STRUCTURAL HEALTH MONITORING EDUCATIONAL MODULES

-

CASE WESTERN RESERVE UNIVERSITY 2017-2018

Michael Pollino

Associate Professor
Dept. of Civil Engineering, Case Western Reserve University

June 2018

TABLE OF CONTENTS

LIST OF TABLES

List of Figures

ABSTRACT

This report summarizes the experiences and observations during implementation of the Structural Health Monitoring (SHM) Modules at Case Western Reserve University during the 2017-2018 academic year. The Foundational Educational Modules (FEMs) were incorporated into ECIV 320 – Structural Analysis I in the Fall 2017 semester while the SHM Structural Educational Modules (SEMs) and Structural Applications Modules (SAMs) were incorporated into ECIV 322 – Structural Design I in the Spring 2018 semester. The Canvas learning management system (LMS) was utilized as the primary interface to distribute all SHM Module materials and for collection of student assessments. However, Survey Monkey polls managed by the Louisiana Transportation Research Center (LTRC) were utilized for the pre-treatment and post-treatment surveys. The main body of this report provides an overview describing implementation of the modules and highlights outcomes of each set of modules. The appendices of this report include detailed data collected from (i) results of surveys and exams and (ii) response to discussion questions and "one-minute papers". Additionally, the appendices include a summary of in-class discussion notes made by the instructor.

1. PROJECT OVERVIEW

This report documents the implementation of educational modules on structural health monitoring (SHM) into two undergraduate courses at Case Western Reserve University (CWRU). This implementation was part of a larger educational project funded by the National Science Foundation (NSF) and awarded to the Louisiana Transportation Research Center (LTRC). The content of the modules were developed by personnel at LTRC along with a general plan for implementation into undergraduate courses.

2. Pre-Treatment Survey Results

An initial survey was taken by each student prior to implementation of the Foundational Educational Modules (FEMs) in the first semester (Fall 2017). The survey questions and results from CWRU students is provided in Appendix A.

The following is observed from the results of the survey:

- Approximately 50% of students intend to concentrate their academic studies and pursue jobs in the area of structural engineering (typical at CWRU)
- Approximately 50% are highly likely or somewhat likely to pursue a master's degree in structural engineering
- At the time of the survey, most students would concurrently be taking a course, Civil Engineering Materials, which introduces them to experimental testing of materials and structural members and thus response about exposure to field monitoring and measurements is mixed (varying from none to a fair amount)
- Most students had little exposure through summer jobs
- Most students felt that field monitoring and measurements had an above average or high importance for engineering practice
- All wanted to see SHM principles included in the undergraduate curriculum if the technology will be of increasing importance in practice in the near future. The majority wanted to see it included if it was used in common practice, if employers sought the knowledge and skills, and it would enhance their skills as a structural engineer.

3. Foundational Educational Modules (FEM) Results

3.1. Implementation Schedule

The Foundational Educational Modules (FEMs) were covered during ECIV 320 – Structural Analysis I in Fall 2017. The schedule for review and submission of modules is provided in Table 1.

Table 1 Master Schedule for FEM SHM Educational Unit (CWRU, Fall 2017)

Unit	Component	Target Completion/Submission Date	Date of Classroom Discussion
	Pretreatment Survey	3pm, Friday, November 17,2017	-
FEM0	Discussion Question	1pm, Monday, November 27, 2017	Tuesday, November 28, 2017
	Post-Treatment Survey	5pm, Wednesday, November 29,	
FEM1	Mastery Exam	1pm, Monday, November 27, 2017	
	Discussion Question		
	Post-Treatment Survey	5pm, Wednesday, November 29,	
FEM2	Mastery Exam	1pm, Monday, November 27, 2017	
	Discussion Question		
	Post-Treatment Survey	5pm, Wednesday, November 29,	
	One Minute Paper	5pm, Wednesday, November 29,	
FEM3	Mastery Exam	1pm, Wednesday, November 29, 2017	Thursday, November 30, 2017
	Discussion Question		
	Post-Treatment Survey	5pm, Friday, December 1, 2017	
FEM4	Mastery Exam	1pm, Wednesday, November 29, 2017	
	Discussion Question		
	Post-Treatment Survey	5pm, Friday, December 1, 2017	
	One Minute Paper	5pm, Friday, December 1, 2017	

3.2. Readiness/Mastery Exams

Students were required to complete exams prior to the classroom discussion dates for each module. For instance, students needed to complete exams for FEM0-2 by 1pm, Nov. 27 in preparation for the classroom discussion on Nov. 28. The exams were administered through the Canvas LMS.

Results for the exams are provided in Appendix B.1 with statistical scores for all students and for each problem of the exam. In summary, the scores show the following:

- 46% of students did not score above 80% on FEM1 exam on the first attempt but all passed (>80%) on the second attempt.
- The passing rate on the first attempt increased for each successive FEM with 92% passing the first attempt for the FEM4 exam.
- All students passed all exams by the 2^{nd} attempt.

3.3. Discussion Questions and In-Class Interactions

Students also submitted short responses to questions related to each individual module (i.e. FEM2, FEM3, etc.). The instructor then reviewed the responses prior to the classroom discussion. Depending on the question and responses received from students, different approaches for in-class discussion were used. The initial in-class discussion period (covering FEM0-2) asked students to form groups of approximately 3-4 to discuss the questions and report back to the entire class following approximately 10 minutes. The instructor sought to stimulate additional critical thinking of responses or engage other groups into class discussion. The second in-class discussion for FEM3-4 was led a bit more by the instructor using a basic simply supported bridge application to describe potential uses of many different types of sensors and requesting student input about sensor decisions (types, locations, etc.).

Student responses to discussion questions for the FEMs are provided in Appendix B.2. Each row of the table is the response provided by an individual student. The following summarizes responses from students for each FEM:

- FEM0: *List the criteria, in order of importance, which you believe should be used to determine if a bridge should be monitored with a Structural Health Monitoring System. Be prepared to justify your criteria and their order of importance.*
    - Students felt that the bridge age, traffic volume, and importance of the bridge were the most important factors in deciding whether SHM should be used.
    - Bridges with a history of damage/deterioration or those that incorporate new design/construction methods would also be likely candidates for SHM.
    - Students raised many questions about the cost-benefit of SHM.
- FEM1: *How does the application of SHM potentially extend and expand the professional responsibilities of the structural engineer?*
    - The discussion primarily focused on the structural engineer's increased role in extending a structure's life through SHM diagnosis and prognosis but also incorporating new knowledge obtained by measuring actual performance into new designs.
- FEM2: *Assume that the installation of SHM systems is warranted for bridges with "high consequences" of failure. List the factors/circumstances you would use to define the consequences of failure. Provide a brief justification for each of your factors/circumstances and rank their relative importance.*

- Students identified the following factors that most affect the consequences of failure of a bridge: traffic volume, environmental impact, economic impact, available traffic redundancy of region, damage to surrounding structures, architectural or historical significance, and importance for response and recovery efforts.

- FEM3: *Thinking about what you have learned in your Mechanics courses (Statics, Dynamics and Mechanics of Materials), Mechanics of Materials Laboratory, and your current Structural Analysis course, list the parameters you would recommend be monitored and why for the SHM of a concrete girder bridge.*
  - Many student responses simply listed many different physical (displacement, force, strain, etc.) or environmental (temp., wind speed, etc.) quantities.
  - The discussion period was held by making a quick sketch of a single span, simply supported bridge and asking: (1) What do you want to know or avoid? (2) How do you measure critical quantities with sensors available? The instructor asks students to think about the relationship between their "desired quantities" and the "measure quantities." Approximately (7) scenarios were discussed.
- FEM4: *SHM systems can be installed on in-service bridges or newly constructed bridges. Given that the basic objective of SHM is to identify damage, discuss the ways in which the analysis and interpretation of the sensor data in these two circumstances differ and identify the factors, which may influence the analysis.*

- The in-class discussion focused on the purposes of SHM for new construction vs. in-service bridges. Some of the module content discussing data analysis and interpretation might have been a bit advanced.

Notes taken by the instructor during the in-class discussion period are provided in Appendix B.5. Some of these notes include hyperlinks or additional critical points made by the instructor to assist with potentially clarifying or aiding in discussion.

Results of

3.4. One-Minute Papers

Following the in-class discussions, students were asked whether they had any lingering questions or misunderstandings. The responses to this are provided in Appendix B.3. Most students reported that their questions were answered during the in-class discussion periods.

3.5. Post-Treatment Surveys

A final survey was given to all students following the in-class discussion for each individual module. The survey sought student feedback to the quality of the educational materials, value of the in-class discussion, and to assess learning outcomes. The results of these surveys are provided in Appendix B.4.

3.6. Recommendations for Enhancement/Improvement of FEMs

- Modules start slow early and finish (FEM4) with dense content

- Some of the early modules would be aided by a simple application (or two) to help students conceptualize some of the concepts presented. I received many questions early about applications.
- The FEM3 discussion question could be re-formulated to result in more critical thinking by students. Many responses simply listed physical quantities that could be measure by available sensors (displacement, force, strain, etc.). Perhaps the question might more specifically ask: "List the type of sensors and its installation location and direction to monitor (i) applied loading magnitude and distribution, (ii) crack opening at a particular location, (iii) bridge vertical stiffness, (iv) abutment settlement, (v) expansion joint performance, (vi) ground vibrations (from adjacent in-service roads or structures, or near-by construction), etc."
- The content of FEM4 was very dense and maybe a bit advanced for students at this level. It would likely be aided by a SHM application that includes some examples showing raw measured data followed by data cleansing and normalization.

4. STRUCTURAL EDUCATIONAL MODULES (SEM) AND STRUCTURAL APPLICATIONS MODULES (SAM) RESULTS

4.1. IMPLEMENTATION SCHEDULE

The SEM and SAM units were implemented at CWRU in Spring 2018 in ECIV 322 – Structural Design I. Approximately 80% of the students in this course also took ECIV 320 and hence the FEM units in Fall 2017. The implementation schedule is shown in Table 2 where the SEMs were introduced approximately mid-semester while the SAMs (and physical demonstration) done near the end-of-semester.

Table 2. Master Schedule for SHM SEM-SAM (CWRU, Spring 2018)

Unit	Component	Target Completion/Submission Date	Date of Classroom Discussion
SEM1	Mastery Exam	5pm, Tuesday, March 6th	Thursday, March 8th
	Discussion Question		
	Post-Treatment Survey	5pm, Friday, March 9th	
SEM2	Mastery Exam	5pm, Tuesday, March 6th	
	Discussion Question		
	Post-Treatment Survey	5pm, Friday, March 9th	
	One Minute Paper		
SAM1	Mastery Exam	1pm, Monday, April 23rd	Tuesday, April 24th
	Discussion Question		
	Post-Treatment Survey	5pm, Monday, April 30th	
SAM2	Mastery Exam		
	Discussion Question		
	Post-Treatment Survey		
	One Minute Paper		

4.2. SHM Demonstration at CWRU

The SHM demonstration performed at CWRU used a simply supported span of approximately 12 feet made of two graded, dimensional lumber members (2"x6" nominal). The demonstration focused on structural damage diagnosis through simple deformation measurements using both static and dynamic load application.

The setup is shown in Figure 1 with the simulated damage already induced in the specimen. The damage was induced by drilling 14 – 1" diameter holes, centered near the ¼ points of the beams. A mass of approximately 240 lbs. consisting of steel plates was applied at mid-span. Three LVDTs were used in the demonstration (see Figure 2) to measure (i) vertical displacement of one beam at mid-span, (ii) horizontal displacement near top of beam at mid-span, and (iii) displacement over an approximate 6-inch gauge length on the bottom of one of the wooden beams near the center of the simulated damage location.

Initial, baseline response measurements were taken of the undamaged beams thus simulating as-built behavior. The vertical displacement at mid-span and strain near the ¼ point was measured in the undamaged condition after applying the load. All results were visually presented on a computer screen connected to the data acquisition system. Additionally, free-vibration tests were performed by exciting the specimen at mid-span (by-hand) and then allowing for free-vibration response decay. Some discussion of natural period and damping was given (as most students had limited exposure to problems in elastic vibrations) however dynamic testing methods were covered in some of the SHM modules. Natural period was extracted and recorded during the demonstration. The holes were then drilled by four students in about 5-7 minutes to induce the simulated damage. The load was applied and measurements recorded. The results from the demonstration are provided in Table 3, which were displayed on a chalkboard the day of the demonstration. Some of the issues discussed after measuring response and observing changes to behavior included: (i) instrument sensitivity and accuracy, (ii) instrumentation placement to detect damage or monitor existing damage, and (iii) data normalization for environmental conditions in the field.

