

Manual for Three-Point Bending Single-Edge Notched Fracture Test with Plain or Fiber-Reinforced Concrete

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Test Purpose:

To obtain a load versus crack opening displacement (COD) that is used for determine fracture properties of the material.

Nomenclature:

α	Notch to depth ratio (subscript: 0 = initial, c = critical)
a	Notch depth (subscript: 0 = initial, c = critical)
b	Beam width
C	Compliance (subscript: i = initial loading, u = unloading)
CMOD	Crack mouth opening displacement
COD	Crack opening displacement
$CTOD_c$	Critical crack tip opening displacement
δ_f	CMOD displacement corresponding to $P = 0.05$ kN at failure
d	Beam depth
E	Modulus of elasticity (subscripts i = initial, u = unloading)
FGM	Functionally graded materials
FGCM	Functionally graded concrete materials
FRC	Fiber-reinforced concrete
$g_1(\alpha)$	Geometric function for the TPB specimen
$g_2(\alpha)$	Opening displacement geometric function for the TPB specimen
G	Fracture energy (subscript: f = initial or critical, F = total)
K_{IC}	Critical stress intensity factor (mode I)
L	Beam length
LEFM	Linear elastic fracture model
LVDT	Linear variable differential transformer
P	Load (subscript: c = peak, w = equivalent self weight)
PCC	Portland cement concrete
S	Beam span
SEN(B)	Single-edge notched beam
TPB	Three-point bending
TPFM	Two-parameter fracture model
W_0	Weight of a TPB specimen
w_f	Final crack opening width
W_r	Area under the load versus CMOD envelope curve
W_t	Total energy of a TPB specimen

Materials Needed:

(Bold text are items which must be reserved in advance)

-11kN (5 kip) MTS testing frame and INSTRON 8500 Plus controller

-4 mm or 0.16 inch range clip gauge

-Mac desktop computer (with *ctodrampGBXL.vi* program)

-Red C-channel and small steel plate (to raise one side such that the pin and roller are at the same height)

-Pin and roller set (if not already attached)

-2 aluminum knife edges per concrete beam

-quick-set epoxy



- hammer
- chisel

Additional materials for FRC:

- laptop with LabView based data logger (for example, GP Contlog program)
- yo-yo gauge (50 mm or 2 inch range suggested for 150 mm deep beams; 127 mm or 5 inch range suggested for 250 mm deep beams) – Celesco PTX101-0002
- 1 aluminum angle bracket with hole on one half (per concrete beam)
- 1 aluminum angle bracket with two screw holes through long portion of bracket (per concrete beam)
- wire (may use fishing wire)
- wire cutter
- screwdriver (and small screws if not provided with yo-yo gauge)
- power supply
- data acquisition converter
- transition box

Test setup

Concrete Beam Preparation:

Size: The recommended size for testing concrete (plain or fiber-reinforced) is with a depth 150 mm. Larger beams can be made (such as 250 mm deep), but generally are too heavy. A concrete beam with dimensions shown in Figure 1 will weigh roughly 40 to 60 pounds. The weight of the concrete beam (preferable measured before testing while the beam is “dry”) should be measured and is used in the analysis.

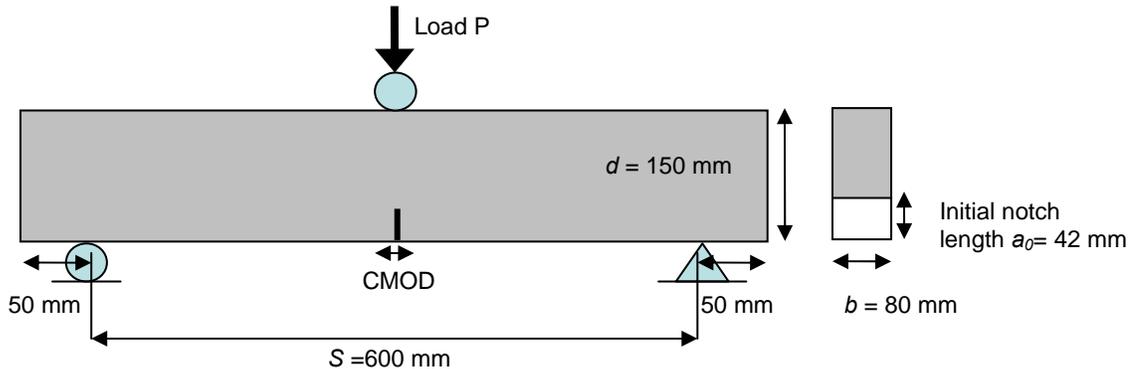


Figure 1. Beam schematic with suggested dimensions.

Moisture condition: All beams should be tested with the same moisture condition. One suggestion is to remove any concrete beams from a moist-curing environment 24 hours in advance in order to saw-cut specimens and allow the surface to dry before attaching knife edges or angle brackets.

Saw-cutting: Each beam shall have a notch cut into the smooth (bottom of mold) edge of the beam. The notch depth will greatly influence the desired fracture properties, therefore be sure to make the correct depth. Also be sure to record the actual depth of the notch to be used in the analysis. The concrete does not need to be dry for saw-cutting, but drying the surface in order to mark the location of the notch may be desired. The width of the notch shall be small compared to the depth of the notch.

Attaching gauges:

Clip Gauge

For all beam specimens, two knife edges shall be glued using a quick-setting epoxy to the smooth surface of the beam, centered across the notch. The shorter side of the knife edge should be placed against the concrete such that the long sharp edge is farthest from the concrete and spaced 10 mm (0.4 inches) apart as shown in Figure 2. The surface of the concrete must be dry in order for the epoxy to glue.

If the epoxy used for the knife edges is not mixed well or does not adhere to the concrete surface, the beam may suddenly break during loading and the data will not be useful for analysis!

