

2006-180: ENHANCING A REINFORCED CONCRETE DESIGN COURSE BY LINKING THEORY AND PHYSICAL TESTING

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Enhancing a Reinforced Concrete Design Course by Linking Theory and Physical Testing

Abstract

The paper presents a model for improving reinforced concrete design courses by incorporating physical beam testing. This model was implemented in a course that did not have a laboratory component. The beams tested were full-scale and demonstrated two flexural failures of varying ductility, a shear failure, and an anchorage failure. The beams were tested throughout the semester as appropriate with the material that had been covered in the course. A reporting process was followed that required students to submit laboratory reports for each beam test, address comments received on each report, and submit a final report covering all four tests. It was found that the beam testing and report writing program enhanced student learning in the course and improved the pedagogy. The physical testing of concrete beams also allowed better coverage of several ABET outcomes. As the course was not scheduled with a laboratory component, the testing did result in reduced coverage of end-of-course material however this was offset by improved understanding of reinforced concrete fundamentals. The paper includes a description of the testing program and reporting process and discussion of the improved pedagogy and course outcomes.

Introduction

Courses in reinforced concrete design typically provide students with the fundamental properties of the constituent materials, apply basic mechanical principles to problems of flexure and compression, and then advance to analysis and design topics as they are more empirically presented in the relevant building codes. The importance of hands-on active learning has long been an integral part of education theory. Educational Psychologist Jean Piaget states that optimal learning occurs through “active methods” which “require every new truth to be rediscovered or at least reconstructed” by the student¹. The National Science Foundation² argued in 1993 that “Engineering curriculum reform is necessary to meet the objectives of enhancing the acceptability of US industrial products in the international market” and that hands-on experiences should be an integral part of that reform³. Having students design, fabricate and test reinforced concrete beams has been shown to effectively enhance two reinforced concrete design courses^{4, 5}. In the first case, the course had additional credit hours in a laboratory component, in the second it did not. When structural testing is part of the course or a lab, it benefits students by providing hands-on experiences and a physical demonstration of the concrete behavior that can be contrasted with and used to emphasize the concepts taught in the classroom.

A non-comprehensive review of syllabi available online for reinforced concrete design courses indicated a variety of approaches, but the majority of programs did not include a laboratory component. When there is a lab component, it is often a calculation/problem solving exercise rather than a physical lab. Examples of how reinforced concrete design courses have been enhanced in other ways include design of two- and three-story frames⁶ and self-selected literature reviews, design, or research projects by student teams⁷. These additional activities are

used to reinforce the technical material and increase higher-level learning. These added course components can also provide a good opportunity to offer alternate patterns of teaching and learning.

The remainder of this paper describes how the physical testing of four beams was incorporated into a reinforced concrete design course to demonstrate fundamental beam failure modes and ductility. The discussion includes details of the project development and implementation, goals and objectives, and project outcomes.

Adding Physical Testing to a Reinforced Concrete Course

Flexural behavior of beams at service and ultimate load often comprises 80% or more of the material covered in a first course in reinforced concrete design. Flexural, shear, and anchorage modes of failure are normally emphasized along with issues such as beam ductility and deflections. As noted above, this is most frequently done entirely in a classroom setting through lecture material, homework assignments, and sometimes, additional research projects. This was true in the Civil Engineering program at Rowan University.

During the period between 2002 and 2003 the program made several significant revisions to the curriculum as part of its regular self-assessment. Among the changes was the elimination of specific tracks of courses geared towards students interested in infrastructure issues or environmental issues. Instead, students now take a common bank of courses with more specialization occurring through selection of elective courses in the senior year. Part of the curricular revision moved the Reinforced Concrete course from the second semester of the sophomore year to the first semester of the senior year. This was driven by what the instructor considered overall poor performance by students in the course. The primary cause of the poor performance was somewhat weak analytical skills at that point in their careers, as they had not had any analysis beyond basic statics and strength of materials. With the new position of the course in the curriculum, the students now enter having an additional analysis course and a course in steel design.