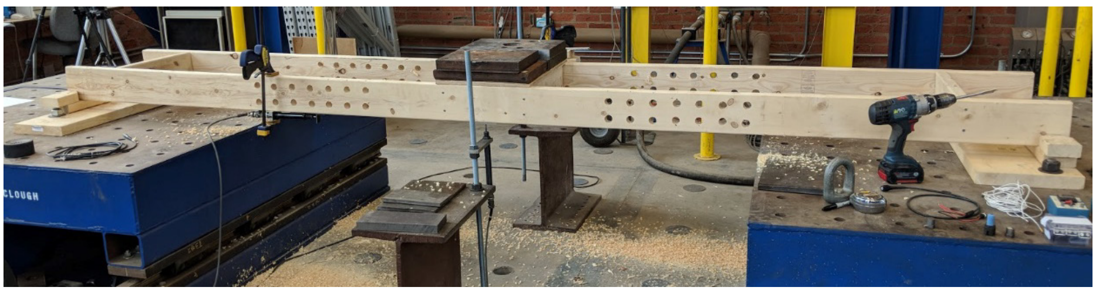
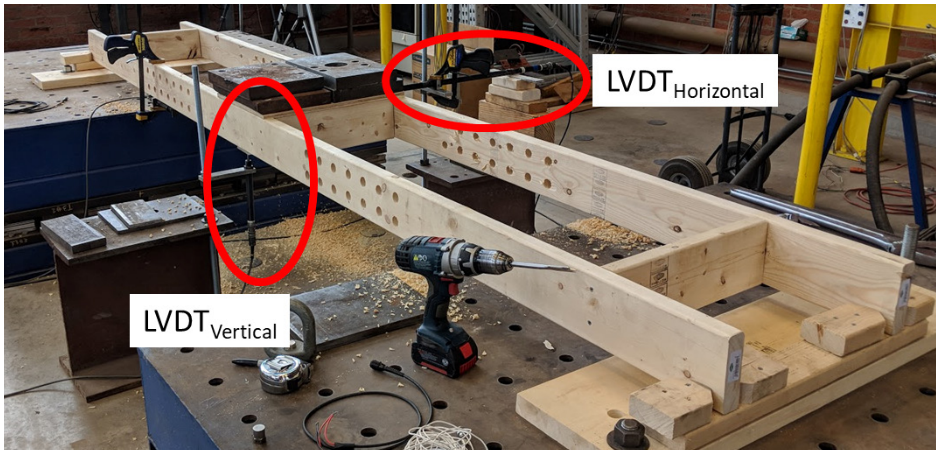
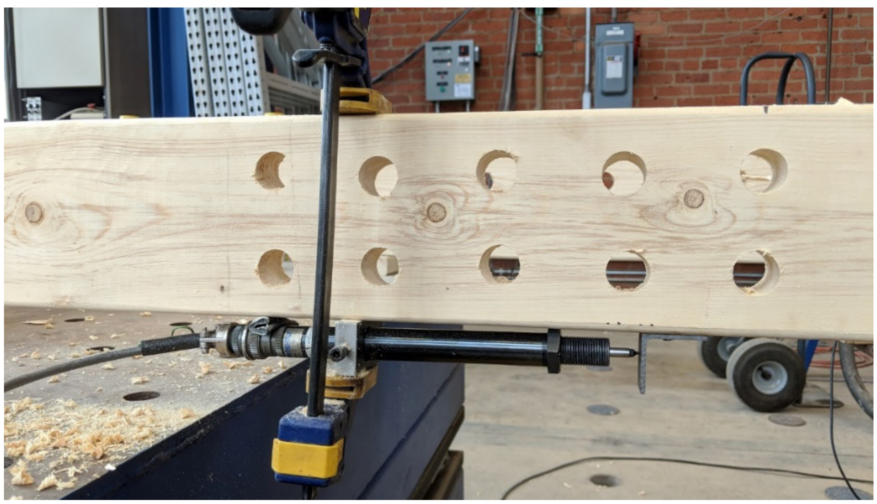


Figure 1. Demonstration Setup



(a)



(b)

Figure 2. Instrumentation **(a)** Vertical and Horizontal LVDTs at mid-span and **(b)** LVDT at Damaged Location

Table 3. SHM Demonstration Results

Specimen	$\Delta_{v,mid}$ (in.)	k_v (lb/in)	$\Delta_{bot,1/4}$ (in.)	$\varepsilon_{1/4}$ ($\mu\varepsilon$)	T_h (sec)
Baseline (undamaged)	0.2138	958	0.0018	248	0.49
Damaged	0.2209	928	0.0022	303	0.50
% change	3.3	3.1	22	22	2.0

4.3. Readiness/Mastery Exams

Similar to the FEMs, students were required to complete exams prior to the classroom discussion dates for each module. The exams were administered through the Canvas LMS. Results for the exams are provided in Appendix C.1 with statistical scores for all students and for each problem of the exam. In summary, the scores show the following:

- All students passed the SEM exams in their first attempt with average scores well above 90%.
- The SAM exams required analysis and critical thinking beyond that required of all other modules and had significantly lower scores. Most students passed the exam by the 2nd attempt but not all. No students contacted the instructor after failing the 2nd attempt (as instructed to do so) which may be partly due to the SAMs being implemented near the very end of the semester.

4.4. Discussion Questions

Students also submitted short responses to questions related to each individual module (i.e. SEM1-2, SAM1-2). The instructor then reviewed the responses prior to the classroom discussion. The in-class discussion for SEM1-2 was limited to about 30 minutes and focused on summarizing student responses to the discussion questions and answering student questions. The second in-class discussion for SAM1-2 was brief since the demonstration was also completed in this 75-minute class session and was conducted similar to the class discussion for SEM1-2.

Student responses to discussion questions for the SEMs and SAMs are provided in Appendix C.2. Each row of the table is the response provided by an individual student. The following summarizes responses from students for each module:

- SEM1: *Human skin has with millions of sensors that send signals to the brain about several measurable quantities, from which the brain interprets the health condition of the body. While it would be great to have millions or at least thousands of sensors in infrastructure projects, we cannot. Why?*
    - Almost all students answered the question with similar responses noting (i) costs, (ii) time/labor, (iii) data analysis effort, and (iv) likely not necessary. It is recommended to revise this question to provoke thinking that is more critical.
- SEM2: *The scope of SHM projects varies widely. Who do you think decides the scope of an SHM project?*
    - This question elicited some good discussion about the roles of various individuals in any sort of large construction project and the purposes for using SHM. This then led to answering the question about who decides the scope and the coordination of implementing the SHM system.
    - The consensus of the class discussion was that individual(s) with control of the budget would ultimately decide the scope unless an SHM system was being required by a building official.
- SAM1: *Standardizing a generic instrumentation plan that can fit all SHM projects is impossible. Why?*

    - Students noted the following: (i) nearly all civil engineering structures are unique in geometry and loading, (ii) each will degrade differently, and (iii) objectives of the SHM plan will vary for each structure.
- SAM2: *Damage can have a significant negative impact on the strength of structural members. However, the impact of damage on deformation depends on whether the damage is localized or distributed over a large section of the structural member. Why?*
    - Responses to this question varied significantly. The instructor did not discuss this question extensively due to time limits in this session, which also included the SHM demonstration project.

Notes taken by the instructor during the in-class discussion period are provided in Appendix C.5. Some of these notes include hyperlinks or additional critical points made by the instructor to assist with potentially clarifying or aiding in discussion.

4.5. ONE-MINUTE PAPERS

Following the in-class discussions, students were asked whether they had any lingering questions or misunderstandings. The responses to this are provided in Appendix C.3. Most students felt they had strong understanding of SHM concepts covered in the modules and that the in-class discussion and SHM demonstration significantly enhanced their understanding.

4.6. Post-Treatment Surveys

Similar post-treatment surveys were given for the SEM/SAMs with results provided in Appendix C.4. However, for some unknown reason, the survey results were not available afterwards for the SEMs.

4.7. Recommendations for Enhancement/Improvement of SEMs and SAMs

- The discussion question for SEM1 is too obvious and does not elicit critical thinking by students.
- The discussion question for SAM2 raises an important point related to implementation of sensors in an SHM system which was illustrated in the SHM demonstration performed at CWRU by installing sensors measuring "global" response (displacement at mid-span) and a sensor measuring "local" response (strain near damaged location). A question that asks about sensor installation decisions for newly built structures vs. in-service structures with known damage might be more appropriate and help lead into the SHM demonstration which was performed immediately after in-class discussion of SAM2.
- The SHM demonstration was very well received by the students. It would be beneficial to more explicitly link content covered in the FEMs, SEMs, and SAM1 into the demonstration and its description in SAM2.

APPENDIX A

-

PRE-TREATMENT SURVEY RESULTS

A.1. Pre-Treatment Suvery Results

CWRU -
Pre-treatment Suver

APPENDIX B

-

FOUNDATIONAL EDUCATIONAL MODULE (FEM) RESULTS

B.1. Readiness/Mastery Exam Results

FEM1

FEM-1 Exam, Attempt 1 Results

FEM-1 Exam, Attempt 2 Results

FEM2

FEM-2 Exam, Attempt 1 Results

FEM-2 Exam, Attempt 2 Results

FEM3

FEM-3 Exam, Attempt 1 Results

FEM-3 Exam, Attempt 2 Results

FEM4

FEM-4 Exam, Attempt 1 Results

FEM-4 Exam, Attempt 2 Results

B.2. Discussion Questions

FEM0

List the criteria, in order of importance, which you believe should be used to determine if a bridge should be monitored with a Structural Health Monitoring System. Be prepared to justify your criteria and their order of importance.	
	External conditions, internal conditions, and age. External conditions being aerodynamic forces (if there is a lot of it ie. Tacoma Narrows Bridge), internal conditions being the traffic loading, and age is how old the bridge is.
	I think that the criteria that should be used to determine if a bridge should be monitored with a SHM system is in regards to the potential damage that can occur. 1) If a bridge has existing damage 2) If a bridge has had a history of damage 3) If a bridge has gone through natural disaster events (earthquakes, etc) 4) If there is a concern with the structural integrity of the bridge from a construction or materials standpoint
	Listing the criteria that I believe should be used to determine if a bridge should be monitored with a Structural Health Monitoring System are the amount of traffic over the bridge each day, the size of the structure, the location of the structure, and the material the structure is made of. I list the amount of traffic as the first criteria, because preventing a high-traffic bridge from failure would help to save the most amount of lives. The size of the structure would be second, because if a bridge that is multiple miles long, or hundreds of feet tall failed, it could be catastrophic. Next, the location of the bridge should be considered to account for any nearby structures that could be impacted by a failure. Last, the material the structure is made of should be considered, as some materials are more susceptible to failure when subjected to unique loads.
	1. Age. Older bridges will have been built differently than modern bridges, and this difference may cause the bridge to fail. Older bridges may also fail as the material used to build them could have eroded over time. 2. Material. The material that a bridge is built with should be the next criteria for monitoring as some older materials may have eroded over time. Also, certain materials may be more prone to failing, and should be monitored to ensure that they do not fail. 3. Company. If a company has a record of creating structures that are unsafe, or that tend to fail earlier than they should, then the structure they create should be monitored. If the company does not have an honest background, then the bridge should also be monitored.
	1. The environment the structure is built around. If it is common for earthquakes, hurricanes, or other natural disasters to occur, it would be important to monitor the structure with SHM.

