DESIGN OF CONCRETE FRACTURE EXPERIMENTS

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The analysis and design of structures in the U.S made from concrete follow codes that rely mainly on strength failure criteria along with additional parameters to account for mechanisms of failure not explicitly recognized in these methods. All materials contain flaws that contribute to the overall performance of the various geometries and sizes of the components used to build structures. Additionally, concrete mixture designs have become more advanced with the use of strengthening methods such as fiber reinforcement, which contribute to the complexity of the failure characterization. The risk in the current design practice for concrete is that flaws inherent in the material can grow under loading to unacceptable lengths. It is therefore imperative that steps be taken to advance the current understanding and design practices associated with concrete in order to reliably account for the possible failure mechanisms that may occur. With this in mind, *CE401/501, Fracture Mechanics of Concrete Structures*, provides seniors and first year graduate students with the history and evolution of fracture theories and design practices along with a detailed study of the current theories used to understand the fracture mechanics of concrete. As part of a programmatic change that is under consideration in the Department of Civil and Environmental Engineering (CEE) at Clarkson University (CU), the lecture portion of the course has been supplemented by an in depth experimental component that requires students to design and perform concrete fracture tests following recommendations provided by the ACI Committee 446.[1] The programmatic curriculum change that is being considered is in response to the ASCE Policy 465 and ABET assessments. These organizations recognize the fact that changes need to be made in current programs in order to better prepare the new breed of engineer and guarantee the advancement of Civil Engineering.

The teaching of fracture mechanics in CEE has traditionally focused on theory, leaving laboratory testing to academic and industrial research settings. However, it can be argued that the traditional lecture style of teaching does not challenge the students' preconceived notions about the physical phenomena they are expected to understand.[2] Moreover, these lecture style courses result in the lowest retention of material by the students because they are not actively challenged by the problems.[3] In addition, employers are not completely satisfied with the individualistic approach to problems that this teaching method promotes.[4] Both ASCE and ABET acknowledge the fact that students need to be given activities more reflective of the demands of the workplace, such as the ability to design and conduct experiments, design systems and components, and function effectively in teams.[5,6] In order to enhance understanding of the theory and provide more in depth knowledge of the mechanisms related to quasi-brittle fracture, it is important for the students to apply the theory to physical experiments. This method of presenting the material has numerous advantages over a strictly lecture style of teaching. Instead of just listening to the instructor, watching the chalkboard and taking notes, the laboratory experience allows time for active discovery, hands on learning, and collaboration within the group and with other students and faculty. In general, the experimental component of the program generates a lot of interest in the course, which is important to its success. While in the laboratory, the students are frequently approached by faculty and other students who are interested in what they are doing and how it is progressing. The question, "When are you going to do a test?" is frequently heard in these discussions. How often do people ask what was done in lecture today? The interest and enthusiasm for a topic that is generated by testing a theory with physical experiments cannot be achieved in a classroom lecture setting. Moreover, getting the students out of the classroom and into a laboratory to work on a physical project is an excellent way to promote engineering in general. There are not many other disciplines outside of science and engineering that can put cutting edge theories and technology to a real test over the course of one semester and get results that were obtained through personal experience. The high visibility of students working in the laboratory encourages other undergraduates to become interested in a specific course that offers a relevant lab experience. It is important to take advantage of this method of learning.

In the classroom, students are presented with the history and evolution of fracture theories, beginning with Griffith and Irwin on up to the present day models of concrete fracture including the Two Parameter Fracture Model, based on the work of Jenq and Shah, and the Level I and Level II Cohesive Crack Models based on Hillerborg's work.[1,7] The motivation for fracture analysis is provided by comparisons of the ideal fracture strength of flawless materials with the actual much lower strength. Examples of actual catastrophic failures, such as the Liberty ships, that could have been avoided with a better understanding of fracture mechanics, are also discussed with the students. Various fracture theories and concepts are thoroughly presented and discussed, such as the Griffith crack, the J-integral, R-curve, Irwin's stress intensity factor and the energy release rate. Particular attention is given to the concrete fracture models presented in the ACI Committee 446 *Report on Fracture Toughness Testing of Concrete*,[1] as this is the backbone of the laboratory experiments the students are to perform. The class works through complete derivations of each of the models and its associated parameters to gain insight into the experiments. Additional time is spent reviewing the requirements of the tests to be performed as per ACI and ASTM specifications. The students are required to conduct the necessary tests and analysis associated with at least one of the fracture models. In order to accomplish this task, several steps need to be performed including concrete mix design, building forms and pouring the specimens, fixture design, construction and setup, programming a LabView VI for experiment control and data acquisition, writing MATLAB routines for data analysis and determination of fracture parameters, followed by a final report and presentation of the experimental results.