The curriculum revision resulted in a three-semester lull in which the course was not taught. During this time the instructor was looking for additional ways to improve the course. One point the instructor kept noting was how his knowledge of reinforced concrete behavior improved through a research program that included physical testing as a graduate student. There was not room in the curriculum to add a formal lab component so it was felt that having the students design, construct, and test a beam would be difficult to add to the course. This was especially true if the students were to design for something other than a flexural failure. However, the instructor still wanted students in the course to observe failures of concrete beams.

In 2003, testing of very small scale beams had been used in the course. These tests were based on demonstrations performed at a seminar sponsored by the Portland Cement Association⁸. The tests were run early in the course to provide the class with an overview of the concepts that would be covered for the rest of the semester. Throughout the semester, when appropriate, the class was reminded of what had been demonstrated. The drawbacks of these tests were that the scale was small and the presentation was relatively passive as the students only observed and

were not required to perform any follow-up exercises. The 18-month gap in offering the course occurred following the spring 2003 offering.

In 2005, the physical testing component of the course was greatly increased. Four full-scale beams were tested during the course to demonstrate 1) a flexural failure with high ductility, 2) a flexural failure with low ductility, 3) a shear failure, and 4) an anchorage failure. The students in the course submitted a sequence of laboratory reports culminating in a final report covering all four tests.

Details of the Beam Testing

Goals and Objectives

The primary objective of the physical testing was to allow students to physically observe the types of failures in reinforced concrete that were being studied in the course. The testing was to provide hands-on experience with the failures to supplement the reading and lecture material. This provided an opportunity for alternative patterns of teaching and learning. The physical testing is especially valuable in providing opportunities for visual vs. verbal, inductive vs. deductive, and active vs. reflective learning – patterns that may be less emphasized in a traditional lecture format^{9, 10}.

Specific goals include:

- Students are able to classify service and failure load behavior in reinforced concrete beams based on observed and recorded data
- Students are able to collect and analyze of laboratory data
- Students linkage theory, design equations, and physically observed behavior
- Students demonstrate improved of writing and reporting skills.

These goals are further clarified and linked to specific outcomes later in this paper.

Design and Construction:

The course instructor performed the beam designs and fabricated and cast the four beams with the assistance of a technician during the summer. The beams were demolded and placed in storage until needed. Initially, plans included having students design and/or construct the beams as part of the course. While the design and construction of a beam would clearly be beneficial to the students, consideration of time available in the course, the lack of a separately scheduled laboratory component, and the desire to show multiple failure modes in an efficient manner lead to the decision to build the beams prior to the start of the semester. The testing of multiple beams proved to have some advantages relating to the analysis of the results and the structure of the laboratory reports described below. The students also had some previous experience mixing concrete and performing standard tests in their Civil Engineering Materials course. The details of the four beams are shown in Figure 1. Figure 2 shows the formwork prior to casting the beams.

Testing and Laboratory Reports

Integrating the beam tests into the existing course was carefully designed to maximize the impact of the exercises without using inordinate classroom time. It was important to make certain that there was follow-up to observation of the tests to prevent them from being treated as a “day off” from the regularly scheduled coursework. This was done by sequencing the physical tests to occur immediately after the related course material was covered and requiring the submission of lab reports for each test followed by a final comprehensive report that tied all of the tests together.

Analysis of the beams by the students began on the first class meeting. After distribution of the syllabus and an introduction to some basic concrete properties, the class was asked to break into teams and a handout detailing the beams was distributed. Each team was asked to describe how each beam would fail and provide predictions of the failure load and deflection. As would be expected, the predictions were not particularly good. However, the intent of the exercise was to have the students refresh their memory and apply some of their basic mechanics as they were returning to the classroom following a summer off. The exercise also served to foreshadow several of the concepts that would be covered during the remainder of the semester.

