implemented and appropriately account for any extra needs to ensure safe and adequate structural integrity.

The use of NDE is increasing as older design and construction techniques need evaluation and updating to maintain an acceptable level of safety today and into the future. NDE concepts and techniques, both researched and practiced, are included in the virtual laboratory in order to provide a good general base understanding of the uses and capabilities of different NDE techniques. This understanding is vital and can be applied both in the laboratory and in the field. The virtual laboratory gives a student or a practitioner an easy to use resource to gain a general understanding of different NDE techniques available and how they can be implemented.

Virtual Laboratory inclusions:

f. Lab 6: Nondestructive Evaluation
    i. Observation
        1. Text
        2. Photo
    ii. Radar
        1. Text
        2. Animation
    iii. Infrared Imaging
        1. Text
        2. Photos
    iv. Cover Meter
        1. Text
        2. Photo
    v. Flat Jack Testing
        1. Text
        2. Video
        3. Photo
        4. Analyzed Results
    vi. Impact Echo Testing
        1. Text
        2. Animation
    vii. Extras (included for each where applicable)
        1. Lab Handout
        2. Sample Results
        3. Sample Lab Report
        4. Photos
        5. Lab Equipment and Materials
        6. Extra Resources

5 Conclusion

By introducing a virtual laboratory system to masonry programs, a greater number of students will be more effectively engaged, utilizing their personal preferred presentation and learning method. By offering a virtual laboratory system, educators will be given another tool to reach out to students; one which requires little or no work on their part. This enables educators to spend more time on other areas of concern in providing the best possible education to their pupils.

Students who experience laboratories will have a clearer understanding of masonry construction and how to apply the fundamental concepts of masonry design. These virtual laboratories are intended to provide thorough exposure to the design, build implementation and evaluation processes. With virtual laboratories available to introduce basic masonry construction practices, building of masonry systems, testing bond strength, compressive strength and nondestructive evaluation, students will be able to better grasp the field of masonry as a whole. The virtual laboratories will provide all students with knowledge and experience unparalleled in any available textbook. Students with a good grasp of the mechanics and characteristics of construction practice, failure, material characteristics, and testing both nondestructively and destructively, will be able to provide better, more concise, efficient and construction friendly designs. Furthermore, they will be better equipped to troubleshoot and work with existing masonry because they are familiar with current field testing and evaluation methods.

NDE is a viable alternative to evaluate the condition and strength of masonry. By combining the new and expanding nondestructive evaluation techniques, a thorough and in depth evaluation of masonry can be accomplished. NDE has been proven through this case study, research, and practice, all of which explored a wide array of NDE techniques. The inclusion of these state-of-the art techniques into the masonry curriculum significantly augments students' laboratory experience which will be carried with them into the future.

Few students are exposed to such testing procedures because many universities do not have the resources or equipment to perform or utilize these tests in class; with implementation of a virtual laboratory, all students, no matter the facilities, can take part in this expanded classroom. Through the development of the virtual laboratory, it was observed that a virtual laboratory can be easily transferred and made available to professors and students for implementation and use. In addition, the development of a virtual laboratory has a high upfront cost but little or no reoccurring costs as in a traditional laboratory. The virtual laboratory has been shown to effectively present the information of the traditional laboratory to all students regardless of their masonry or engineering background based on the results from a survey. The focus group's resulting comments reinforced the implementation of a virtual laboratory as an asset to both students and professors which can be easily incorporated at any institution as a resource to the current curriculum.

The development of the virtual laboratory system is very versatile and was not meant to replace any existing traditional laboratory sessions. It is the University of Wyoming's goal to expand all masonry curriculums.

5.1 Future Work

The virtual laboratories can be used not only to allow students with no laboratory access to vicariously experience laboratories, but also to supplement and augment the laboratory experience of those who currently have traditional masonry laboratories. In the future, further masonry laboratories will be added. These laboratories include one on grout and mortar. In the laboratory, students will explore the behavior of grout cured both in a non-porous cylinder and in a CMU unit. The mortar portion of the laboratory will expand the compressive strength laboratory already being carried out to further emphasize the complex relationships present in the compressive strength of the overall masonry system. Laboratories under development for possible incorporation include further research and facilities in NDE. These may include a full scale NDE of a test CMU wall in order to illustrate how NDE techniques are utilized together to evaluate a masonry system. With the addition of future laboratories, the virtual laboratory's goal will continue to be to enhance all masonry students' current classroom experience as well as provide a useful resource for all those in search of knowledge.

It is important to note, however, that as a result of new test methods, including but not limited to NDE, and new codes, masonry is ever changing and the masonry laboratory modules will be in need of constant updating and revision. As new ideas for design, construction, and testing are introduced, the laboratory modules will need to be updated to keep students knowledgeable of state-of-the art practices as well as current practice as they continue with their studies in engineering through school and ultimately into the workforce.

6 References

6.1 Referenced Standards and Reports

At time of publication, the standards below and used were current; as they are regularly updated; it is recommended that the reader ensure that the latest version is obtained.

ASTM

C231	Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
C270	Standard Specification for Mortar for Unit Masonry
C 321	Standard Test Method for Bond Strength of Chemical Resistant mortars
C 1072	Standard Method for Measurement of Masonry Flexural Bond Strength
C1437	Standard Test Method for Flow of Hydraulic Cement Mortar
E 72	Standard Test Methods of Conducting Strength Tests of Panels for Building Construction
E 518	Standard Test Method for Flexural Bond Strength of Masonry

These publications can be obtained from:

ASTM International
100 Barr Harbor Drive
PO Box C700
West Conshohocken, PA 19428-2959 USA
www.astm.org

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