The most recent class, Fall 2002, chose to look at the Level I Cohesive Crack Model[1] (CCM), as this is the simplest of the three to conduct. The advantage of the CCM is that independent

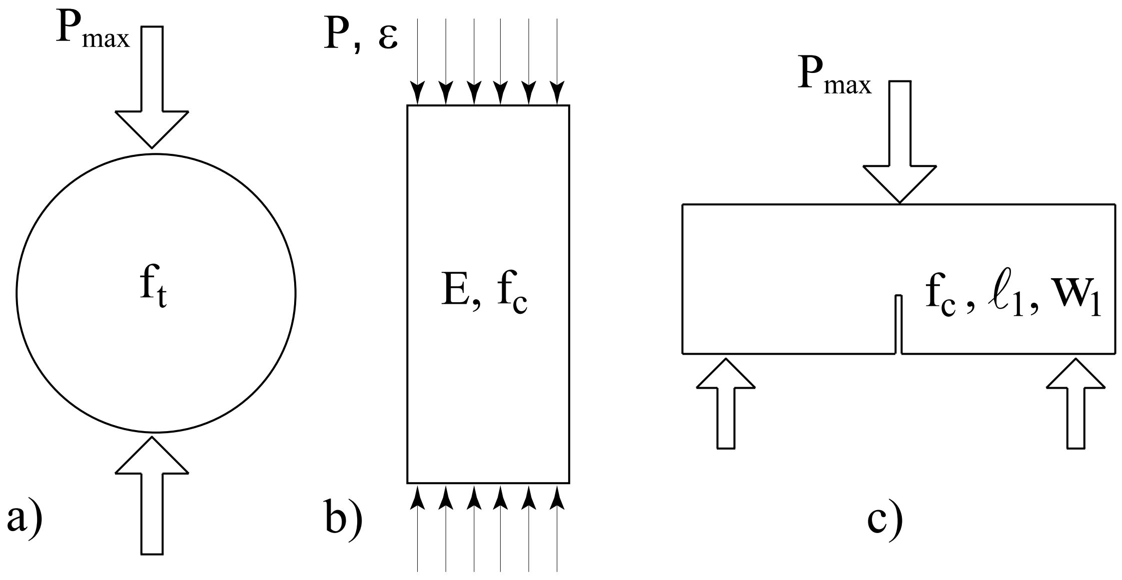

Figure 1: Summary of Tests for the Level I Cohesive Crack Model: a) Splitting Tensile Test; b) Cylinder Compression Test; and c) Single-Edge-Notched Three-Point-Bend Fracture Test

geometries and tests are required to obtain the fracture parameters. A number of splitting tensile tests, uniaxial compression tests and single-edge-notched three-point-bend tests must be conducted in order to obtain the necessary data. The three test geometries and the quantities to be measured are portrayed in Figure 1. From the perspective of the student, the three different tests offer an opportunity to see the concrete fail under different modes. The splitting tensile test is purely a tensile strength based failure and is very abrupt. The cylinder compression test is a compressive strength failure and occurs relatively slowly while the three-point-bend test is accompanied by the stable growth of a zone of localized fracture that happens over the course of minutes. In the latter case, during each beam test it is possible to actually observe stable cracking as the load the specimen can carry gradually decreases to zero. The first hand experience of different failure phenomena is, first and foremost, invaluable and reinforces the need for fracture analysis to be included in concrete design.