The first beam was tested after the concepts of gross and cracked section properties, analysis of flexural strength, and design of singly reinforced beams were covered. The student teams were required to make predictions of when the first crack would form, of beam deflections at a designated load that was in the linear range and at failure, as well as the load that would cause failure. Students were provided with cylinder strength data (collected the day before the beam test) to use in their predictions. During testing, students were designated to mark cracks as they formed, run the data acquisition system, and control the beam loading. The remaining students were responsible to observe the test and take photographs as they deemed needed. After the test was completed the class was given a short period of time to make any additional measurements they desired such as height of the cracks. The beam was also left available in the lab for further examination as lab reports were written. The students then returned to the classroom where the results were discussed in comparison with the predictions.

Most of the student teams had greatly under predicted the deflection at failure because they simply projected the stiffness of the beam during the linear phase into the nonlinear phase. Although the difference between internal stresses under service and failure conditions had been covered, it was clear that most of the students had missed this point. The physical testing of the beam proved beneficial in reinforcing this concept. Most teams had also under predicted the failure load. This led to the opportunity to revisit the nature of design code equations and the distinction between nominal and actual properties for items such as area of a reinforcing bar or yield strength of steel. Similar to the linear and nonlinear behavior issues, these concepts had been discussed in class but were not absorbed by many of the students until they saw the physical test. As a follow-up, each student team was required to submit a laboratory report that included the following discussions:

- Comparison of the observed behavior of the reinforced concrete beam to predictions of its behavior (consider failure mode, sequence of crack formation, etc).

- Comparison of the actual flexural strength of the beam to the “nominal” strength of the concrete beam.
- Comparison of the pattern and location of cracks on the failed beam to expectations found in the textbook. Explain why the particular pattern of cracks formed.
- Comparison of the actual deflection of the beam at 500 pounds load with the theoretical deflection value.
- Comparison of the actual deflection of the beam at 5000 lbs load with the theoretical value.
- A load-deformation diagram and discussion of the shape including such issues as behavior under elastic and inelastic conditions.

The reports were read and returned with comments related to inaccuracies in the analysis or discussion, general formatting of reports, and other issues that the instructor felt warranted further discussion. A few weeks later students made similar predictions for the second beam (which was designed to fail with less ductility). A second report was submitted addressing similar issues as the first with the additional component of comparing the behavior of the first two beams. This report was again read and returned with comments.

The same approach was used for the two remaining beams with testing occurring at a point when the related material had been covered in the classroom. Each physical test was followed up with a period to make additional observations, further discussion in the classroom, and the submission of a laboratory report. A final laboratory report was required that included all of the original reports together and included further global discussion of the testing program. Specific requirements of the final report included:

- Comparisons of theoretic and measured deflections and failure loads and an explanation of why there are differences between predicted and measured results. What-if analysis such as consideration of actual area of steel, yield stress or compressive strength, and actual bar placement. Results of the what-if analysis in the body of the report with calculations in an appendix.
- Description and discussion of the crack patterns. The location of the neutral axis based on measured depth of cracks in the linear range was to be compared to the calculated neutral axis depth.
- Description of the failures. For beams 1 and 2 a discussion of the relative strength and ductility including comparisons of the nominal strength of each beam. For beams 3 and 4, a focus on theory vs. actual results. For the anchorage test (beam 4), there should be a calculation the stress reached in the steel.
- Address the various comments made on the previous reports.
- Discussion of all of the results including the implications for design.

Some of the fundamental concepts demonstrated by the physical tests were various failure modes, ductile and non-ductile behavior, elastic and inelastic behavior, location of the neutral

axis, and the distinction between predictive equations and the actual variability of real results. The beams upon failure are shown in Figure 3. Figure 4 provides the load-deflection plots from the four tests.

Pedagogy

The addition of physical beam testing improved the pedagogy of the course through the observation of the tests and the use of those tests and the laboratory reports to reinforce and clarify classroom material. The laboratory reports required work in all six levels of Bloom's cognitive domains¹¹.

Level 1 (Knowledge) – Students were required to describe what they saw in the physical test and state the type of failure observed.

Level 2 (Comprehension) – Students had to work with the experimental load-deflection data to identify or recognize the load level at which behavior transitioned from essentially linear to non-linear. They also had to report their findings on cracking and failure loads.