	2. Time- Every structure will degrade and become damaged so it will be important to monitor their conditions after a certain amount of time 3. Going off of time, if inspections of structures over time show probable sources of future damage, SHM should be implemented to enhance the ability to detect damage.
	1. How likely the bridge is to fail (i.e. age, material, loading, etc.) 2. Volume of vehicular/pedestrian traffic across the bridge/number of people likely to be endangered if the bridge were to fail 3. How essential is the bridge to overall traffic patterns 4. Architectural uniqueness or history of the bridge
	1. Bridge was built using new design methods or building techniques - Since such a project would have no historical experience to draw on for anticipated issues or overall durability, it would be most crucial for such a project to have utmost priority for a SHM system, as it would indicate these issues before they became problematic as well as provide immediate data for analysis to determine if the design is a successful one in a much shorter time span than the entire life of the bridge. This situation should be prioritized first because the an SHM would both provide needed data for future projects as well as mitigate risk, thereby having both significant economic and scientific benefits. 2. Bridge is built in an area known to have harsh conditions - If a bridge is built in an area known to have harsh conditions, like high winds, heavy precipitation, extreme temperature fluctuations, exposure to sea water, etc. it would be crucial that such a bridge have some SHM system in place, as such conditions have real potential to shorten the life of the bridge to far below its anticipated service life, and may cause structural failure in ways not apparent without SHM that could put lives at risk. 3. Bridge is incredibly large in size or span - Since a very large bridge would be incredibly expensive to replace, the cost/benefit analysis for SHM is heavily skewed in favor of implementation, as the cost associated with implementing an SHM system is definitely worth the potential benefits of detecting structural issues as they arise and potentially extending the life of the bridge much longer, ultimately saving a lot of time and resources. Additionally, very large bridges are likely to cause catastrophe in the event of failure, thus there is adequate safety incentive to monitor them. 4. Bridge has high amount of traffic - Similar reasons to 3, but without as much economic incentive. 5. Location of bridge is of high environmental value - The incentive of avoiding environmental damage is of high importance and thus if the area has

	high environmental value, it should be worth the cost of implementing an SHM system to determine potential damage to the surrounding environment. 6. Bridge is very old and may have existing structural issues - For the very obvious reason of preventing disaster, any bridge that is approaching the end of its anticipated service life is a good candidate for SHM. However, this should not have as high priority, as the bridge has likely already suffered substantial damage, and thus SHM would not be nearly as economical of a choice, as there is not much potential for preservation, and the bridge would likely be replaced or repaired soon anyways.
	-Ownership of the bridge, federal, state, etc - The age of the bridge (Should warrant more frequent inspections) - The typical load capacity of the bridge i.e traffic flow on the bridge. - Structural materials used in construction.
	Location of the bridge (environmental loads on bridge-> wind, seismic, snow) Age of the bridge I believe environmental factors are slightly more important when considering damage to a bridge because many bridges are exposed to these factors/conditions on every day whereas age is something that affects bridges over a long period of time.
	Largest potential for loss of life Largest potential for loss of property Environmental effects of failure "Structurally Deficient" or similar rating Age
	Importance of Structure to Area Average Usage Constructability Available Funds
	age/lifespan of bridge, observed deformation/deflection/damage, whether or not bridge has been used over intended capacity

	If its older than it was originally expected to last, since that means it could fail very soon. If the bridge is made in a no longer used way, meaning not only is it old but its also outdated. If the bridge is driven on an excessive amount because more force on it could lead to more damage.
	1. Time in which the bridge was built(year it was constructed) The age of the bridge would be the most important factor as to why it should have a SHMS attached to it. The older the bridge, the higher the chance of failure due to many factors such as deterioration and fatigue of materials. Also constant loading of bridge over time could have made damages to bridge that we cant monitor frequently 2. Frequency of use. Abridge that has constant amount of live loading everyday should have SHMS attached because if a bridge were to fail when many people use it everyday, that would affect many peoples lives and we as engineers need to ensure not only the safety of the bridge, but the safety of people as well. 3. Environmental impacts Bridges that are in constant contact with wind loading and seismic loading should have SHMS due to these factors affecting the life of a bridge more rapidly and could cause sever damage to a bridge than most humans cant see until complete failure of a bridge. 4. Materials used for construction of bridge. older bridges made with non modern materials such as wood on non-reinforced concrete should have SHMS due to the likability of those materials failing more frequently then bridges made with reinforced concrete.
	I think there are a few important factors that go into whether or not a bridge should have a Structural Health Monitoring (SHM) System. To me, those factors are the age of the bridge, i.e. when it was constructed, the load the bridge undergoes on a daily basis, the type of bridge (some designs could be more susceptible to failure than others, such as the specific design type of Silver Bridge), and potential exposure to extreme weathering conditions. I find the most important factor to be the load the bridge regularly undergoes, because high-traffic bridges could cause the most damage to property and life if they were to fail. Any high-traffic bridge is likely to deal with a high load passing over it, which could cause potential issues such as exceeding the

	design load or over-stressing the bridge components. An SHM system would be beneficial in these situations to observe if the bridge needs to be reinforced, repaired, or if adjustments need to be made to traffic patterns to ensure safety. Next, I think that age and design of the bridge are two equally important factors. The older the bridge is, the harder it may be to inspect, and the less smart features exist in it now. Many designers of older bridges did not have the technical knowledge we do today, so they might not have been aware to account for certain future issues in design. That is why age goes hand in hand with design, because certain structural characteristics that would potentially make SHM useful could be a result of a design that is no longer popular or the most sound structurally. An SHM system here could act as a warning sign for issues that we do not know to look out for in regular inspections and can hopefully prevent unexpected failures. Finally, I think that an SHM system could work for a bridge that undergoes extreme weathering conditions. Though bridges should already be designed with their environment in mind, an SHM system could aid in determining the proper maintenance for bridges that are subjected to stress from low temperatures or constant heat or moisture conditions.

List any questions you might have concerning SHM in general, the SHM Education Unit and your responsibilities.	
	Is SHM expensive? How many structures have SHM installed on it today?
	In the case with the I-35W Mississippi River Bridge, was the recommendation to install a SHM system ignored because of cost? Or was it simply forgotten?
	I have no specific questions at this point, but I generally would like to learn more about structural jobs as a SHM engineer.
	I do not have any questions yet about SHM
	Are there other reasons besides economic ones that would prevent SHM from being used?
	What is the exact cost/benefit ratio for implementing SHM? What different options are there for implementing SHM? What is the current procedure? What is the outlook for SHM?
	General Questions about SHM What are the costs associated with SHM? How is data from SHM analyzed? What are the cases in which SHM yielded real benefits, and how? Questions about the SHM Education Unit How will I be able to retain what I learn from the SHM Education Unit? Is the depth of detail that which the SHM Education Unit goes really worth my time to learn?
	I was wondering whether SHM was better as a college built in module instead of a professional certification. I think it is very beneficial, I just wonder if it will be better effective as a professional course.
	Who is responsible for conducting these assesments in America?
	None yet
	What size design usually qualifies for the usage of SHM systems and what is the cost relative to construction?

	What are some of the costs and benefits associated with modern Structural Health Monitoring as opposed to previous methods used for determining structural safety? How do these methods differ? What are some of the fixes used on structures determined to be unsafe by SHM? Are these a temporary or (relatively) permanent solution? How will SHM be implemented into policy for structure rehabilitation? Will SHM results be taken seriously by project managers?
	N/A
	Are there cheaper alternatives/better units that don' cost as much to install onto structures?
	I am currently curious about how SHM can be retroactively applied to bridges already constructed and what the differences are between SHM and smart technologies used in newer construction projects or if those are the same things. Otherwise, I have no questions about my own responsibilities for this unit and look forward to learning more and hopefully being able to answer my questions.

FEM1

How does the application of SHM potentially extend and expand the professional responsibilities of the structural engineer?	
	It makes them analyse data extracted from the senors on the structure to help improve the life and reliability of the structure.
	It allows structural engineers to monitor the actual health of the building through its life. This allows the structural engineer to figure out what works in specific conditions. However, if something goes wrong, the structural engineer would have to figure out what happened and how to fix it.
	The application of SHM extends and expands the professional responsibilities of a structural engineer because he/she is now responsible for management of the structure to ensure the safety and serviceability of the structure. This is different from the past, where the engineer was only involved with the structure if an issue or problem was found during annual inspection. Now, they are usually required/asked to compare predicted vs. actual performance.
	Using SHM keeps the structural engineer involved in the bridge's life beyond initial design and construction. If issues arise, the structural engineer can be aware of them and can work to fix them before they become a significant issue, therefore expanding the bridge's lifespan.
	This can potentially expand and extend the responsibilities of the structural engineer, because the engineer can now have the ability to evaluate the structure after it is built to compare and evaluate data about the structure and relate it to designed capacities. The structural engineer can also extend responsibilities to maintenance of the structure, possible improvements, and other additional design changes that may become necessary after gathering the real life field data on the structure.
	Before SHM, the structural engineer was only responsible for the analysis and design of a bridge and would rarely deal with the project again unless a problem arose during its construction or something was detected during its annual inspection. No attempt was made to compare the actual performance of the project with its predicted performance but now with SHM, the structural engineer also has to manage the project after it has been been to ensure its safety and serviceability.
	It expands the responsibilities of a structural engineer because it ensures that structural engineers keep constant watch over structures they have built. Unlike now, structural engineers will not just be done with a project upon completion but will be responsible for it in the long run. It also helps to avoid unforeseen failure costs for structural engineers.
	It means that a structural engineer not only will help to design a structure by calculating loads and using proper materials, but also analyze how the structure responds to various loads over time. By analyzing how the

	structure responds, a structural engineer can also help to extend a structure's lifetime.
	With the implementation of SHM, structural engineers now have to be concerned with the management of the bridge and how to use SHM to keep the structure safe and functioning. Before, they would only have to look at the bridge again if there was a problem at the annual inspection, but with SHM, data is recorded continually and not only once a year. Engineers now can compare the actual performance with predicted performance as well as look at durability of the structure and effects of secondary factors.
	If SHM is used, then an engineer's responsibilities can extend past the design and construction phase. Because SHM monitors buildings over time and identifies possible structural problems, structural engineers need to be available for a longer period of time for a project. Also, the structural engineer may be responsible for deciding what to do if and when SHM shows structural problems occuring.
	In addition to working on new projects, the engineers will be responsible for staying up to date with the structures they've designed in the past and making sure they aren't suffering any damage.
	With SHM, Structural Engineers must now also be familiar with how to interpret the data that is resulting from these systems. Additionally, they must be able to understand these systems and when and where they should be applied as well as how to apply the system.
	Traditionally, a structural engineer's job has been more or less done after the completion of the bridge. With the introduction of SHM, the structural engineer would be responsible for determining whether the actual performance of the bridge matches with the expected performance of the bridge; that is, the structural engineer would be involved with the bridge for years after it has been built.
	The job no longer becomes create a structure that is sturdy and meets safety requirements when it is initially constructed, but rather, create a structure that can show extended and maintained strength over years to come. Additionally, making repairs easy to implement and planning for replacement of supports may be a wise choice since ease of maintenance and repair becomes important when using SHM.

	SHM expands the professional responsibilities of a structural engineer by enabling them to be more proactive in their design assumptions. Instead of just making vaguely applicable assumptions about the loading on a structure and then designing simply on such assumptions, the structural engineer is forced to constantly monitor the loading and environmental conditions of a structure and the responses of the structure to these conditions, and evaluate whether or not these conditions match the assumptions assigned in the design of the structure. This allows assumptions to be corrected and redefined by actual evidence, and makes it possible for subsequent implementations of similar designs to have potentially more liberal assumptions to save on costs, or more conservative assumptions when it has been proven that a previous design failed to account for some unexpected loading or environmental conditions. Additionally, by making the current status of a structure easily accessible at practically any time, it shifts a lot more responsibility on to the structural engineer to design structures that are more durable and of better quality, as there is much greater transparency as to which designers properly account for safety concerns. This has the effect of forcing the design engineer to consider the structure as an on-going project rather than simply design and construction. Both of these effects combined also have the added effect of improving competition between designers.
	Instead of only being responsible for the design of the structure (and clarifying issues during construction), the design engineer is now also responsible for maintenance of the structure, being proactive, and checking the actual load case/resultant structural behavior against the assumptions used to design the structure. The involvement of the structural engineer is expanded from the design and construction phase to also include the whole lifespan of the building.
	The structural engineer can become responsible in the continued maintenance of a structure through periodic data processing and giving recommendations as to the best use of resources to help in increasing structural integrity.
	The application of SHM extends the responsibility of the structural engineer to include monitoring a structure over its entire lifespan instead of just during design and when major problems occur. It expands their professional responsibilities to include more types of analysis including comparisons of actual vs predicted performance, durability of the structure over time, specific damage to the structure over time, impact of maintenance on the structure's performance, etc.
	Since SMH is so helpful and gets a lot of date and information for the engineer, the engineer is then tasked with more things given their new info.
	SHM Gives real life results form sensors that can give data to evaluate damage done to the structure being measured. This system gives

	engineers a very clear understanding of what actual loading is being applied to the structure and how an engineer can improve the design of structures to come.