The uniaxial compression tests were the first to be conducted by the students. For this series of tests, 100 mm diameter by 200 mm long cylinders were used with a maximum aggregate diameter of 20 mm. The design compressive strength (f_c) was 27.5 MPa. Unfortunately, the students realized while mixing their first batch of concrete that the aggregate and sand had more moisture in it than had been anticipated and the mixture was too wet. They were forced to make another batch. However, after filling the forms for 4 beams there was only enough mix left for 6 cylinders, 2 of which were used for the compression tests and 4 for the splitting tests. All specimens were kept in a curing room at 90 - 95% humidity and approximately 18 - 24 °C until the time of the test. To determine the modulus of elasticity of the concrete specimens, the ASTM 469 standard was followed and a compressometer was

	Specimen 1	Specimen 2	Specimen 3	Specimen 4
Peak Load (kN)	137.5	129.0	114.2	144.3
Tensile Strength (MPa)	4.6	4.3	3.7	4.9

Table 1: Splitting Tensile Tests

used to measure the axial strain. The students designed and built mounts for LVDT gages to use in the fixture to take continuous data during the test instead of the mechanical dial indicators that were normally used. Figure 2a shows the setup of the specimens prior to the tests. The average elastic modulus (E) for the two tests was found to be 17.3 GPa. After the elastic compression tests, the specimens were loaded to failure for comparison with the design mixture and the compressive strength was found to be 40 MPa.

The cohesive tensile strength (f_t) is approximated by the splitting tensile strength and was performed according to the ASTM 496 standard and recent additional recommendations.[7] A total of 4 cylinders were tested in this manner with a mean tensile strength of 4.37 MPa. Figure 2b shows the split cylinder after completion of a test and Table 1 contains the results from each test.

The students in this most recent class took on the task of designing and building a three-point-bend test fixture that would be suitable for the fracture tests as well as being beneficial for other use in the structures laboratory at CU. Figure 3 shows the bend fixture designed by the students supporting one of the beam specimens prior to testing. The fixture was designed using roller bearings for the lower load rollers and pivots on the upper and one lower load roller to minimize the effects of torsion. The load capacity of the fixture is 100 kN and is limited by the roller bearings used. The span is adjustable from 300 mm to 900 mm and the load rollers can easily be changed to accommodate different specifications. With the help of CU's Engineering Research Machine Shop , the bend fixture was completed in

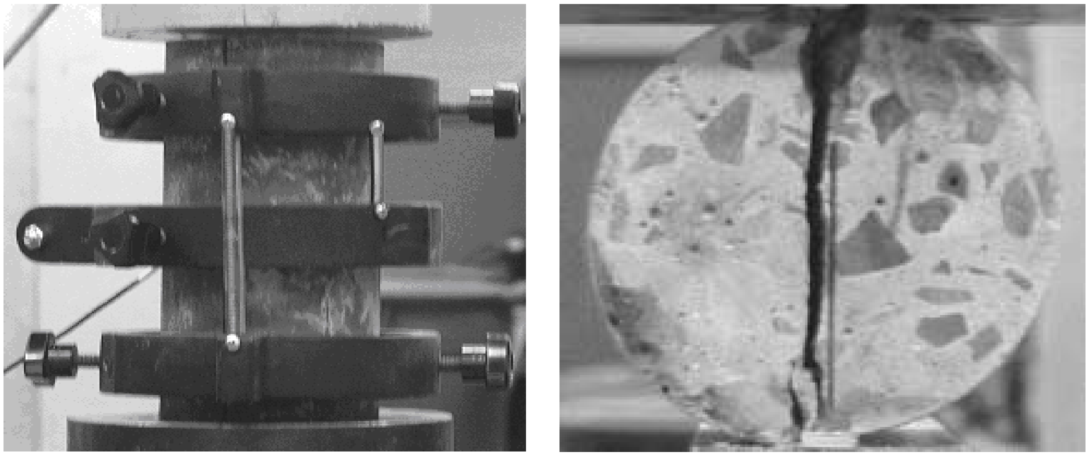

Figure 2: a) Cylinder Compression Test Setup; b) Splitting Tensile Test.