Level 3 (Application) – At the first class meeting, students applied their previous knowledge of materials and mechanics to predict the behavior and failure loads and modes of a series of reinforced concrete beams. As the course progressed, the new knowledge was applied to revise these predictions.

Level 4 (Analysis) – Students analyzed the test data and contrasted the observed results with predictions.

Level 5 (Synthesis) – Students were required to propose possible reasons why the predicted and actual behavior differed which required an understanding of how each of the components in the beam interact and affect beam design.

Level 6 (Evaluation) – The level 5 reasons for the differences between predicted and actual behavior had to be tested (Level 3 application) and then judgments rendered on which single cause or combination of causes were likely most important.

The addition of physical testing of beams also strengthened the Reinforced Concrete Design course in meeting ABET Civil Engineering Program outcomes¹². These outcomes are shown in Table 1. The table indicates the outcomes that were already strongly emphasized in the course and the improvement in meeting ABET outcomes achieved by the addition of the physical beam tests. Three outcomes were not previously addressed in the course and one was significantly improved.

Additional experience for the students in collecting and critically analyzing data was an important contribution of the beam tests. The teams were required to collect the test data from the computer, evaluate the quality of the data (note that one experiment was unintentionally conducted with one of two deflection gauges malfunctioning), plot the data, and draw

conclusions from it. The second improvement was that the prior version of the course did not include any formal teamwork.

The third improvement was in the students' ability to communicate. Without the laboratory reports the only real communication aspect of the course was that demonstrated by the students on their homework assignments. The lab reporting process was structured so each team submitted reports and received feedback multiple times during the semester. This continuous feedback process greatly improved the quality of the final reports in areas such as formatting, quality of the graphics presented, and quality and depth of the analysis.

Finally, it is argued that the addition of physical testing improved the students' ability to design reinforced concrete components. This was achieved through a better understanding of how detailing and selection of reinforcement influences the strength and ductility of concrete beams. The interplay of steel area, strength and ductility was especially emphasized as well as the brittle nature of anchorage and shear failures.

Outcomes

The success of the project was measured through course evaluation scores and comments and through student performance on the final course exam. Table 2 shows the overall course evaluation score for each time the Reinforced Concrete course had been offered by the same instructor. A marked improvement in the evaluation of the course occurred once the physical tests were added. It cannot be discerned whether this is the result of the tests or reflects moving the course to a more appropriate position in the senior year compared to the sophomore year.

The benefit to the addition of the physical beam tests is seen in the course comments shown in Table 3. The comments are generally positive and often point to an improved understanding of the material. Most of the negative comments cite a dislike of the repetitive preparation and submission of laboratory reports. The instructor does not intend to change the reporting requirements. As one student stated, "Forcing us to write about this/any subject will require that we explain the concepts on paper--that helps a great deal."

The instructor found the overall course grades and especially the performance on the cumulative final exam were the best seen in the five times he had taught the course. Table 4 shows the final exam grade and the average score of all assignments and exams for each year. The standard deviation of the overall final grade was also reduced in the semester the beam project was incorporated, indicating few students scoring extremely low grades. In fact, it was the first time the course was taught in which no students received grades less than a C-. This was not the result of softened grading requirements or "curving" of grades.

The addition of these physical beam tests did require some small preparation work prior to the start of the semester (approximately 1 day to construct formwork and rebar cages, and half a day to pour the beam). Positioning each beam for testing required about one hour. Four class meetings (of thirty total) were used to test the beams and discuss the results. This was slightly more time than reported by Roberts⁵. The difference was primarily in the number of beams being tested. While this time requirement meant less material was covered, the material covered

was better understood. The material omitted was in-depth coverage of one-way slabs and continuous beam systems, although these topics were still discussed. These topics have been inserted into an Advanced Reinforced Concrete course just prior to coverage of two-way slab systems, which is a fairly natural position for this material. About half of the students in the first concrete design course have continued into the advanced course however, at the time of this writing, their performance in the follow-on course cannot be assessed.