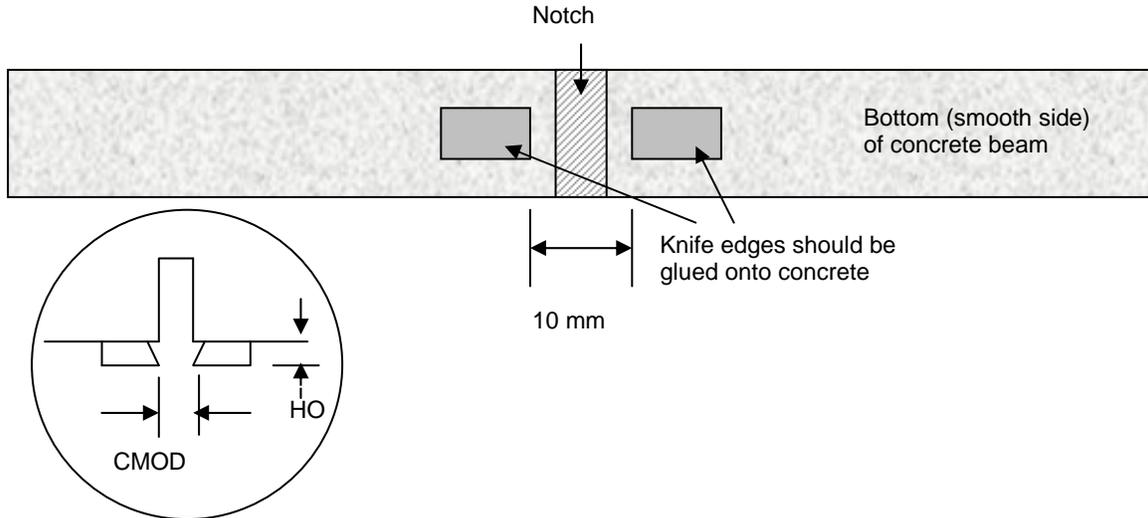


Figure 2. Details on attaching the knife edges to concrete beams which measure crack mouth opening displacement (CMOD).

Yo-Yo Gauge

When testing fiber-reinforced concrete (FRC) and the full fracture curve is desired, a yo-yo gauge is used to capture the opening of the notch once the clip gauge goes out of range. The yo-yo gauge is screwed to an angle bracket and tied to another angle bracket such that it spans the notch and is located as close to the bottom of the beam for a more accurate measurement of the same notch opening distance as the clip gauge (the most accurate measurement for comparison to the clip gauge would be to have the string from the yo-yo gauge lie in line with the bottom of the knife edges). Figure 3 provides more details on how the angle brackets should be glued to the concrete using the quick-setting epoxy. To determine the optimal distance between angle brackets, once the data acquisition system is set up, one can select ⇌ on the laptop LabView program to check the voltage reading from the yo-yo gauge. When the reading is close to zero and the string from the yo-yo is closest to the gauge to give a maximum reading range, then attach the end of the string with a wire to the other angle bracket.

However, one should note that the epoxy must be set before the beam is tested in order to have good data from the test.

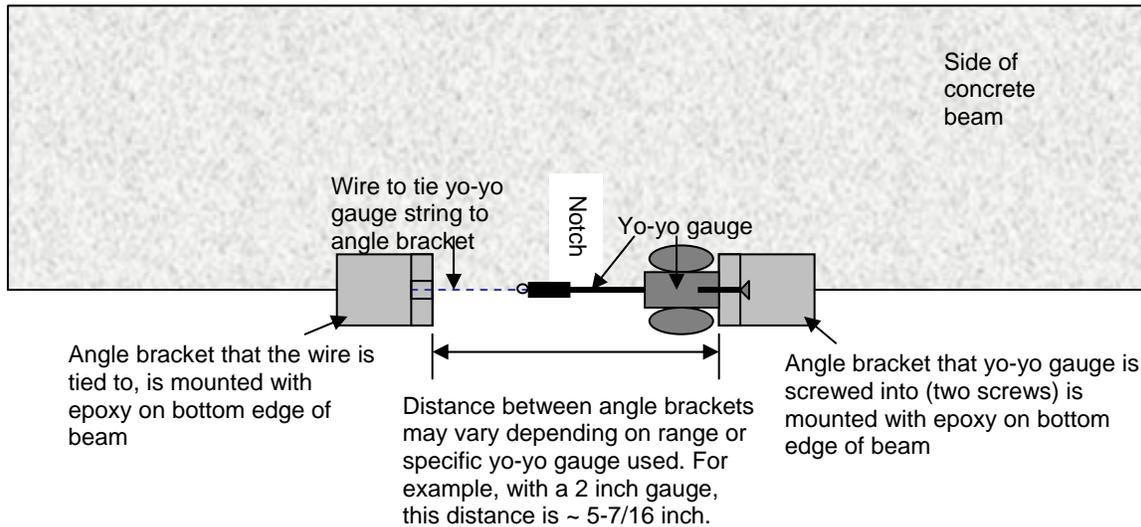


Figure 3. Details on attaching the yo-yo gauge for FRC beams.

The yo-yo gauge produces a voltage output and can be calibrated later as part of the analysis. In general there will be a range after the crack has occurred in the beam where the clip gauge and yo-yo gauge both will give good readings. This range will be used as the data set for calibrating the two gauges together. The yo-yo gauge itself has a recorded calibration printed on the side of the apparatus (such as 477.95 or 479.45 MV/V/inch) which may also be used if desired.

Figure 4 shows a close up photograph of the gauge attachments to a fiber-reinforced concrete beam during testing.