List any questions you have concerning the content of FEM1. Your's and other student's questions will be answered in a subsequent class period.	
	How does the sensor work?
	What types of sensors are used to monitor the health of the structure? How many existing structures are getting SHM systems?
	It would be great if we could go over a detailed example of how SHM is implemented in a real-life situation to get a better understanding of how it is used.
	Not actually a question but just made me think more about how using SHM can teach us what designs, materials, or construction methods are successful or not to make future projects more successful. Also more thought on how to pick projects which are most worthy of SHM, which goes back to original thought - if you don't pick a certain project that contains an innovation, how much more difficult will it be to figure out the benefits of that innovation?
	What types of programs are used to evaluate this data? Are there multiple types of software used?
	Is it expensive? How are the sensors applied? Can they be applied externally - after the bridge has been built or should it be applied while the bridge is being constructed?
	A lot of the information I got from fem 1 was clear. I was just wondering what the procedure is like when the sensors discover the damage. How specific is the information given by the sensors?
	How difficult is it to maintain the various sensors needed to analyze a structure? Are these sensors put in easy to access locations, and how does this affect the design of a structure?
	I understand that sensors can't measure damage, but how does the data get converted to damage information? I read its converted by feature extraction through signal processing, but what does that mean?
	Can we go into more detail about the specific types of monitoring systems that can be used for SHM? What type of data do they transmit and what type of analysis happens for an engineer to understand the data and act on it if needed?
	What is the cost efficiency of SHM? Is it viable for use in both small projects and large projects?
	Is there any component of SHM that would help with a situation like the Tacoma-Narrows Bridge discussed in FEM 0, where the resonance failure happened unexpectedly in an otherwise sound structure and therefore would likely have gone undetected until failure was already occurring?
	Is there a point where a structure is just not important enough to merit expensive SHM? i.e. a grain silo or barn where using SHM may cost far more than any possible benefit of catching early damage?

	FEM1 exam seemed way too easy to bullshit. (Not a question, but a very noteworthy comment.) What are the limitations of the testing used in SHM? What concerning design issues can SHM address? What influences on design and design firms has SHM already made? Expected to make?
	Given that this allows for a real-world check on theory, does this typically confirm that the theory is correct or does it say that theory is consistently too conservative, not conservative enough, or inconsistent?
	N/A
	How is the continuous monitoring used in SHM done? Do the sensors used in continuous monitoring have any effect on the structure's design or performance? Are there any downsides associated with the use of this technology? Will SHM results change structural standards in the future? Will this eventually become a required technique for many structures?
	N/A
	How to determine the difference between noise and actual data points?

FEM2

<table>
<tr><td colspan="2">Assume that the installation of SHM systems is warranted for bridges with “high consequences” of failure. List the factors/circumstances you would use to define the consequences of failure. Provide a brief justification for each of your factors/circumstances and rank their relative importance.</td></tr>
<tr><td></td><td>Some qualities that could make a bridge "high consequence" are if it is moving through its lifespan and we would want to know if it is reliable, or if it is high traffic and we want to see the effects of that high amount of loading. Therefore, I think the most high consequence bridge would be a bridge later in its lifespan that has a lot of traffic, because it would be the most likely to cause problems if it failed.

Other high consequence bridges could include bridges with irregular or innovative design or construction techniques because it is interesting to see how they perform. This kind of observation is not as integral as the previously listed one because there is less at stake, but it is still important because it can make design more efficient in the future.

Also important when deciding if a bridge warrants SHM is the area that it is in. Having SHM has long term economic benefits, so if the bridge is constructed in a county with a low budget, it could help the county save money on maintenance costs and reduce needs for earlier construction.</td></tr>
<tr><td></td><td>1. Danger to human life - First and foremost, an engineer has an ethical duty to keep people safe, and thus the most important consequence to consider is an analysis of how many human lives could be lost from structural failure, given various considerations such as traffic flow, bridge height, and terrain effects.

2. Potential environmental impact - The next important consideration would be the environmental impact, as this has very lasting potential beyond the life of the structure, and may not be easy to reverse when they occur. This evaluation would consider the surroundings of the structure, and how any components or runoff that may be generated by the structure in the case of failure may harm it.

3. Economic value of structure - Simple cost benefit analysis of cost of SHM mitigation to outright failure. Straightforward, but the only damage considerations are monetary, and so it is of lower priority.

4. Time to repair/replace - Similar to considerations above, but with time instead of money. Has about similar consideration to monetary costs.</td></tr>
</table>

	1. Serious defects or deficiencies is most important because this is where something can fail dramatically. 2. Difficult to measure performance issues is second because something can go wrong without someone knowing. 3. New materials, construction and/or design because people need to know if it works or not 4. Bridges near unity 5. Movable bridges is last because there have been precedents for these types of bridges.
	1) Death of individuals on the bridge -leads to lawsuits, investigations, etc 2) Serious injury to individuals on the bridge -same as above, but not as serious 3) Structural issues with the bridge -leads to uncertainty with government, construction company, and their work 4) Structural damage risking closure/destruction of the bridge -leads to more government spending to replace the bridge, etc 5) Lengthy closure of the bridge for repairs -leads to traffic issues, road closures, detours, etc
	The span of the bridge - if it was very long and there were a lot of vehicles on it, the more people would get hurt if the bridge failed. The location of the bridge - if it was located near a residential area/where would its impact zone be.

	1. Bridge fails due to a large amount of traffic going over it. This would be ranked the highest as it would put the largest amount of lives at risk. 2. Bridge fails due to natural disasters. It would be important to monitor bridges that are in areas with a high risk of natural disasters such as floods, earthquakes, or hurricanes. 3. Bridge fails due to the materials used to build it. This would need to be monitored as older materials may have weather over time. It is also important to monitor as bridges built using similar materials can be compared. If one bridge failed and was built using a material that had significantly eroded, other bridges could be checked to ensure they didn't fail as well.
	1) Civilian Lives Lost: Certainly the most important factor to think of when thinking of consequences of failure. This would be the worst consequence. 2) Nearby Structures Damaged: This would be the second worst consequence, because homes or other buildings could be destroyed or damaged, and people could be injured. 3) Environmental Impact: Third worst, if the structure caused an impact on the environment, it would be costly and could impact both wildlife and civilian life (impact on waterways) 4) Impact on Community: 4th worst, if a bridge necessary for travel in and out of a city was damaged or failed, it could impact the flow of traffic for weeks and impact businesses and civilian life. 5) Cost of Failure: 5th worst, major failure could cost the owner millions of dollars, certainly not a good consequence but not nearly as bad as death.
	1. Bridges that have serious deficiencies: Some bridges that have serious deficiency should be considered as bridges with high consequences.This is because the deficiency could result in the collapse of the bridge at any time and so SHM is needed. 2. Bridges with new materials/designs that could be questionable: bridges which are constructed with new materials or designs should be put under SHM because it is beneficial for engineers to know how that structure and future structures will hold up. 3. Bridges with load rating factors near unity: Bridges that show little signs of distress. It is beneficial to have sensors that can detect internal stress.

	1. Location- If the bridge is located in a large populated area and is used regularly, then the failure of the bridge could lead to big transportation issues or other factors. Also if the bridge were to fail while being used, that would lead to many deaths. 2. Day-to Day use of Bridge: If the bridge was used regularly, the failure of it would cause a lot of consequences for the surrounding city and population. 3. Economic factor: If the bridge failed and destroyed surrounding structures, that would cause a lot of money to be put back into the rebuilding process. Also, failure of the bridge would cause transportation issues which means money would have to be put into creating an alternate transportation route.
	1. Frequency and amount of travelers across bridge. If it is a frequently traveled bridge with lots of passengers, there will be more people affected if the bridge fails. 2. Whatever is underneath the bridge (another road, body of water, a field, etc.) Depending on if there are more people underneath the bridge or if there are other travelers on a road or water, the effects of the bridge failing will vary. 3. Height of bridge. This could affect the sorts of injuries that could occur if failure were to happen.
	Loss of human life - human life should always be the first concern Large damage to environment/ecosystem - destroying the environment is (hopefully) obviously a bad thing Property damage - a concern since the government/bridge owner might be sued for damages

	Factors of consequences of failure: 1. Loss of life- This is by far the worst outcome of a structural failure and should be avoided at all costs. 2. Significant local/ environmental damage- If the structure fails, it is likely to cause damage to surrounding structures and/or require a significant cleanup effort. Such cleanups can be costly and time-consuming. 3. Disruption to traffic- If a bridge collapses in a major highway, it would cause large disruptions to the flow of traffic and commerce to an area. Closing a bridge before it collapses allows for time to explore detours, as well as to plan for the deconstruction and reconstruction of a replacement bridge, thus minimizing the interruption to traffic.
	High consequences of failure include: 1. Potential for injury/death-- above all, the safety of the bridge should be considered so that pedestrians and drivers can expect to use public roadways and bridges without harm to themselves or others 2. Large impact to traffic patterns as the municipality recovers from the bridge failure and redistributes traffic-- this could cause displeasure/loss of faith in the DOT on the part of the residents affected 3. Significant economic loss as a result of failure of the bridge-- this would strain the DOT's budget and make it more difficult to provide for safe and efficient roads and other bridges 4. Significant cultural or architectural loss as a result of the failure of the bridge-- arts and culture add life to a place, and bridges often have a lot of meaning for many people
	1. Bridge collapses - the bridge is completely unusable and could've fatally injured people on it when it collapsed 2. Bridge cracks/deforms significantly - the bridge is still unusable but still fixable to an extent, may have hurt a few drivers 3. Bridge cracks/deforms a bit - bridge is usable, but maybe barely. Little to no damage to drivers

	1) Importance during natural disasters: Institutions that help in emergency scenarios such as levies, hospitals, and bomb shelters should have SHM 2) Average Usage: If there is great usage then the potential for loss of life increases needing greater assurance of user safety 3) Cost of Structure: Cost of repair may be debilitating to communities and thus the hardest to foot the bill should be given the most care to avoid cost later
	The three main "high consequences" of failure could be high deaths associated with bridge failure (potentially due to constant high traffic usage), high economic cost (due to loss of time/materials put into bridge or from traffic costs associated with rerouting), and high environmental costs (failed bridge destroys ecosystem underneath it, materials toxic to environment when bridge fails, etc.).
	Wind Loading Failure. If the bridge is located in an area that is subjected to heavy wind loads and is in danger of failing due to constant wind loading, then an SHM system should be applied for this consequence of failure. Live Loading Failure. If the bridge is located in an area that is subjected to mulitiple live loads and is in danger of failing due to constant live loading, then an SHM system should be applied for this consequence of failure Seismic Loading Failure. If the bridge is located in an area that is subjected to heavy seisimc loads and is in danger of failing due to constant seismic loading, then an SHM system should be applied for this consequence of failure

List any questions you have concerning the content of FEM2. Your and other student’s questions will be answered in a subsequent class period.	
	What is dynamic field testing? Also more information on periodic field testing and ambient traffic.
	How is the data from SHM used to ultimately repair structures? What are the advantages to implementing each different level of SHM systems?
	N/A
	I don't have any questions about FEM2.
	Are there areas that are best for placing the sensors to optimize the number of sensor sites?
	How quickly can an older bridge be categorized as structurally deficient as there is no older data to compare with?
	Is the National Bridge Inventory the largest governing body for bridge standards/performance for the US?
	What is the response time for detected damages? and I am guessing it is dependent on the level of damage.
	Are we trying to implement SHM in every bridge that is going to be built or are we only using it right now for bridges that have high consequences of failure? I understand that there is a criteria for determining which structure will implement SHM, but I don't quite understand what the end goal is for SHM and whether every building will have it or it will be primarily used for structures that have shown signs of deterioration.
	What are the differences between SHM and FMM? They seem to be quite similar. What is hardware redundancy?
	Does SHM only include structural measurements (strain, load, etc.)? The presentation made it sound like it only included those measurements, but the quiz seemed to indicate that it included all the other types of measurements as well (traffic counts, water flow, pH, etc.), but I thought that was included under FMM and not also in SHM.
	Why exactly is hardware redundancy desirable? (Not explained in PowerPoint)
	The content was very sporadic, and didn't quite adhere to the quiz we were expected to take. A definition that was part of quiz and key to seeing how we apply data from SHM was "structurally deficient" but no definition was given in the lesson nor directly stated in any of the links. Even the first question of this discussion is unrelated to the content. It's not as if we are not to do outside work but there should be some content to lead u down that path and at least give us a sense of what we should get out of this.

	How expensive is SHM? How much are the costs offset by less of a need for maintenance/check-ups on the structure and by less of a need for replacing structures? How many of the "notable bridge collapses" could have been prevented by using SHM? Were they all predictable collapses or were some of them newer, healthier bridges whose collapses could not have been prevented?
	What are the exact devices used?