Conclusion

The importance of hands-on activities in the classroom has been understood for some time now; this is nothing new. However, the physical testing of concrete elements to underpin the book learning remains more an exception rather than a rule in most concrete design courses. This paper presents a model of how physical testing can be incorporated into a course without requiring an extensive laboratory component. Physical testing has been included in other settings. Some of the unique features of this effort were the use of several physical beam tests to demonstrate fundamental failure modes. The reporting requirements were structured to link theory to physical reality, through comparisons made between recorded data and theoretic calculations. The submittal, review, and re-submittal process used to build to the final report was designed to strengthen technical writing skills. As with many educational measures, it can be difficult to attribute positive outcomes to a single item, as a course evolves each time it is taught. However, multiple positive outcomes are evident after the program was included. The author intends to retain the physical testing program as part of the course in future offerings.

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Table 1. ABET outcomes originally covered in the course and those improved by the addition of physical beam tests.

ABET Outcome	Covered	Improved
(a) an ability to apply knowledge of mathematics, science, and engineering	•	
(b) an ability to design and conduct experiments, as well as to analyze and interpret data		•
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	•	•
(d) an ability to function on multi-disciplinary teams		•
(e) an ability to identify, formulate, and solve engineering problems	•	
(f) an understanding of professional and ethical responsibility	•	
(g) an ability to communicate effectively		•
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context		
(i) a recognition of the need for, and an ability to engage in life-long learning	•	
(j) a knowledge of contemporary issues		
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	•	

Table 2. Results of course evaluations for Reinforced Concrete Design ("Overall, how do you rate this course?").

Term	Evaluation (out of 5)
Spring '99	4.19
Spring '01	4.29
Spring '02	4.33
Spring '03	4.28
Fall '05	4.47

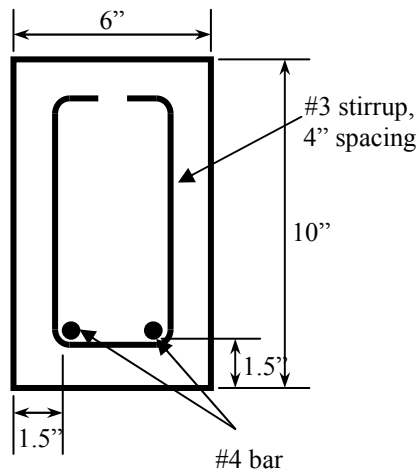
Table 3. Student comments regarding the project recorded during 2005 course evaluation.

I thought demos & discussion was helpful but really didn't like the reports--they probably made it more confusing.
Beam breaking was great--greater understanding of why it's important.
Beam braking helps in understanding. Breaks up long classes.
The course was very good. I particularly like the beam bending labs. Visualizing the beams break help to better understand what we are actually calculating.
The beam labs were helpful is sharing how the beams would fail under load & helped understand the material covered in the course.
I liked watching the beam breaks & didn't mind summarizing the results, but I didn't know enough background.
The beam breaks were interesting to see how beams fail more instruction for the reports would be helpful.
No big report at the end, 4 small ones is fine.
The beam breaking was worthwhile but the step by step process of the reports weren't.
Beam project was definitely a good thing. It helped to show what we were learning in class.
I liked the project, it was a good way to see our calculations be applied in a "real life" situations.
Labs were good; lab reports kind of repetitive.
The beam project was definitely helpful to understand the material. Instead of writing each report then a final report, just do individual reports.
Beam project was good. You could actually see happening what we talked about in class.
I think that the beam lab project was a good thing for the course. I felt that it showed how the theoretical calculation compares to the actual.
Liked breaking beams, Calcs should be in place of HW too much writing.
The beam project was awesome. If you require lab reports w/more depth of study/requirements the general principles you are trying teach us will become clearer.
Forcing us to write about this/any subject will require that we explain the concepts on paper--that helps a great deal.
Labs were good to see the failures. Would like to see how reinforcement is held in place when beams are made without stirrups.
It was useful to see how the beams behaved during failure, but disappointing at discovering the inaccuracy of the equations. However, you should keep doing it.
It was interesting to break a beam, but did not feel it worthwhile.