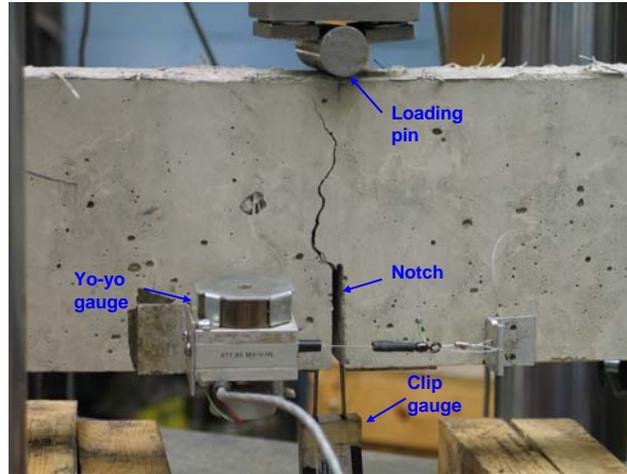


Figure 4. Photograph of a fiber-reinforced concrete beam highlighting the location of the loading pin, saw-cut notch, clip gauge, and yo-yo gauge attachments.

Data Collection Configuration:

The testing equipment details are in this section. Before testing you should have the following setup:

- 1) Base plate
- 2) Loading fixture
- 3) Check connections
- 4) INSTRON/ MTS setup
- 5) Waveform function (for FRC)

Base plate

First of all, you will need the base supports to be set up to handle the size beam you will be testing. The details of this set up are shown in Figure 5.

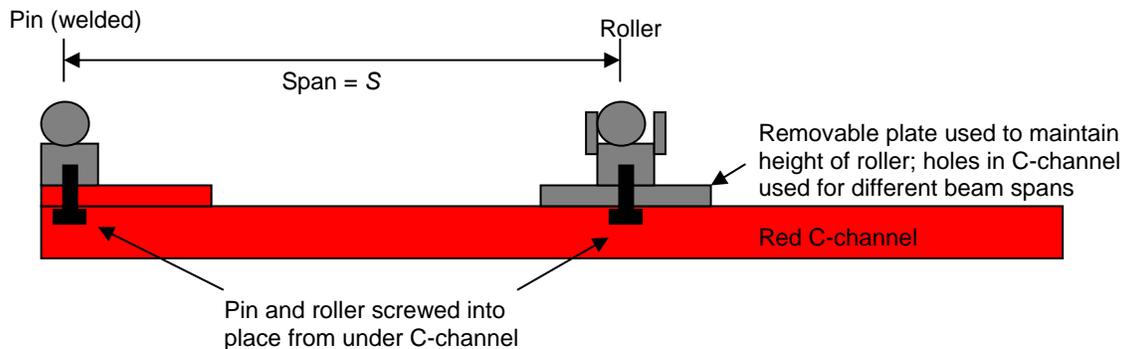


Figure 5. Base plate configuration schematic.

Loading fixture

You will also need to make sure a single roller configuration (see Figure 6) is screwed into to the 11 kN (5 kip) load cell.

Check connections

A diagram of how all the components are connected is shown in Figure 6. For measuring plain concrete beams, the Mac computer, load cell and clip gauge are connected to the INSTRON computer. When testing FRC, you will need to set up a laptop computer to read the outputs of position, load, and strain1 (clip gauge) from the INSTRON computer. You will also need to use the yo-yo gauge, which needs to be connected to a transition box which receives 10 V from a power supply, and the output goes also through the data acquisition card to the laptop.

You will need both the Mac computer to control the strain-controlled looping of the fracture test, and when testing FRC, you will need the laptop in addition to record data from both the clip gauge and yo-yo gauge for the entire load-displacement run-out test.