FEM3

Thinking about what you have learned in your Mechanics courses (Statics, Dynamics and Mechanics of Materials), Mechanics of Materials Laboratory, and your current Structural Analysis course, list the parameters you would recommend be monitored and why for the SHM of a concrete girder bridge.	
	Displacement, tilt, corrosion, pressure, and acceleration should be monitored. These are all key parameters that would help determine the stability of the girder and the overall health of the girder.
	It would depend on the structure that is being analyzed, but I would say the most important parameters would be degradation, loads, and displacement.
	- displacement, force/load, strain, : monitoring these parameters will help engineers keep a closer eye on the deformation or overloading that can occur which could lead to damage and collapse
	Stress, strain, loads on bridge, cracks, joints, traffic, environment,
	1. Displacement of Abutments - Want to ensure that abutments remain relatively stationary, and would want to detect when they begin sliding to intervene and avoid failure of the bridge. 2. Strain in Concrete - Want to be able to determine if and when concrete is cracking, as well as an estimate of the stress in the concrete using strain and modulus of elasticity. Both are critical for determining when concrete requires repairing. Also critical to determine if the allowable loads on the bridge must be reduced, and thus restrict certain traffic types or magnitudes. 3. Ambient Temperature - Want to determine the range of temperatures the concrete experiences, as well as how quick it fluctuates, as very large or very quick changes in temperature can cause thermal strains that can lead to cracking, which would need to be addressed quickly. 4. Moisture Content of Concrete - Water absorption is a serious concern in concrete, and would want to determine if concrete is in danger of shrinkage damage or damage from freeze/thaw. 5. Load in Concrete girders - Want to determine if bridge experiences loading that exceeds design loading in order to determine if modifications or restrictions to current design are needed. 6. Dynamic Acceleration - Particularly useful in determining response of structure under seismic loading. Can compare to design parameters to determine if modifications to current design is needed.
	Strain, actual loading, if reinforced I would like to make sure the reinforcement is holding up as expected.

	1. Stress 2. Strain 3. Creep 4. Displacement 5. Axial forces 6. Shear forces 7. Moment
	1. Deformation of girders at midpoints of span 2. Force acting on supports
	Some parameters that should be monitored include vertical/lateral accelerations and temperature. Vertical and lateral accelerations should be measured to record movement of the bridge based off of environmental or load effects, while temperature should be measured because it can have an effect on the material composition of the bridge.
	moisture content - concrete has high strength when more moist exposure to weather conditions stress and strains on the bridge deformations and cracking
	- The loading capacity - The reaction system - Structural material - Bending of material
	Displacement, tilt, temperature, and corrosion.
	I would recommend that parameters such as acceleration, displacement, tilt, strain, pressure, and force should all be monitored for the SHM of a concrete girder bridge. I would recommend these parameters be monitored because it would be the best way to account for the static behavior of the structure when thinking of displacements and equilibrium situations. Additionally, it captures the dynamic behavior of the structure, which is important when considering loads moving across the structure as well as major weather events.
	stress, strain, displacement, especially at joints and foundation

	Displacement, strain, force, and pressure should be monitored to check the concrete girder bridge's dynamic behavior, performance, and static behavior of the bridge and its settlements.
	-displacements -strain -vibrations in bridge deck -torque in bridge deck -loading on bridge -temperature and wind Significant change in any of these parameters could lead to structural problems and ultimately failure. If the bridge is moving more than it should or is experiencing more loading than it was designed for (from cars, people, or weather), actions need to be taken to help prevent failure.
	Strain - concrete cracking Stress - yield stress Deflection at mid-span
	Monitor everything so nothing can go wrong. More specifically monitor the amount of weight acting on the bridges and if any cracks form.
	There are many forces and parameters to account for when analyzing if a girder will fail or not, some parameters are loads, displacement and many more. The main parameters I would monitor are Live Loading and Displacement. Live loading could be very detrimental to a bridge girder if a heavy enough load is applied,the girder could fail and cause the bridge to collapse. so measuring live loading and setting maximum loading requirements for the bridge could drastically expand the life of the girders and the bridge. Displacement is very important to measure especially if a bridge is starting to settle. when a bridge starts to settle, it could put a concrete girder in tension instead of compression making the girder very weak and susceptible to failure. so settlement displacement should be measured quite frequently.

	-deformation/strain in concrete bridge deck components, beams, girders, abutments -stress in bridge deck components, beams, girders, abutments -creep in bridge deck components, beams, girders, abutments -temperature across bridge (calculate thermal st

List any questions you have concerning the content of FEM3. Your and other student's questions will be answered in a subsequent class period.	
	N/A
	N/A
	What are tilt sensors?
	For what scenarios would you apply each sensor for as is relates to SHM?
	What data processing and manipulation methods are implemented in SHM systems? Though it is stated that wireless systems are generally more efficient, in what situations would wired systems be much more advantageous?
	Generally how many sensors are used? Are they placed on every beam and girder or just in areas where a problem is predicted to happen?
	Is there a difference in reliability of sensors which yield an analog response vs. a direct response?
	None
	I do not have any questions about the content of FEM3.
	I don't have any
	N/A
	I do not have any specific questions about FEM3.
	What types of building materials are the easiest to collect data on, if there is a difference at all. Thinking along the lines of concrete members v. steel members.
	Which type of sensors give the most useful information about potential damage to the bridge? Is sensor data interpreted individually, or do you need data from many types of sensors to get an accurate picture of the structure health?
	Can you charge the wireless sensor? Do you think there will be a solar powered wireless sensor? How long is the battery life of a wireless sensor?
	How expensive is it to use SHM and implement these monitoring systems? What happens if/when one of the sensors fails or is giving faulty information? How would the data analyst know?
	none
	No, I do not have any questionss.
	What are the best types of sensors to measure robustness?
	How do you determine what accuracy is needed for each of these sensors for SHM applications? Could the Carlson strain meter theoretically be used for finding stress for ECIV 211 purposes (instead of the load cell)?

FEM4

SHM systems can be installed on in-service bridges or newly constructed bridges. Given that the basic objective of SHM is to identify damage, discuss the ways in which the analysis and interpretation of the sensor data in these two circumstances differ and identify the factors which may influence the analysis.	
	For a newly constructed bridge data can be interpreted to assure that the bridges design is sound or it can be used to make adjustments to the design. For in-service bridges the data is mostly analyzed to detect degradation and assure the safety of the structure.
	The in-service bridge would be more focused on the upkeep and any potential sources of issues, especially in its weaker points. They would also need to take into account that it already existed and things may have happened already. Newly constructed bridges would be more focused on the change of the bridge that could lead to potential issues in the future.
	Sensor data for newly constructed bridges would probably look at the data to compare with the assumptions made when building or create the baseline data for the structure when its not experiencing damage. For in-service bridges, the analysis is probably more focused on looking for specific areas where damage could occur and analyzing the trend of deformation it experiences.
	In a bridge that is already in service, a very important factor to consider is that the structure itself may already have incurred damage before SHM installation. Because of this, the structure does not really have a true baseline case, and thus a model of the structure may need to be created to provide an estimate for it instead. Additionally, the goal of an SHM on an existing structure would likely be to determine the existence and location of damage, which would favor using an unsupervised learning mode, whereas the goal of a new structure would tend more toward a general prognosis, which favors a supervised learning mode. For an existing structure, given that it may already have incurred damage, the risk of failure outweighs the inconvenience of unnecessary intervention, and thus a testing method that tends more toward false positives than false negatives would be more favorable. For a new structure, the concerns are inverted, and thus a testing method that tends more toward false negatives than false positives may be more appropriate.
	It depends on the environment that the structure is in because that would vary the data that the sensors pick up. If placed on a newly constructed bridge, the sensor would have information of the bridge when it is new and engineers would be able to use this information to compare it to the data when the bridge is older.
	The in-service bridge may differ from a newly constructed bridge in that it may already have deflections/damage that needs to be accounted. These preexisting damages might need to be determined by a physical inspection before SHM is installed on the in-service bridge. These damages could then be used as an initial

	condition when looking at changes in the sensor results. A newly constructed bridge would have a different initial value since it should start with no damage/deformations and so analyzing the sensor data will yield different end results.
	For in-service bridges one can use SHM to find out if the bridge needs to under go a repair or if it is not fit for service. One can also use SHM for in-service bridges to see what in the design went right and why the bridge has out-lived its original intended life span (if applicable) For new bridges one can use SHM to see where their design had flaws and how their assumptions turned out. To me I like to think of it how football players go back and watch the film of their previous game to see what worked for them and where they went wrong. SE can use SHM to the same effect so they can improve on their designs and see things they may not have while designing.
	With older bridges, data will be considered more heavily before being cleansed because they would be more prone to damage and degradation than a newer bridge. Additionally, older bridges will be subject more to prognosis analysis while for newer bridges, prognosis should not be an immediate concern. Additionally for a newer bridge, a baseline for subsequent comparisons would be advantageous as to see how the data is changing in comparison to its non-damaged stage. An older structure would not have this luxury as it would most likely be already under some sort of damage and a baseline might not be helpful to obtain.
	The sensor readings from SHM systems installed on a new bridge and an in-service bridge would look very similar, but the in-service bridge might already have degradation and damage.
	A way that the analysis and interpretation of the sensor data can vary in in-service bridges vs. newly constructed bridges is that with new bridges, the material is probably analyzed to see if the actual properties match the hypothetical/ideal properties, while for an in-service bridge, the focus may be on the history of the bridge and how the properties are holding up after a period of time. Another way that the circumstances may differ is that with an in-service bridge, SHM is more likely to be to assist/aid in finding damage, while SHM for a new bridge would be for preventative aspects.
	For the in-service bridge, it may be expected that there will be some existing weathering or damage. Therefore, there should not be too much alarm if the data immediately shows that the bridge has some erosion or damage. For new bridges, it should be alarming if the data immediately shows damage in the bridge. This might signal that something was not constructed correctly.
	- The types of damages they will be looking for e.g. bridges that might be currently experiencing failures.

	- Analyzing the overall structure vs areas of concern.
	For the in-service bridges, SHM would be able to see the damage/impending damage. Using this data, new bridges can be constructed more optimally/less conservatively. SHM data on new bridges can be used to see if the bridges react to the environment/loading the way it is supposed to. SHM data from in-service bridges can be used for maintenance and management.
	I believe that the sensor data for newly constructed bridges would look more scattered over the course of a small time period compared to in-service bridges. In-service bridges would have less data distribution because they would be monitored more. Older bridges would potentially have higher traffic loads compared to younger ones. Age would also be a factor for older bridges.
	Some differences would be the degradation of the material, as the existing bridge may have corroded members compared to a newly constructed bridge with new members. Another difference could be that the old bridge may have experienced some settlement over its lifespan, where sensors on a new bridge might record settlement as loading occurs. This could influence the analysis, as age and time can impact the behavior of the bridges and result in different quantities being watched closer for some cases as compared to others.
	For an in-service bridge, age will be a greater factor when performing SHM than for a newly constructed bridge. An in-service bridge is going to have had loading for some amount of time, maybe years or decades. A newly constructed bridge will have not experienced loading over a great period of time. The material and design of the bridge may also be a factor. Older bridges may be built of materials that we know now have certain things to look out for. A newer bridge has brand new material that is expected to be at it's peak performance. If sensors detect large deformations from the new bridge, it is more likely that the problem will be identified and fixed before failure. Sensor data from an in-service bridge may have been installed a longer time ago and has a larger amount of data stored that can be used for analysis. A new bridge only has data starting from when it was built.
	Installing SHM systems on an in-service bridge requires understanding the loading history and current state of damage of the bridge. Unlike a new bridge, where the entire history of loading can be detected and recorded by the sensors, the old bridge will require some investigation.

	For in-service bridges, many damages already exist, so when on first starts acquiring data and analyzing it, one will have to know what already exists, such as a crack, and then the data taken for crack growth will be more accurate as to how much the crack grows. for new bridges, there are rarely any pre-existing conditions to account for, so data analysis and interpretation will be much more normal not having to account for the outlying conditions to measure accurate data.
	If an SHM system is installed on a newly constructed bridge, it will most likely be used to focus on the difference between the observed behavior of the bridge under actual loading and the theoretical behavior of the bridge under calculated loads. However, if an SHM system is installed on an in-service bridge, it will most likely focus on the serviceability of the bridge-- how reliable it is, how many years it has left, etc.-- instead of comparing it to its design. That is, the data taken, whether it be loads, strains, or anything else, will be looked at in terms of its future outlook instead of an evaluation of the design.