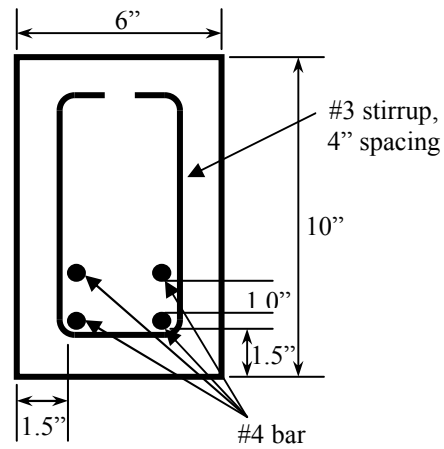
Table 4. Grading results 1999-2005.

Year	1999	2001	2002	2003	2005
# students	11	21	19	20	26
Final Exam Average (%)	81.0*	76.0	69.5	70.0	78.5
Course Average (%)	71.0	78.0	71.7	72.5	81.9
Course STDEV	16.0	9.4	13.5	11.3	8.3
Grades < C-	2	2	6	2	0

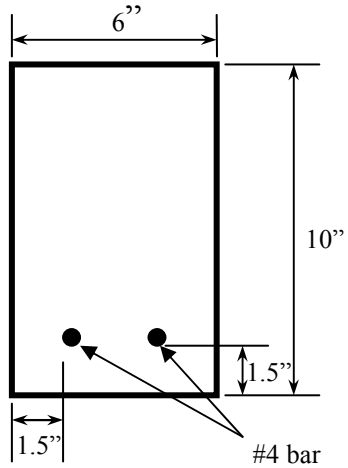
* 1999 final exam was not cumulative



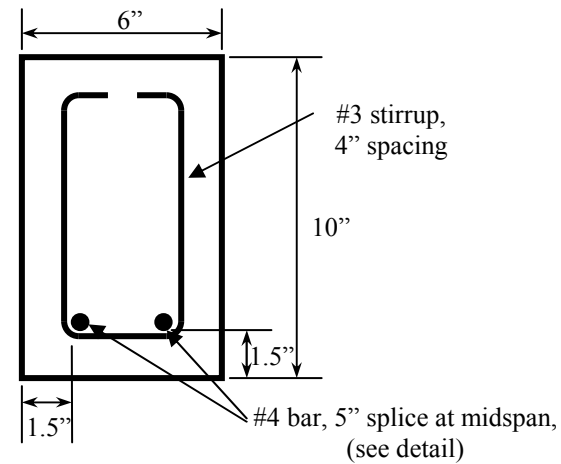
a) Beam 1 – Ductile flexural failure



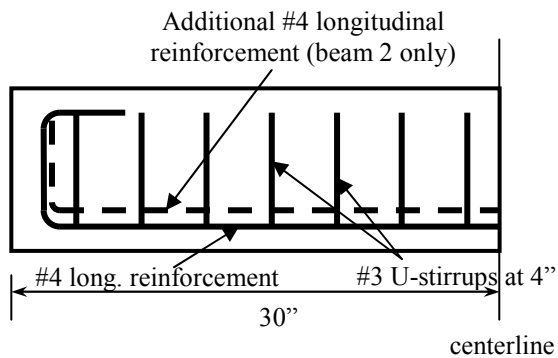
b) Beam 2 – Low ductility flexural failure



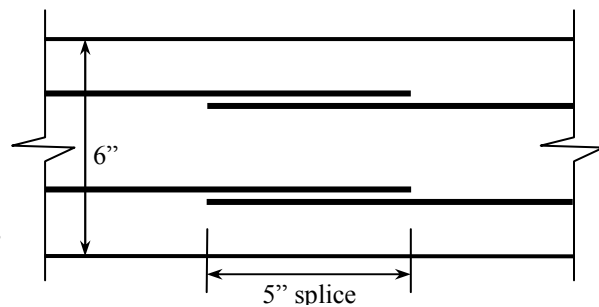
c) Beam 3 – Shear failure



d) Beam 4 – Anchorage failure



d) Side view beams 1, 2, and 4
(symmetric about beam centerline).



e) Top view of beam 4, centerline reinforcement lap
splice (stirrups not shown).