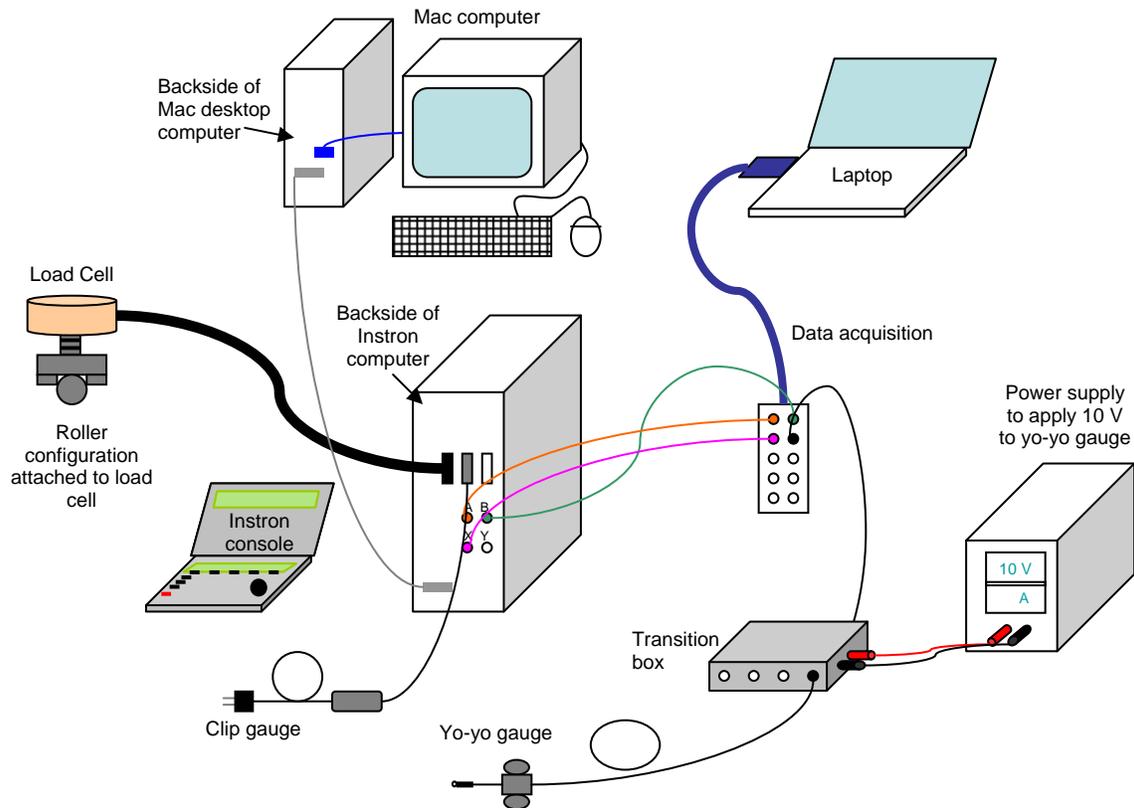


Figure 6. Detailed schematic of all the components and how they are connected.



Figure 7. Picture of the Mac computer used to run the controlled strain loading and unloading cycles and to collect data for plain concrete beam tests, and laptop used to collect all the data for a FRC beam test.

INSTRON / MTS setup

You can follow the "Operation Manual for Instron 8800/8500" available online at <http://cee.uiuc.edu/nsel/website2008upgrade/facility/instr/manuals.htm> for further instruction on operating the equipment. It is recommended that each new user reads and understand the manual prior to testing.

- Be sure to turn on the pump, hydraulics and actuator before testing.
- Make sure you have LOAD PROTECT → ON while setting up the equipment for the test.
- Check the gain (under strain1 channel – click SETUP, click key for LOOP) should have PROP value somewhere between 10 and 15.
- If the load values on the Instron console are not close to zero when the load cell is not in contact with the specimen, then you should balance the load. Turn off LOAD PROTECT or any limits on load channel. Under the load channel, click SETUP, CAL, CAL, BALANCE and wait until the light stops flashing.
- Check that the clip gauge (strain 1) is set to ENABLE (under strain1 channel – click SETUP, click key for CAL)
- Be sure the clip gauge is calibrated (use c-clamp to move the gauge to close to 0 mm on the Instron console, under the strain1 channel, click SETUP, CAL, CAL, AUTO and wait until the light stops flashing).

Waveform function (for FRC testing)

When you are testing FRC, you can set up the waveform information under the position channel in advance, otherwise this can be done as step 12c in the test procedure section. A recommended position-controlled loading would be a SRAMP function with amplitude -75 mm and frequency/rate of 0.0167 mm/sec or 1 mm/min.

Testing Procedures

Before testing be sure to read both Testing Procedure Parts 1 and 2 before beginning the test to know what steps you will have to do. A photograph of what the beam setup should look like before you test is shown in Figure 8. Also some of the key buttons used during testing are marked on the photograph of the INSTRON 8800 console in Figure 9 to aid in testing.

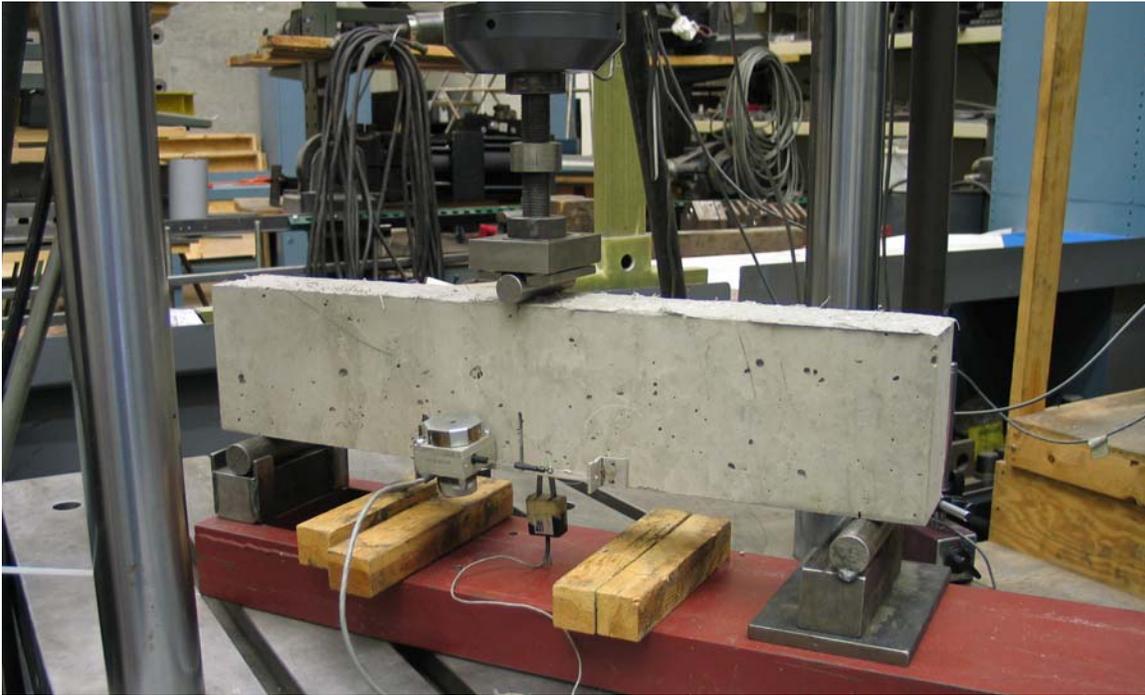


Figure 8. Photograph of completed setup for a fiber-reinforced concrete beam.