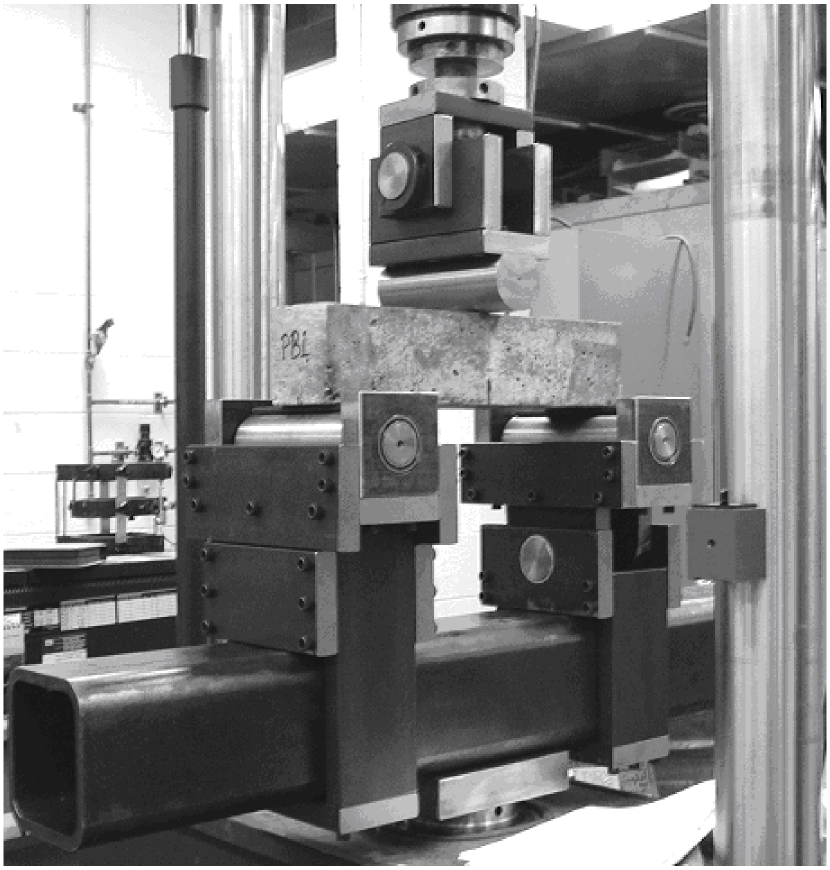

Figure 3: Three-Point-Bend Test Setup

time for the experiments.

A total of 4 beams were tested to determine the brittleness length (ℓ_1), the net plastic flexural strength (f_p), and the horizontal intercept of the linear portion of the softening curve (w_1). These parameters can be used to estimate a good portion of the fracture energy of the notched beam specimens. The results of these tests are given in Table 2. The notched beam test is an excellent tool for the students to observe the softening effect within the fracture process zone.

	Beam 1	Beam 2	Beam 3	Beam 4
f_p (MPa)	1.64	1.98	1.87	1.61
ℓ_1 (mm)	55	108	86	52
w_1 (μm)	28	55	44	27

Table 2: Level I CCM Fracture Parameters

In addition to the data obtained, it is easy to physically observe the growth of the crack

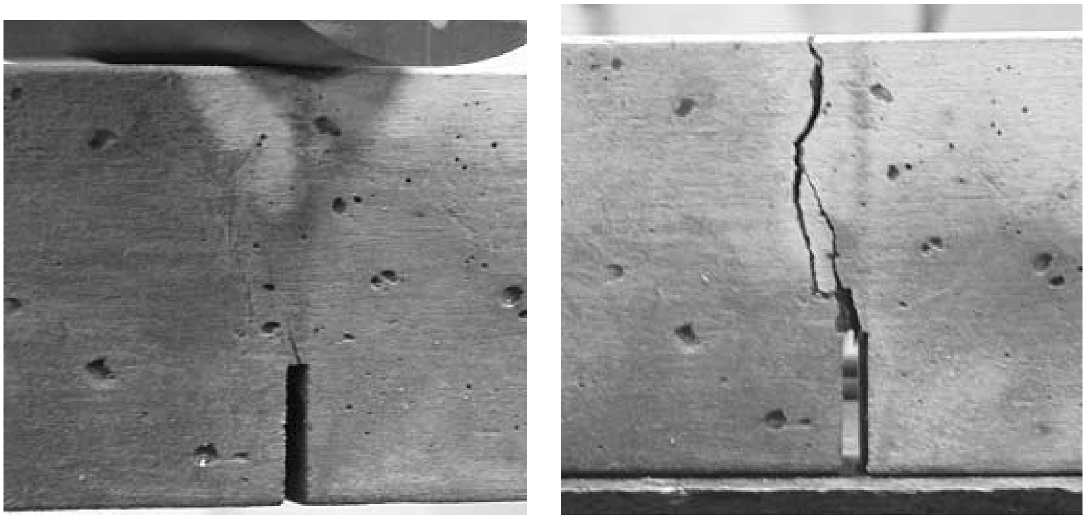

Figure 4: Initial Crack Growth and Complete Fracture Path for Beam 3.

through the depth of the specimen while the load displayed in the LabView VI gradually decreases. Figure 4 shows details of the crack propagation during one test.