List any questions you have concerning the content of FEM4. Your and other student's questions will be answered in a subsequent class period.	
	If false-negative data is given, how is the damage uncovered?
	What are more of the differences between supervised and unsupervised learning modes? What are some of the details of the methods used to determine the prognosis of a structure, and generally how accurate are they? When would direct examination of the structure be recommended over information obtained from SHM systems?
	Data cleansing seems like a very complicated process. What other skills do the engineers who analyze SHM data need to possess? Do these engineers need skills in statistics or computer science or could any structural engineer learn how to interpret this data easily?
	Not really, glad CWRU requires a Circuits course for Civil Engineers
	How is damage accumulation testing conducted? Is it on a smaller scale model of the structure, a same-size scale of a piece of the structure or on the structure itself?
	None.
	I do not have any questions regarding the content of FEM4.
	I do not have any questions for FEM4.
	What type of structural engineers are required to analyze the data gotten? Is there a special training for such engineers?
	Would data from the SHM go towards the supervised learning/has SHM data been used for supervised learning?
	In the module, it said that the algorithms fell into three categories. Are the categories supervised learning, unsupervised learning, and outlier or novelty detection? I was a little confused because it said that outlier detection was a subcategory of unsupervised learning.
	Does the rate at which monitoring systems are being added to new structures exceed the rate that these similar systems are being added to older/existing structures?
	What is the next step after a sensor has indicated there is some sort of structural problem? Will there be more inspections? Who is ultimately responsible if there is a bridge failure, especially if SHM is being used?
	None
	How often does one calibrate a sensor if data is taken for such long periods of time?
	Is there a possibility of data that can't be normalized-- the variability is too great, or the data didn't fit a normal distribution to begin with? What happens then?

B.3. One-Minute Paper Responses

FEM 0-2

Please list any lingering questions or misunderstandings you have regarding the content of FEM0, FEM1, and FEM2.	
	no further questions
	None-- the classroom discussion helped clear up all questions I had.
	I really enjoyed the flow chart that you had on the white board during class. Learning the whole process and how SHM fits in it and can improve it really increased my understanding of SHM. More examples will be helpful in the future, a basic format such as: This bridge was designated for SHM, an engineer noticed these signals, then interpreted those signals to find out x was wrong with the bridge. After finding out x was wrong they followed this process to repair the bridge. Also maybe a little less on all the Data units. I can see where a lot of that information could be helpful for someone who has not had technology around them all their lives but most college age kids taking this course have been around technology all their life and can grasp those concepts quickly. A basic flow chart with short and simple explanations would suffice. Also I know this was intended for Structural Engineers but I learned a lot that I can use as a future CM (I have worked for ODOT and will most likely work there post graduation so this has a lot of future use to me). Maybe introduce another FEM that focuses on the CM side of it so everyone can gain a greater understanding, and it doesn't hurt the SE to learn a little more about construction.
	I do not have any, the in-class discussions answered them.
	Is there/Can there be an instance where SHM fails to produce the valid data?
	No, I don't have any remaining questions. The in class discussion was really helpful.
	I don't have any major/lingering questions regarding the content of these modules. I am very interested in how these types of systems could be implemented to earth structures. Obviously, the sensors would have to be configured differently and other innovations would need to be made. But, given my interest in earth structures, I would like to learn more about the potential for this type of application.
	I do not have any lingering questions or misunderstandings.
	N/A
	N/A

	Are there cheaper alternatives instead of SHM? And why can't we install sensors on all bridges to take data? Would this be a lot of money?
	N/A
	I do not have any other questions or misunderstandings regarding FEM 0-2. The ppt/quiz and class discussion covered everything I was curious about.
	My general concern with FEM 0 - 2 is that I am not entirely sure of the depth of understanding of SHM systems that was intended to convey. I feel like I have a very vague notion that SHM systems are an amalgamation of sensors applied to a structure to constantly collect data on the status of the structure combined with a computer system that analyzes this data, but that is essentially the furthest extent of it. I am not sure what I really was expected to learn. Because of this, I don't really even know if I have any questions or misunderstandings.
	N/A
	No questions.
	I understood the content of FEMO, FEM1, FEM2 and any of my lingering questions were answered during the class discussion. However, I found that some of the quiz questions were vague or had answers that were not discussed in the powerpoints.
	I do not have any lingering questions about the content from FEM0, FEM1, or FEM2.
	At this point, most of my questions have been answered. I still have some questions about how exactly data transmitted from the various monitors is turned into usable information for engineers to make decisions about what to do with a bridge/structure when faced with structural problems. On that note, who makes the decision to decide whether or not a bridge needs more maintenance or is doing fine as it is. What is the threshold level for various types of monitoring to induce an engineer being called in to asses the bridge?
	In FEM0, it described that the SHM System costs 1.3 million dollars for the bring in Bangkok. is this system the most economical financially?

FEM 3-4

Please list any lingering questions or misunderstandings you have regarding the content of FEM0, FEM1, and FEM2.	
	I do not have any other questions about FEM 3 and 4. All of them were answered in class.
	The classroom discussion was really helpful in regard to clearing up any questions people asked about these two units.
	None
	Do you think SHM will be integrated into future civil engineering courses?
	I think I am good.
	N/A
	I currently do not have any questions or misunderstandings regarding the content of FEM 3 and FEM4. The ppt and in-class discussion cleared up everything for me.
	I have no major lingering questions or misunderstandings regarding the content. I really did like learning about these types of systems. I downloaded and saved each of the powerpoint so I can view them again if I ever find myself needing to apply these to a project/in the workplace.
	no further questions
	We have definitely answered a lot of questions about SHM during FEM3 and FEM4. One question I have is how feasible this is in reality. Are clients/owners willing to pay the money for SHM? Are governments actually using SHM to monitor bridges and buildings or is this still somewhat of a new technology that is still being developed?
	How important is this to people, job wise, who aren't civil engineers?
	When calibrating an SHM System, how often should one calibrate? how long due SHM Systems last?

B.4. Post-Treatment Survey

FEM0

FEM-0
Post-treatment Surv

FEM1

FEM-1
Post-treatment Surv

FEM2

FEM-2
Post-treatment Surv

FEM3

FEM-3
Post-treatment Surv

FEM4

FEM-4
Post-treatment Surv

B.5. In-class Discussion Notes

You Tube Video (Benefits of Structural Health Monitoring)
https://youtu.be/Kr8obPsWFEw

FEM0 Discussion Question: List the criteria, in order of importance, which you believe should be used to determine if a bridge should be monitored with a Structural Health Monitoring System. Be prepared to justify your criteria and their order of importance.

- Age (1, 1, 1, 1, 1, 1
- Existing or History of Damage/Deterioration (1, 1, 1
- Exposed to severe loading event (1, 1,
- Total traffic volume or importance to local/regional transportation network (1, 1, 1, 1, 1
- Size of bridge (1
- Architectural/historical significance
- New design or construction method used (validation of assumptions, more accurately quantify risk, and data for future designs) (1, 1, 1
- Environmental impact of failure (1, 1
- Bridge in-service beyond design life
- Structural redundancy
- Cost of monitoring system (1

FEM1 Discussion Question: How does the application of SHM potentially extend and expand the professional responsibilities of the structural engineer?

- Note: original design SE and SHM SE not necessarily the same individual
- SE may be involved in in-situ evaluation of performance to assure safety and serviceability
    - Note: SE not necessarily liable if current code provisions and due diligence performed
    - Allows for more applications and verification of performance-based design methods
- Gather in-situ data that can be used to enhance our understanding and limitations of design codes and the impact of particular construction practices (1
- Extend structure's lifetime: Diagnosis and Prognosis -> Decision making (1, 1, 1, 1
- SE must be familiar with SHM (DAS – Processing – Diagnosis – Prognosis) (1, 1, 1
- SE can incorporate repair/maintenance into original design as more long-term monitoring knowledge is obtained (1, 1, 1
- SE designs more durable, sustainable structures? (1,

FEM2 Discussion Question: Assume that the installation of SHM systems is warranted for bridges with "high consequences" of failure. List the factors/circumstances you would use to define the consequences of failure. Provide a brief justification for each of your factors/circumstances and rank their relative importance.

- Age (relative to lifespan)
- Traffic volume
- Environmental Impact
- Economic impact to local/regional economy
- Available redundancy in transportation network
- Damage to surrounding structures or roads (cascading effects)
- Architectural or Historical significance
- Importance for response and recovery efforts (community resilience)

FEM3 Discussion Question: Thinking about what you have learned in your Mechanics courses (Statics, Dynamics and Mechanics of Materials), Mechanics of Materials Laboratory, and your current Structural Analysis course, list the parameters you would recommend be monitored and why for the SHM of a concrete girder bridge.

- Sensors, Sensors, Sensors…
- Deformation, Force, weather, time, "behavior", everything…
- See proposed discussion problem

FEM4 Discussion Question: SHM systems can be installed on in-service bridges or newly constructed bridges. Given that the basic objective of SHM is to identify damage, discuss the ways in which the analysis and interpretation of the sensor data in these two circumstances differ and identify the factors which may influence the analysis.

- New Construction
    - Check design assumptions
    - Provide system baseline
    - Begin monitoring
- In-service
    - Detect damage/degradation
    - Existing health should include estimate of distress at time of SHM install (pre-existing conditions -> estimate with updated model and loading through previous "life")
    - Operate SHM limits/warnings (diagnosis) more sensitively
    - More prognosis

APPENDIX C

-

STRUCTURAL EDUCATIONAL MODULE (SEM) AND STRUCTURAL APPLICATIONS MODULE (SAM) RESULTS

C.1. Readiness/Mastery Exam Results

SEM1

SEM-1 Exam, Attempt 1 Results

SEM-1 Exam, Attempt 2 Results

SEM2

SEM-2 Exam, Attempt 1 Results

SEM-2 Exam, Attempt 2 Results

SAM1

SAM-1 Exam, Attempt 1 Results

SAM-1 Exam, Attempt 2 Results

SAM2

SAM-2 Exam, Attempt 1 Results

SAM-2 Exam, Attempt 2 Results

C.2. Discussion Questions

SEM1

Human skin has with millions of sensors that send signals to the brain about several measurable quantities, from which the brain interprets the health condition of the body. While it would be great to have millions or at least thousands of sensors in infrastructure projects, we cannot. Why?	
	Adding many sensors could actually detract from the initial purpose of testing, as too many sensors could lead to an overwhelming amount of data. The number of sensors that are placed on a structure should be well thought out in an attempt to best determine how a structure behaves.
	The cost of installing millions of sensors to measure a structure would be very expensive, although the information would be better then cost benefit analysis would indicate that millions of sensors would be illogical.
	There are three main factors preventing SHM projects to have millions of sensors. 1) Cost- Millions of sensors would cost a lot of money and most projects have a tight budget as is and adding senors on the magnitude of millions would blow up the budget 2)Time and Labor- The amount of time that would be required to install millions of senors would be way to high and thus the labor costs that are associated with it would be enormous also 3) Data Interpretation- It would take a large team to break down all of the data from millions of sensors
	We cannot have millions of sensors in infrastructure projects because it would be too costly, use too many resources, be too labor intensive, and the data that would be recorded would be overwhelming.
	We cannot have this many sensors mainly due to budgetary restraints and labor time restrictions. It would also be extremely overwhelming to take readings from that many sensors.
	Evan Zgrabik 1. There are a number of practical constraints that limit the number of sensors that can be used on a project: Cost - Budgets are not unlimited, and because sensors cost money to purchase, install and monitor, only so many can be used. Power Supply - Local power supplies can only supply a certain amount of energy to the sensor system, and thus the number of sensors that can be used is limited by this quantity.