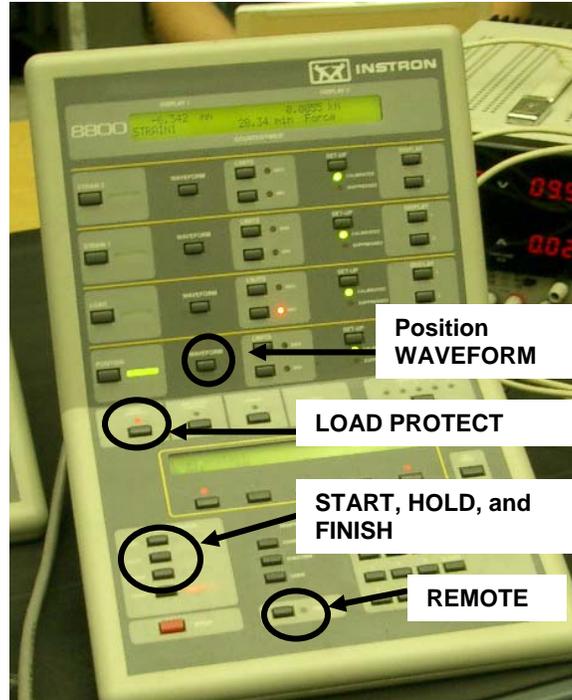


Figure 9. Picture of an Instron console labeled with locations of the buttons used for testing.

Test Procedure (Part 1: Looping):

This “looping” test is done using the Mac desktop computer and controlled by the clip gauge to produce loading and unloading curves automatically. The unloading can be done manually if desired – see note later in this section for more discussion on manual unloading.

1. Open the LabView program entitled **ctodrampGBXL.vi alias** (should be located on the desktop).
2. Start the program by clicking the arrow ⇨ in the top left corner.
3. Initial panel:
 - a. Make sure the switch is down ▲ for strain in millimeters.
 - b. Click on the green GO button.
4. Instron 8500 status panel: at the top in yellow are listed the voltages through channels 1 through 4 from the Instron 8500 computer.
 - a. Be sure to have the collect strain1 data ▼ enabled.
 - b. The collect strain2 data may be set to disabled ▲.
 - c. Click the green ENTER button.
5. Set limits panel: the four channels labeled position, load, strain1 and strain2 are sectioned on this page.
 - a. Under the LOAD section, set the “min load” to the value - 20, turn the “arm” button ON (becomes black when on), and
 - b. Under the STRAIN 1 section, set the “min str1” to the value - 4, turn the “arm” button ON (becomes black when on), and set the “load trip action” to “unload”.
 - c. All other sections should be unarmed (“arm” button will be grey)
 - d. Click on the green PROCEED button.

6. Remote control panel: you are instructed on the page to “locate the remote button on the 8500 console and be ready to press it when it flashes”
 - a. Before you click anything on this panel in the program, be sure to turn LOAD PROTECT → OFF on the Instron display console.
 - b. Click on the green PROCEED button once you have verified that load protect is off (the light above the LOAD PROTECT button will be off).
 - c. The REMOTE button on the console should be flashing so click on REMOTE to activate remote control. This should turn the light next to remote on solid red. The Mac computer is now controlling the load cell and MTS equipment.

If you forget to turn off Load Protect, follow these steps:

- I. Stop program – click on  at the top of Labview program.
 - II. Under the WINDOWS menu, click on “Show Diagram”
 - III. Change the number in the box with arrows <[_]> to “9” for the last panel page
 - IV. Double click on “RETN CTRL”
 - V. Click on the green PROCEED button
 - VI. On INSTRON 8500 control panel, push the red STOP button
 - VII. Go through the test procedure again starting with step 1. Some screen panels may not show up when going through selections (for example, the set data point slide may not show)
-
7. Waveshape generator setup panel: this is where you input all of the loading rates and constraints for testing (some of these can be changed during testing as described in step 10)
 - a. Set “peak strain” to -4.0 mm. This is the maximum amplitude and direction the clip gauge will move towards.
 - b. Set “strain ramp slopes” to 0.001 mm/sec. This value will depend on the test you are performing, but this is the general rate used for the concrete beams).
 - c. Set “reversal point” to 95 % of peak load. This is the magnitude of load drop at which the computer will automatically unload the specimen.
 - d. Put the “load ramps” slide to the bottom/red end for “constant times”
 - e. Set the “load ramp time” to 10 sec. This will be the time which the computer will try to take to unload the specimen.
 - f. Click on the green PROCEED button.
 8. Data logger setup panel: this is for determining the amount of data to record and the rate at which data will be recorded
 - a. Slide the arrow or type into the box for the “data point interval (msec)” the value 250.
 - b. Click on the green PROCEED button.
 9. Header and filename panel: this creates the information for the .h file and sets up the computer pathname for which subsequent data files (one .dat file made for each loading cycle) is stored as.
 - a. You may enter your name under “name”, a description of the material under “material tested”, a label to remember your specific specimen under “specimen ID”, and a label which will go as the start of each cycle’s .dat and header file under “filename”. An example would be: name: bordelon; material tested: FRC; specimen ID: fracture2; and filename: FRCf2
 - b. Click somewhere on the screen’s greyspace to accept information for 9a.

- c. A window will open up asking where to save the file. You can start a folder on the desktop with your name and testing date (example: bordelon20080912) and select “choose” once you highlight the folder choice.
 - d. Click on the green **PROCEED** button.
10. Run test panel: this is where you will physically start loading your specimen and where you can change some loading rates or criteria for unloading. The current cycle is displayed below the reverse button to aid in showing the number of loading cycles which have occurred.
- a. Before you start loading, change the “X plot choice” to read “Strain1 mm” and the “Y plot choice” to read “Load kN” located above the graph.