Figure 1. Details of beams used in testing.

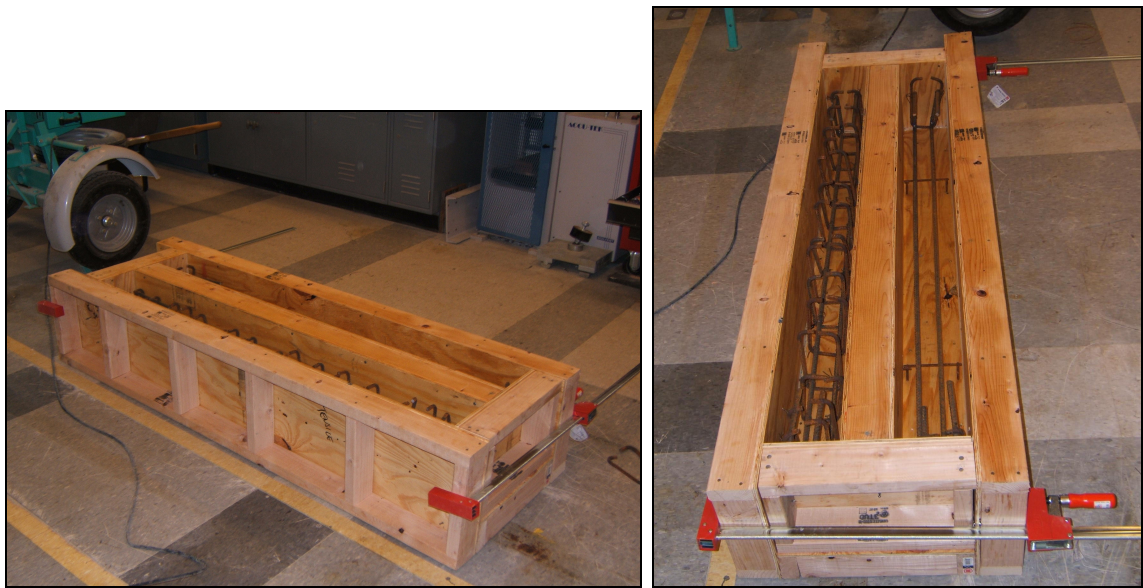


Figure 2. Formwork prepared for casting.



Figure 3. Failure of the four tested beams.