	Analysis - Though more sensors can supply more data, and thus increase the accuracy of the readings, the amount of time and effort required to analyze that data also increases. Because the difficulty of analysis grows rather constantly as the number of sensors grows, but the rate of accuracy improvement decreases, there is a practical limit to the number of sensors at which the improved accuracy is not worth the time and labor of analysis.
	It would cost too much, be too labor intensive, and the data would be overwhelming.
	Cost prohibitive Labor intensive Overwhelming amount of data
	Because there would be a lot of data that the sensors would record which would be overwhelming.
	That number of sensors would be wildly expensive and would be less efficient at it's job. The amount of data produced would be too much to effectively go through and requires a greater data acquisition system. More imprtantly, not all of them are needed. If critical points are identified, those can be utilized to create an numerical model that is good enough.
	We cannot have millions of sensors, because we have several things that limit us. One such thing is the cost of placing in those sensors and then monitoring them. Another issue is the large amount of time it would take to place in these sensors and the time it would take to monitor every one of them. The labor to place them in and to monitor them would be another issue. Finally, the resources that it would take to place in millions of sensors on every project that is monitored would be ridiculous. This is why we cannot have millions of sensors to monitor buildings.
	It would be incredibly expensive to install millions of sensors on a structure, both in material and labor costs. Also, while computers are amazing, they aren't able to process millions of signals and pick out the important ones like human brains are.
	There are many restrictions as to why we can not implement that many sensors on a bridge. limits include budgeting to fund the cost associated with that many sensors, also power sources available to supply energy needed to ensure all sensors are functioning properly. essentially humans are limited to a number of resources available to put that many sensors on a structure.
	It would be extremely time consuming and costly to interpret that much data. Additionally, utilizing that many sensors would create a lot of noise that would confuse the helpful data. Though it is good to interpret as much data as possible, it is not practical or convenient to put millions of sensors on infrastructure projects.
	Having all these sensors would cost too much as well as require excessive amounts of resources. There is also a problem with how long it would take to place all the sensors and the labor needed to do this.

	We don't have enough resources or money to install thousands of sensors on every structure. Also it would take too much time/labor to install and monitor them all.
	Maddie Hart- responses Having millions of sensors on a structure would be extremely costly because of how many sensors would need to be purchased, purchasing equipment to install the sensors, and needing to hire people trained in sensor installation. Also, the amount of time to not only install enough sensors but to make millions of sensors would make the project last significantly longer, which would then increase the price more.
	A high volume of sensors would have too high a cost, would require an unrealistic amount of labor to install and maintain, and millions of data points could not be effectively analyzed. For these reasons, representative data taken from certain points on the structure is adequate for the current SHM systems.
	It would be completely impractical. It would cost too much and require too much time and labor. Also, having so many different readings would be overwhelming, and mistakes could be made trying to interpret it all.
	We need a lot of money, resources, time and labor. In addition, interpreting data from millions of sensors is overwhelming; this is why we need to be selective when choosing the amount of sensors and types of sensors used to optimize data collection.
	We cannot have millions of sensors for different reasons, which are: -cost -time -resource -labor
	We cannot have thousands of sensors on infrastructure projects due to several reasons: costs, resources, time and labor. And out of those four reasons, the cost is one of the most limiting factors. Also, it could be overwhelming to interpret data from the millions of sensors so while it would be great to have thousands of sensors in infrastructure projects, it would be best to be selective and optimize the choice of sensor and the type, to ultimately maximize efficiency.
	We cannot use thousands or millions of sensors in infrastructure projects as it would require excessive amounts of money, resources, time and labor. Additionally, too many sensors would create too much data which would be complicated and overwhelming to sort through. We have to be smart and select the type and location of sensors based on the need of the structure and the project.
	There are many obvious reasons why we cannot have millions or thousands of sensors in infrastructure projects. The first being the excessive cost of placing that amount of sensors on a structure. In addition to the cost, the amount of time and labor required to install that amount of sensors would be astonishing. Lastly,

	the data that would be recorded from this amount of sensors would surely be overwhelming when trying to analyze.
	A few constraints, like cost, time, and labor can mean that it would not be practical to input millions or thousands of sensors in infrastructure projects. Also, it would be overwhelming for data analysts to have to interpret and manage so much data.

List any questions you have concerning the content of SEM1.	
	No questions at this time.
	Can this be applied to more than just buildings?
	I have no questions concerning the content of SEM1
	N/A
	I do not have any questions on the content of SEM1
	What is the advantage of periodic monitoring over continuous monitoring? If sensors can collect and transmit data continuously, how is continuous monitoring not inherently better?
	none
	None
	N/A
	None.
	None
	N/A
	I have no questions at this time.
	Is dynamic field testing commonly used on buildings or is it only used in special cases?
	I have no major questions concerning this module
	Maddie Hart- responses What are the rules around installing SHM systems? Do structures have to include some sort of monitoring system in order to be built?
	What methods are used to assess the health of structures built without SHM systems? Can the collected information be used to improve the health of a structure?
	I don't have any questions.
	Are there any structures that have SHM installed today?
	- How exactly are old buildings monitored and is there a strict enforcement agency? - Why cant sensors be placed on the surface of already existing building? I understand that for example they are sometimes put on the reinforcement cages but I do not u

	1. Is there a potential for SHM to get hacked through its remote data retrieval system (or is there a security limitation) and the data could get altered/ or used by an unauthorized party? 2. Can the selection of monitoring system (sensors, data acquisition, and management) vary by individuals or groups? Is there a standard/specification that one must follow in the selection of SHM system design? 3. Can SHM provide data not only about damage but also predict the area of damage and the best mitigating solution?
	1.) Could SHM monitoring be used in conjunction with IoT sensors? I feel like this would greatly expand the usage and versatility of the data. 2.) Is it more common to use SHM on new construction or to retrofit old structures? Overall, I have no conceptual concerns or questions regarding SEM 1, my questions are just things I was wondering as I read.
	I'm curious to know how much power is required to operate a SHM system for an infrastructure system.
	Is there any research being done to try to create smaller, cheaper, easier-to-install and manage sensors so that more sensors could be placed on a single SHM project?

SEM2

The scope of SHM projects varies widely. Who do you think decides the scope of an SHM project?	
	I think a range of different professions such as civil engineers, electrical engineers, architects, contractors, and potential accountants are responsible for a project.
	The engineer hired for the project
	I believe that the scope of a SHM project is decided by the owner, some SHM projects can get very expensive so it is up to the owner how much information they want to measure and how much they want to spend on it.
	I think the designers and the owner of the structure work together to decide the scope of an SHM project
	The company hired to install and analyze the data from the SHM system.
	I believe whoever is investing the money for the SHM project and/or their advisement team should decide the scope. Scope has a big influence on the cost of the project and the person/organization backing the project should decide what they think is important to monitor or what they are willing to invest. However the should receive input from other parties, mainly the SE of record for the job.
	In the case of a structure under construction, because the owner is concerned with costs, the engineer is concerned with data analysis, and the contractor is concerned with how the system installation will affect the constructability, the scope of an SHM project must be a collaborative effort that balances the concerns of all parties with invested interest in the structure.
	The scope of the SHM is determined by a variety of people. One person involved is whoever is incharge of the budget. Since funding is not limitless the person in charge of how much is spent can determine what falls into the scope. The lead project design engineer probably also decides the scope of the system being implimented. They probably will be the one who collects the data and interprets it so they will be in the decision making process for the scope. Lastly the owner probably will be the one who decides the scope of the SHM as they are the one in charge of the system being tested.
	The owner of the project, working in conjunction with the design engineer & contractor
	The owner decides the scope of the project. They are the ones that would require the SHM data and so the decision as to whether to have SHM and what kind ultimately lies on them. They should have the input of the engineer as well as the construction manager to make sure that whatever system is selected is possible and helpful.
	I believe the owner of the structure makes the final decision on the scope of an SHM project, but I believe a structural engineer determines the recommended scope.

	It depends on what the most important aspects of the structures are and what the budget and time constraints on the project are.
	The scope of an SHM project depends on uses of an SHM System along with the environment in which the structure is susceptible too. say a structure is located in the ever changing climate that is Northeast Ohio, a structure is susceptible to many environmentally impacting seasons and an SHM system could be installed to measure temperature change and crack width change over time to determine what materials could be used to improve the longevity of the structure
	I think the project designers, engineers, and project commissioners all have a say. Depending on the type of design, SHM may be more or less useful, so the designer should have some input on that. The engineer should have similar concerns. However, the project commissioner should also have an input on the scope of a project, because SHM can sometimes be costly or difficult to implement. If the project commissioner doesn't want to pay above a certain amount or limit the accessibility of the project, they should have a major say in the scope of the project.
	Whoever is paying for it has part of the task with deciding the scope of the project. I think the lead engineer and other managers on the project have a right to have input in the scope; they have to design sensors into the project and figure out how to make it feasible and cheap.
	The scope is likely decided in a collaboration between the designer and contractor. The designer will decide where the most critical points to be monitored are while the contractor will know how to coordinate the installation of these sensors during construction.
	the designers, contractors, and owners of a project each have an interest in gaining information on the health of a structure, and must collectively determine the extent of the project while considering the costs and other factors.
	I think an individual who is specialized in SHM system design would decide on the best fit scope for a project, but not without consulting with several other individuals in a project first. For example, the structural engineer would have to have been asked about his/her opinion of the system investigating the new detail used in the JJA bridge. Also, whoever is in charge of financing, or really just whoever owns, the project at hand would always need to be consulted because they would be the person to decide how expensive a project can get. So, while an expert in SHM design may be the individual who sets the procedures, deadlines, and other major components of a system, they cannot complete their job without working with other positions.
	I think the owner decides the scope of the project with feedback from the structural engineer because the owner knows what resources can be put into the SHM project.
	There are various entities that could decide on the scope of an SHM project. I think the most prominent entities involved with SHM project are the structural engineers and government officials (State DOT or FHWA). SHM gives important data about how the structure will behave under certain

	loading or which sections are in danger by monitoring the structure. These data are important in ultimately coming with up reasonable mitigation measures for the structure as well as help the development of other future structures. As a result, I view that government officials and structural engineers would most likely decide on the scope of an SHM project as they can utilize the data from SHM the most.
	I think the scope of an SHM project would be initially determined by the owner of the structure. The owner would be the one noticing the problem, or looking to prevent a problem. However, the structural engineer may have some suggestion in the scope of the project as they will be able to offer advice and guidance to the owner based on experience in the field.
	I think that the public and its usage of a structure decides the scope of an SHM project. If a structure is being heavily used by the public on a daily basis, then the scope of the SHM project should be all encompassing and thorough.
	I think the structural engineer determines the scope of a project. Along with the people who are going to implement the SHM design and installation.
	I think that the scope of an SHM project is decided by both the engineer/design firm and the owner of the infrastructure system.
	The group who decides the scope of an SHM project depends on what type of SHM project this is. If it is a project that will be implemented on a new structure, the engineers on the project, as well as the owner/architect and the construction manager will all have some say in deciding the scope. If a project is being completed on an existing bridge, than maybe the owner of the bridge will have more of a say. At the end of the day, the owner will have the final say in the scope of an SHM project because they are the ones paying for it.

List any questions you have concerning the content of SEM2	
	No questions at this time.
	None
	Are there a finite number of tests that can be run?
	I have no questions concerning the content of SEM2
	N/A
	I do not have any questions or comments regarding SEM2
	In the three scenarios included in SEM2, it was not apparent what sort of action was taken after the collected data was analyzed. Is it common for SHM monitoring to merely find a prognosis for a structure rather than a means for identifying ways of potentially repairing the structure?
	none
	For the Neisse Railway Viaduct it says there were "no obvious irreversible influence on crack evolution" yet there was a crack throughout the cross section. Explain?
	None.
	None
	N/A
	I have no questions at this time.
	Did the continuity detail on the John James Audubon Bridge lead to a significant reduction in the design life?
	Do you think that the problems/patterns associated with any of these case studies could have been discovered without using SHM (and instead using standard inspection methods)?
	the continuity detail in case study 1 was found to shorten the life of the structure; were any modifications made to the bridge to reduce this effect?
	For systems/investigations like the M6 bridge, did they test other bridges as well? Can you make assumptions about a structures behavior solely based on the behavior of another structure?
	For the third case study, why did they need to measure the reaction at the pile if they were looking at the natural frequencies of the girder webs/flanges? And why did they need the temperature?
	1. Has data obtained from SHA of one structure helped to model of another structure? 2. Why did the performance of continuity detail for the John James Audubon Bridge taught through the SHM if SHM is considerably pricey (especially to incorporate solar panel as well)? Why was SHM the best method? 3. In what ways the appropriate power source availability can improve (economically, or in technological-advancement) as it appears that it can get tricky to get a power source for SHM in general?

	I have one main question after reading through the SEM 2 notes....The 3 case studies we read about were bridges or viaducts. I was wondering how common it is for SHM technology to be used with other structures such as roadways or buildings in order to help prevent or provide more information on existing structural health/issues?
	Has anything been to the John James Audubon Bridge in accordance to what the results of the SHM said? (The bridge built in Louisiana is not suitable for Louisiana summers; what is being done/has been about this?)
	- No questions
	Are there currently any codes requiring SHM systems to be used on newly built structures given certain size/risk category criteria? If not, do you think there will be in the future.
	Is it more common to see SHM projects on bridge structures rather than buildings? Can SHM still be used on building structures?