*If you are planning on testing FRC run-out, be sure to hit the green **START** button on the laptop computer program **before** you start loading the specimen in order to record all the data including the cycles.*

- b. As long as the switch is green for RUN , you may click the green **START** button to begin loading the specimen.
 - c. At any point during the test you may do the following:
 - i. Manually unload the specimen – click the blue **REVERSE** button.
 - ii. Change the magnitude at which the computer will automatically unload – enter a value into the green “reverse point %” box and click on the screen or hit the ENTER key to accept the change. This is useful when you want to do a run-out test as describe in test procedure Part 2a. This will take effect once the next “peak” load has been reached. *For plain concrete run-out, during your last desired loading cycle you can change the “reverse point %” to zero and the test should end on its own (you can skip step 10d) as long as the limits in step 5 were set.*
 - iii. Change the loading rate – enter a value into the green “strain slope” box and click on the screen or hit the ENTER key to activate the change. This will take effect immediately.
 - d. To end this controlled strain test, click on the switch on the left such that it turns down for  **HALT**. Depending on where the test is at, it may take a while before the computer returns the load to zero. *For testing FRC run-out, you may want to end the controlled strain test (click **HALT**) during the unloading phase of your last desired cycle.*
 - e. When the test is ended, the button labeled **DONE** will turn yellow and a blue button labeled **EXIT** will appear on the bottom left. Click on the button EXIT.
11. Return control panel: this will allow you to switch out of remote control back to the Instron console’s control. Click on the green **PROCEED** button.

Test Procedure (Part 2a: Plain Concrete Run-out):

10.c.ii. After a certain number of loading cycles, you may want to finish off the test as one loading loop (no unloading). You will need to change the value in the green “reverse point %” box to be a low value such as **0.00** %. This change will take effect once the next “peak” load is determined by the computer –

ideally you can do this change during the unloading phase of the last desired cycle or during the elastic range of loading (below the threshold where the beam may exhibit a peak load).

10.c.iii. The loading rate may be increased if desired. Any change in loading rate will take effect immediately after you enter in a value + click on the screen or hit ENTER. A suggested loading rate for the plain concrete run-out would be at **0.005 mm/sec**.

Test Procedure (Part 2b: FRC Run-out):

The goal with FRC is to have the full load versus opening displacement curve. Since the computer program on the Mac is useful for capturing the displacement through the clip gauge and can do loading/unloading loops, it is useful for capturing any initial fracture properties and monitoring the smaller displacements. However, the clip gauge only works for a small range (4 mm) and therefore it is useful to have another gauge to measure the larger ranges and a data recording system to capture this information. Thus the yo-yo gauge is used to measure larger displacements and a secondary computer is hooked up which records all data, including the clip gauge, cyclical loading and yo-yo gauge.

If you are going to use FRC run-out, be sure to have started recording data through a data acquisition system such as with the laptop computer program.

12. After you have ended the Mac computer controlled test, such that the Instron console now has control of the apparatus, you need to set up the waveform function.
 - a. Click on the POSITION button and then the key under IMMEDIATE for position control.
 - b. Under the "position" channel, click the WAVEFORM button.
 - c. On the control display, the first location should be set to "**SRAMP**". The third location should give you the test limit – direction and amplitude of test – and should be set to "**-75 mm**". The fourth location is the loading rate and should be set for example to "**0.0167 mm/sec**" (or 1 mm/min).
13. Start loading the specimen by clicking the START button on the Instron console.
14. During the test you may do any of the following:
 - a. Click the HOLD button to temporarily tell the MTS to hold the current position.
 - b. Increase the loading rate under the WAVEFORM button. Any new loading rate entered will take effect immediately.
 - c. Change the position limit under the WAVEFORM button. A new set point will take effect immediately. This may be useful if you wish to have another cycle by changing the set point to positive 75 mm; you will want to change this back to a negative value as the load approaches roughly zero or the loading roller will continue to move off of the specimen.
15. To end the test, click the FINISH button on the Instron console.
16. Be sure to turn ON load protect before you touch the specimen or try to remove the gauges.

You may want to move the clip gauge out from under the specimen after it has dropped from the knife edges to be sure it does not get damaged during the test.

Clean-up

-After testing the beams, you may remove the gauges and angle brackets. Be sure to scrape off any remaining concrete or epoxy from the knife edges and angle brackets using the hammer and chisel. This can be done along with using the C-clamp on the south wall of the east end.

- Any chunks of concrete can be thrown out in the big concrete dumpster outside the north crane bay doors.
- Sweep up any concrete or trash from the floor.
- Copy any files you had off the computer. Turn off the monitor on the Mac and close the laptop. Turn OFF the actuator and hydraulic buttons on the Instron console.
- Be sure to check with Greg first, but you may need to turn off the valve to the MTS machine and pump for the hydraulics.

Sample Results

The data from the Mac computer can be found in the desktop folder (the title and location of the folder were defined during step 9). The `_h` file contains the header information from the LabView program. The `_d#.dat` files, where the # is the specific cycle number, contain the raw data – typically including the “position”, “load”, and “strain1” results needed for analysis. The load values in the raw data are negative and displacement values are absolute; generally when presenting the data, it is preferred to switch the sign on the load readings and adjust the strain1 readings to have a relative displacement value beginning with a displacement of zero. Figure 10a shows the combined results from 3 cycles of a plain concrete beam tested in fracture where the displacements are all normalized by the same initial value. Figure 10b shows a sample of a plain concrete beam tested with many cycles before run-out.