It is clear from these pictures that the crack propagation is very complex and that it will choose a path based on the structure of the material. In each test, the load returned to zero such that only the beam weight was being supported just prior to complete failure of the specimen. Following the breakage of each specimen, the students inspected the surfaces of the fracture path, thereby verifying some of the toughening mechanisms present in the fracture process zone.

As part of the continuous curriculum improvement process and to aid in the assessment of the students level of conceptual understanding, general course and faculty evaluation forms are compiled along with an additional questionnaire specific to the laboratory component of *CE401/501, Fracture Mechanics of Concrete Structures.* The general faculty and course evaluation form is bubble sheet style with additional space provided for written feedback. This allows major strengths and weaknesses of a particular course to be highlighted quickly so that action can be taken. While this type of feedback is effective in general it does not require nor stimulate the students to put sufficient effort into their responses. In order to encourage more in-depth, thoughtful student feedback, a questionnaire specific to the course and laboratory experiment was prepared. This assessment of the course provides much more constructive feedback as the students who participated in the experiments have a more personal view on the subject matter. Following several questions generic enough to be used with any course, feedback with respect to the particular course objectives is obtained as well. Next, an evaluation of the various teaching and learning methods, lectures, homework assignments, reading assignments, designing and conducting laboratory experiments, analyzing and reporting data and results, etc., is conducted in order to help provide a basis for the effectiveness of the learning tools. Finally, several questions are asked pertaining to the relevance of the experiment to what was taught in the lecture as well as ways in which different aspects of the the laboratory experiments could be improved. When the different evaluation forms and student responses are compared with each other and those from courses that do not have a laboratory component, it becomes obvious that students who had the opportunity to actively participate in hands-on learning to supplement the lecture portion of the class provide much more feedback as to strengths and weaknesses of a course. Additionally, it shows that they have a better understanding of the effectiveness of the teaching and learning methods used, what was expected of them, and whether or not they felt they achieved those expectations. The student reactions over the past couple of years to the concrete fracture mechanics course and experiments has been very positive. The evaluations show that they are becoming more satisfied with their overall experience and that the students understanding of the topic is very satisfactory.

The initial outcomes of the programmatic curriculum change under consideration in CEE at CU is very promising. The interest among students and faculty alone that the laboratory experiments have generated is enough to justify its continuation. There were several students who approached the group in the fall who wanted to know if the course was to be offered in the spring. This is a very positive outcome as the topics covered are very challenging and *CE401/501, Fracture Mechanics of Concrete Structures* is not a required course. The primary goals of this curriculum change are to produce a better engineer more suited to the complicated demands of the future and encourage students to continue their education beyond their bachelor's degree. The experimental portion of the course work described here obviously helps to achieve these goals as it provides a more physical first-hand understanding of the topics covered in the lecture. Also, seniors get an opportunity to work in teams with first-year graduate students which probably would not happen outside of the laboratory experiment setting. The opportunity to research, design, build, test, analyze and report is a series of steps crucial to the profession and a very effective method of learning. There are many questions that that get asked in class during the design of an experiment which is a level of interest otherwise not forthcoming. These questions are on the material being presented in lecture and helps create a more open, comfortable and productive classroom environment. They are asked, more often than not, because students feel they must understand the material in order that the experimental design can proceed forthwith. The feedback from the students with respect to positive outcomes from the experiments as well as improvements that could be made shows that they are actively engaged in the entire process. The important benefits come at the end of the semester when the students know that they have accomplished a set of learning objectives that are by no means trivial. This is especially relevant to seniors who will be graduating and looking for employment; courses structured in this manner can have a rejuvenating effect on their commitment to learning. The feelings of accomplishment gained through a successful series of sophisticated experiments are impossible to reproduce in a classroom lecture setting alone. The benefits of active, hands-on learning to supplement strictly lecture style courses is well documented and should be taken advantage of in every possible situation.

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