SAM1

Standardizing a generic instrumentation plan that can fit all SHM projects is impossible. Why?	
	Because all projects have different scopes to monitor. Not one instrumentation can measure all different types of SHM projects.
	Standardization of a generic instrument plan is impossible because not all structures are identical. Even small variations in the location of supports, or differences in materials can cause drastic changes in load or strain concentrations. Additionally, not all structures will experience the same environmental effects and damage. Even if two structures were exactly identical, the difference in location will expose each to much different conditions, whether it be temperature, precipitation, wind or earthquakes.
	This is because all projects have different objectives and different structures and therefore instrumentation plans have to be done accordingly.
	Each project has different components that need to be monitored, and there is no simple/economic instrument that can be installed that can account for all situations.
	Each SHM project includes different structures that all serve a different purpose.Not all structures are subjected to the same loads or environmental impacts and have to be monitored based on there function and potential failure. standardizing a generic instrumentation plan is just not feasible for the many different loads applications and different deformations that a structure can have applied
	There are to many variations in the loading and geometry of different structures to always gave the same points of interest
	It is impossible because every structure is unique. This is due to differences in the structure's design, the ground conditions it is built in, the forces exerted on the structure, the structure's age, the material it is made out of, etc. Also, every project may be looking to obtain different data from a similar site.
	1. Sensor locations have to be determined and different projects would need different locations according to the structure's shear, bending moment, and torsional moment diagrams. 2. Each project has a different purpose or goal they are trying to reach and therefore need instrumentation plans that specifically assess what they need for the project.
	There will always be slightly different conditions due to differing loads, dimensions, support conditions, etc. Two non-identical structures with non-identical loads will not have the exact same shear/bending diagrams; therefore, a one-size-fits-all instrumentation plan is impossible.
	Each project will have different points of likely failure that will need to be predicted before implementing the system. The projects will also perform

	differently over time depending on the conditions of their surroundings, and SHM will need to be readjusted as needed on an individual project basis.
	Each SHM project is going to be different in terms of the type of structure, types of loading, and types of monitoring that are being completed. It would be impossible to come up with one plan of SHM because every project, even similar types of bridges, are going to have different specific conditions and aspects that need to be addressed. Additionally, there are a lot of types of SHM instrumentations that could be used for a project.

List any questions you have concerning the content of SAM1	
	What is the proper orientation of shear crack monitor? (It was one of the questions from the modules)
	Evan Zgrabik How is torsion measured using SHM devices? How can shear cracks be fixed in reinforced concrete, and how often is it viable?
	N/A
	I have no questions about SAM1
	None at this time
	N/A
	Are those the only four orientations for sensors? Overall, no major questions from the module.
	N/A
	For Project #2, we're asked about the sensor orientation to measure the shear crack at A. Should the sensor be in the direction of the crack or should it go across the crack?
	What exactly is a load cell? Is SHM most commonly used for traffic-related projects because of the dynamic loads associated with these types of structures? (or were those just the examples they picked for this module?) Similarly, is SHM more commonly used on structures that experience more dynamic loading patterns? Or is it equally used on structures that experience high static loading?
	At this point I do not have any questions.

SAM2

Damage can have a significant negative impact on the strength of structural members. However, the impact of damage on deformation depends on whether the damage is localized or distributed over a large section of the structural member. Why?	
	Localize damage causes higher stresses and bigger failures in structures. If the damage is distributed then stresses are less and more spread out.
	Because deformation is something that is affected by the whole body of the structure therefore it is greatly dependent on whether the damage is localized or distributed.
	Localized damage will lead to large deformations in the area of damage but not to whole system. Damage to the whole system will cause minor deformation at the local level with noticable differences at the system levvel
	Damage on a member reduces the effective strength of the member. However, the specific form of damage (localized vs. large) informs the possible modes of failure. A large damage near the support of a beam could mean the beam fails in shear, meanwhile a long distributed load across the middle section of the member could mean it will fail due to bending.
	There a a few critical points depending on the cause of the damage that if it is localized in those areas it could cause large amounts of problems
	If damage is localized, it will cause significant deformation only in the area of damage, meaning the rest of the member and structure may still function properly. If damage is distributed across the member, however, the whole member deforms, which could lead to serious issues in he structure as a whole.
	Yes, the location of the deformation can determine the impact of the damage. If the damage is localized, the failure will happen more abruptly than when the damage is distributed.
	Spread damage can lower the strength properties of the member slightly, but localized damage is more likely to fail under the same load.
	If the damage is distributed over a large section of the member then it will not impact the structure as much since it is not concentrated in one portion of the beam.
	The impact of damage on deformation as a function of local v. distributed areas of damage are certainly different. For local areas of damages, the location that damages occurred could be in a member that has minimum impact on deformation. But when damage is distributed across a larger member, more connections or important cross-section properties could be effected and may result in more/more intense deformations.
	If a structural member has localized damage, there is a higher chance that it'll fail abruptly under a load. However, distributed damage allows for the beam to spread out the extra stress that it is resisting.

	Because a localized damage can fail the member completely but the distributed damage over a large section may not experience enough deformation to completely fail the member.
	Local damage would have a greater effect on the strength of a concentrated area of a structure, and can more likely be fixed easily, while damage to a larger area would affect the whole structure more evenly.
	Localized damage would have a greater impact because it would cause failure more immediately since its focused on one location which would cause larger deformation. If damage is distributed over a larger section, it wouldn't have as great of an impact on any one section since its been distributed and will take a longer time to cause failure.
	If the damage is localized, the structural member fails more easily than that of if the damage is distributed over a large section of the structural member. This is because the moment of inertia of the cross section at the localized damage area is reduced greatly.
	If the damage is localized, the local stress conditions come into play. This is especially important for wood structures such as the one we tested in lab, since wood often has local stress concentrations due to inherent flaws in the wood itself.
	If the damage is localized, it is probably not affecting a huge portion of the structure. If the damage is over a large section, more of the structure is affected. Therefore, the damage has a greater effect on the structure if it is distributed over a large section. However, if there is just a little bit of damage across a large section of the structure, the member may still be ok, at least in that it might not have failed completely. If there is a small, but severe deformation over a small section of a structure, this could be more catastrophic in terms of failure. Either way, the impact of damage on deformation is going to depend on how the deformation is distributed over the structure.
	Different loading patterns create different shear and moment patterns in the member. The impact of damage changes based on how these patterns affect the member.
	If damage is localized, then the structure is more likely to be stable on not have a large deformation, whereas if the damage is distributed over a large section, then the structure will be more likely to fail.

List any questions you have concerning the content of SAM2. Your and other student’s questions will be answered in a subsequent class period.	
	No quesitons
	NA
	N/A
	none
	I have no additional Questions
	I have no questions.
	N/A
	None
	It would be interesting to perform the same test on different species of wood, and steel.
	I have no questions at this time.
	No questions at this time.
	Is what we did in the demonstration of damaging the structural member considered to be a significant impact on the member? Would the impact of damage dependent on and vary in structure's medium / or would they all respond in a similar manner?
	n/a
	N/A
	N/A
	None at this time.
	I do not have any questions at this time.
	No questions about this module.

C.3. One-Minute Paper Responses

SEM 1-2

Please list any lingering questions or misunderstandings you have regarding the content of SEM1 and SEM2.	
	I have none at this time, although I was glad it was not just a review of last semester and there were new topics so I was able to learn more about SHM.
	All my answers were answered in class. I will just like to know if SHM will be most likely implemented in all buildings in the future.
	None
	I don't have any questions pertaining to the content of these modules.
	N/A
	none
	None. It was very straight froward and easy to understand.
	I do not have any questions regarding SEM1 and SEM2
	I was not present for the lecture (I notified Dr.Pollino beforehand). But I would love to know if SHM system has a potential for hacking so that the data obtained could be altered?
	N/a
	Could these systems be used in pipe networks/other types of infrastructure? As an environmental concentration student, I think it would be interesting to monitor the health, movement, and other changes occurring of pipes. Personal inspection is kind of a pain, so using digital monitoring could be really interesting.
	No lingering questions. SEM2 in particular was very interesting; it was cool to see specific, real-world examples of SHM monitoring systems.
	Overall, I feel like I have a decent general knowledge of the subject now. One thing I am wondering is if there will eventually be a system of rules or regulations that will govern/suggest uses, applications and locations of the sensors? Thanks for teaching this module, it was very interesting!
	I don't have any lingering questions or misunderstandings.
	At this point, I do not have any major questions regarding SHM, but I think it would be neat to learn about more SHM examples and how the monitoring was decided upon and put in place, as well as what type of data was produced and what, if anything, happened because of the data produced.
	I have no lingering questions about these modules.
	none

SAM 1-2

Please list any lingering questions or misunderstandings you have regarding the content of SAM1 and SAM2.	
	no questions
	N/A
	I have no questions. I thought the hands on demo in the lab was great. Please in the future try to work that demo in because I think it is helpful to see what you are learning, especially in SHM which is very applicable to professional life.
	I have no questions.
	N/A
	N/A
	None
	I have no further questions regarding the content of SAM1 and SAM2
	I would just be interested in seeing how the technology progresses and how these sensors get implemented with other big data concepts. No major lingering questions. Overall, an interesting module!
	I'm still a little confused as to who it is that implements the monitoring systems. Is this something that someone specializes in? Are there companies who just do health monitoring?
	N/A
	No further questions at this time.
	I have no questions at this time
	Actually going to the structures lab and performing a test on a beam really helped me to see how SHM can be used in a real situation. It is still a little bit tricky to be tasked with picking which SHM instruments to use in a situation and understand all of the options one has when using SHM.
	I have no questions regarding these modules.

C.4. Post-Treatment Survey

No post-treatment surveys were available for the SEMs.

SAM1

SAM-1
Post-treatment Surv

SAM2

SAM-2
Post-treatment Surv

C.5. In-class Discussion Notes

Good overview and Examples of Structural Health Monitoring:
http://www.di3.drexel.edu/DI3/Events/PaperPresentation/FHWAGuideFull-web.pdf

Some companies specializing in SHM or SHM sensors:
https://www.iisengineering.com/
http://bditest.com/
http://www.clevelandelectriclabs.com/
https://youtu.be/70nDMqqQPro?list=PLXfa2aLXW1-UP0kqbjkYs8WEZ6xqx4B92
(CEL role in Delaware Bridge SHM project)

SEM1: Planning SHM Projects

Phase of the Life	Human Skin Health	Structural Health
Birth	Birth Monitoring	Process Monitoring
Sound Life	Health Check-up	Health and Usage Monitoring
Illness and Death	Clinical Monitoring	Health (Damage) Monitoring

SEM1 Discussion Question: Human skin has with millions of sensors that send signals to the brain about several measurable quantities, from which the brain interprets the health condition of the body. While it would be great to have millions or at least thousands of sensors in infrastructure projects, we cannot. Why?

- Cost
- Time/Labor
- Data Analysis Effort
- Many sensor may be useless

Desired Quantity <-> Measured Quantity

SEM2: Design of SHM Systems

SEM2 Discussion Question: The scope of SHM projects varies widely. Who do you think **decides the scope** of an SHM project?

- Owner
- Civil/Structural Engineer
- Engineering Team (Civil, Electrical, Architects, Contractors, Accountants?)
- Designer and Owner
- Company hired to install SHM system and analyze data
- Whoever has the $$$
- Building code official

Why ("initializes" the scope):

- Evaluate design assumptions (loads, behavior) from in-situ response, understand uncertainty and more accurately quantify risk, learn for future designs
- Assess in-service performance and monitor for damage (long term or before/after major event)
- Evaluate evolution of damage and make prognosis -> define reasonable maintenance and inspection and evaluate impact of maintenance efforts
- Identify critical action criteria (intervention)

Who:

- Owner: typically non-technical, interest in long term health, reducing risk, decreasing lifetime costs
- Engineer: responsible for public safety, interest in long-term health
- SHM System Specialists: understand sensors, electronics, long-term sensor calibration and reliability, software interfaces
- Building code official: enforcing the building or bridge code
- General Contractor: responsible for initial construction of structure (primarily)

EOR/Owner (ask fundamentally why) -> EOR (Identifies response quantities to provide data for decisions) -> SHM Specialist/EOR (identifies sensors, system)