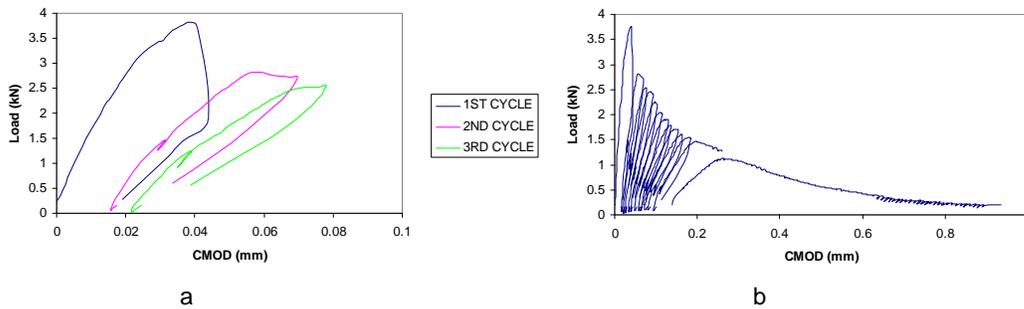


Figure 10. a) Sample result of load versus CMOD curve for each cycle, and b) combined cycles for load versus CMOD for plain concrete [from Bordelon 2007]. CMOD values have been adjusted so the initial displacement is zero.

A sample of a FRC beam tested until complete run-out is shown in Figure 11. Typical peak loads for plain concrete and FRC are around 3 to 4 kN, and with FRC, the maximum opening displacement was shown to reach even up to 45 mm as shown in Bordelon’s MS thesis (2007).

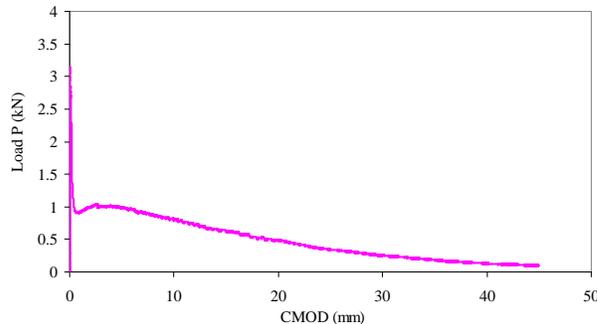
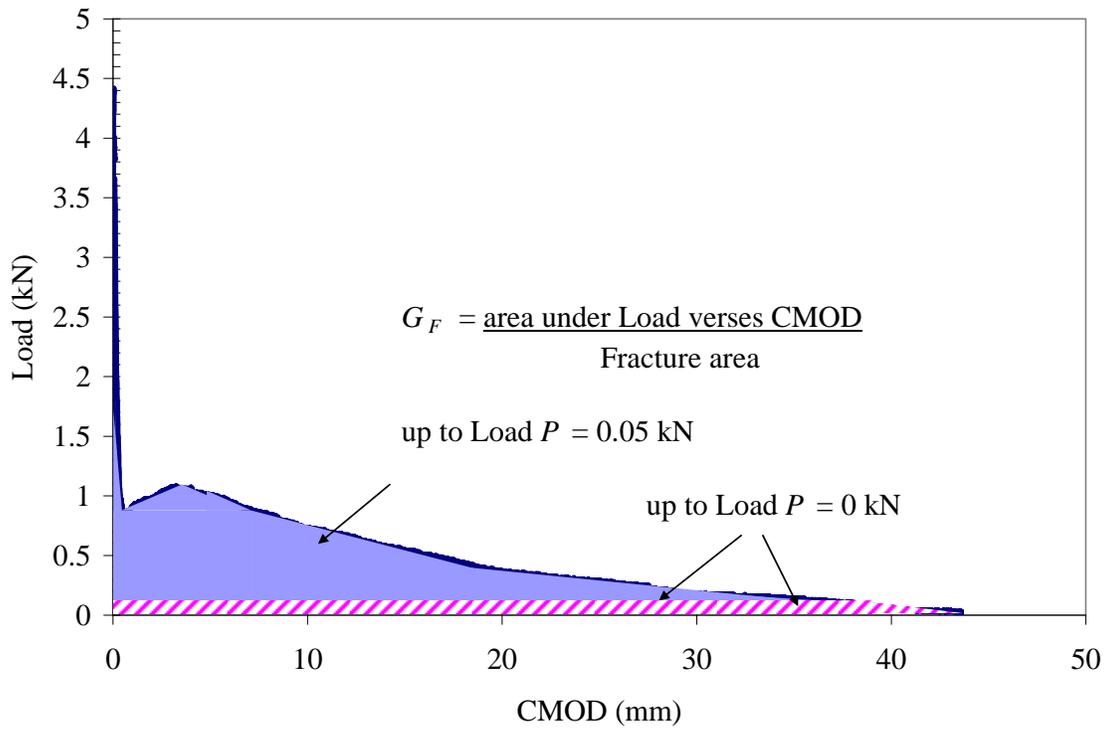
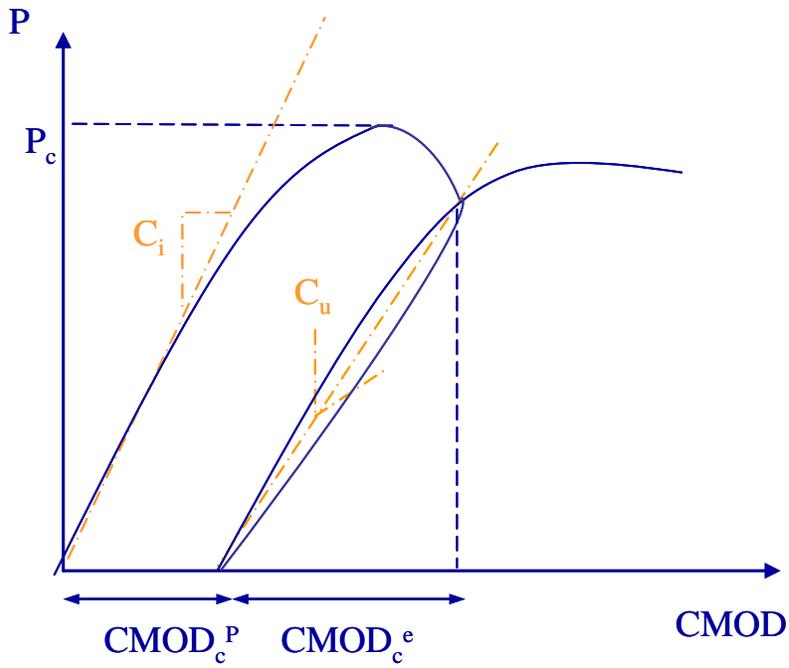
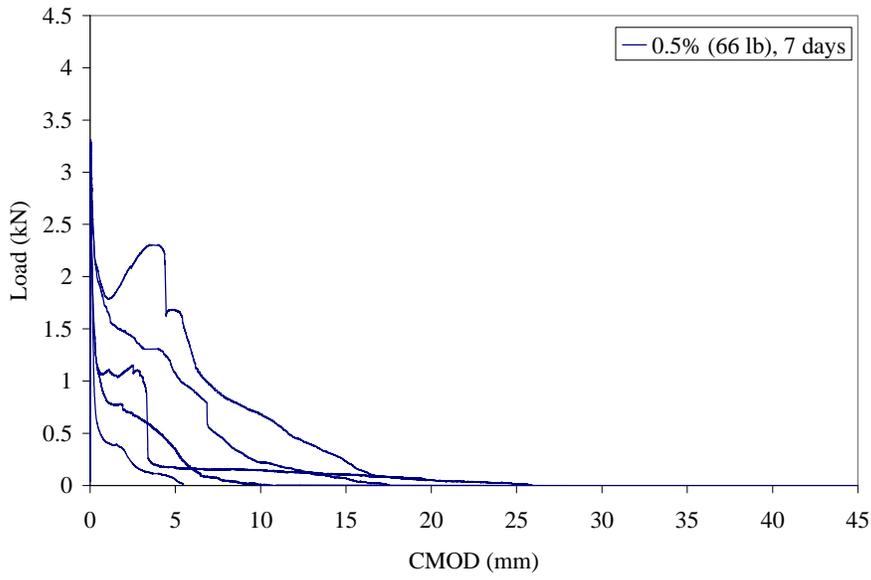