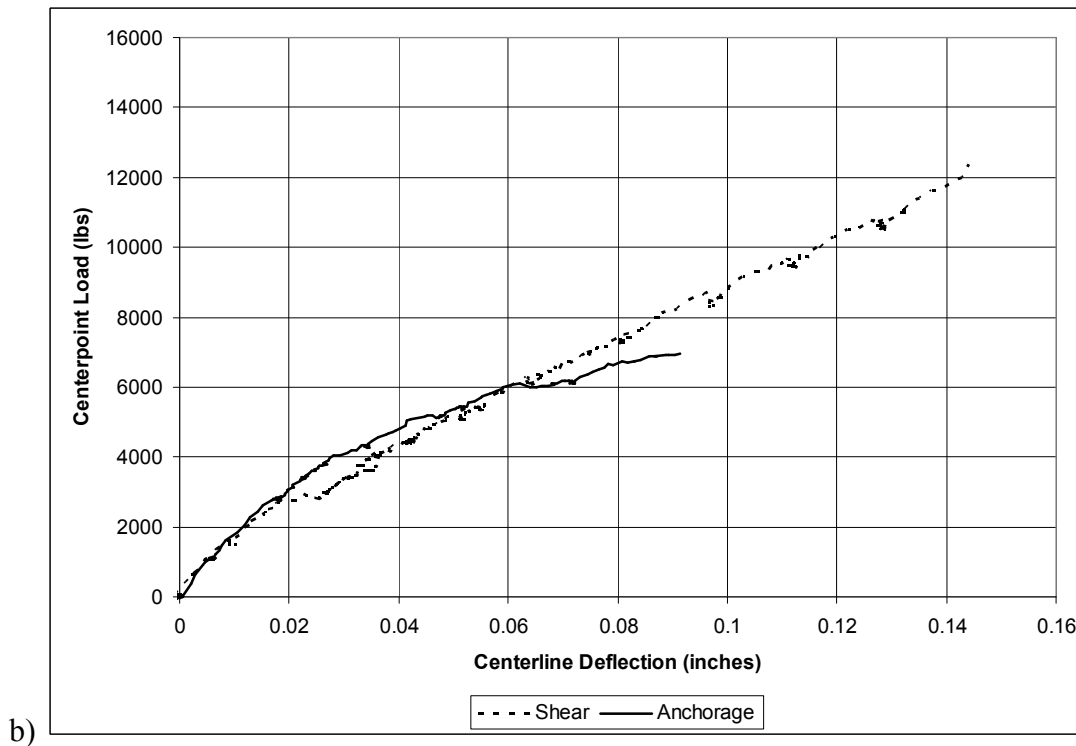
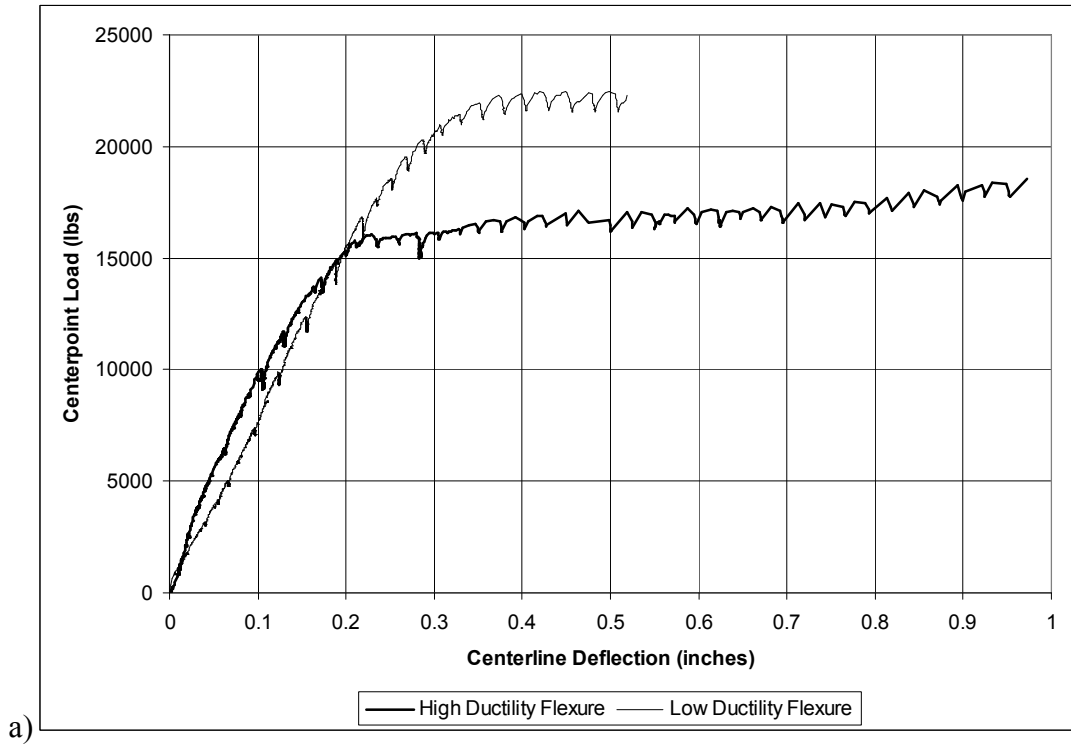


Figure 4. Test Results a) beams demonstrating low and high ductility flexural failure, b) beams demonstrating shear and anchorage failures.