Figure 11. Sample result of entire load versus CMOD curve for a fiber-reinforced concrete beam [from Bordelon 2007]. CMOD values have been adjusted so the initial displacement is zero.

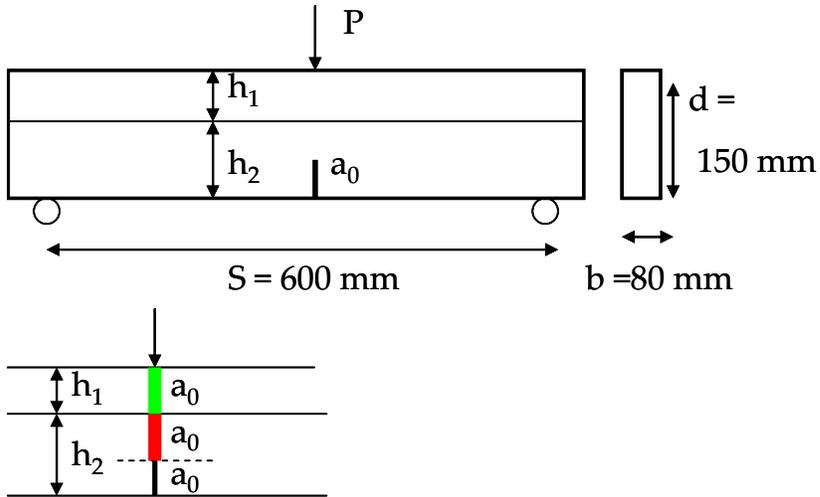
Sample Analysis



Three Point Bending Fracture Test Manual



Alternative: Two-layered casting



$$\alpha_0 = \frac{(a_0 + HO)}{(b + HO)} \quad E = \frac{6 * S * a_0 * g_2(\alpha_0)}{C_i * b^2 * t}$$

$$E = \frac{6 * S * a_c * g_2(\alpha_c)}{C_u * b^2 * t}$$

$$g_2(\alpha) = 0.76 - 2.28\alpha + 3.87\alpha^2 - 2.04\alpha^3 + \frac{0.66}{(1-\alpha)^2} \quad a_c = a_0 * \frac{C_u * g_2(\alpha_0)}{C_i * g_2(\alpha_c)}$$

$$K_I = 3 * (P_c + 0.5W_h) * \frac{S * \sqrt{\pi a_c} * g_1(a_c / b)}{2 * b^2 * t}$$

$$g_1\left(\frac{a_c}{b}\right) = \frac{1.99 - (ac/b)(1 - a_c/b) * [2.15 - 3.93 * (a_c/b) + 2.70 * (a_c/b)^2]}{\sqrt{\pi} * [1 + 2 * (a_c/b)] * [1 - (a_c/b)]^{3/2}}$$

$$G_f = \frac{K_I^2}{E}$$

where

HO = distance from clip gauge to specimen
 K_I = critical stress intensity factor
 P_c = peak load
 W_h = W_{ho} * S/L, with W_{ho} = self weight of a beam
 G_f = initial fracture energy

GF = (bt)⁻¹ * [Area under P versus CMOD]

Reference

Bordelon, Amanda. "Fracture Behavior of Concrete Materials for Rigid Pavement Systems", MS Thesis, University of Illinois at Urbana-Champaign: Urbana, IL, December 2007.

1	mm/min	1.67E-02	mm/sec	1.67E-05	mm/msec
0.001	mm/min	1.67E-05	mm/sec	1.67E-08	mm/msec
0.005	mm/min	8.33E-05	mm/sec	8.33E-08	mm/msec