Invitation for Concrete Fatigue Prediction Competition (body of Email)

Dear Madam/Sir,

You are invited to participate in a competition to predict the compressive fatigue capacity and behavior of plain and reinforced concrete cylinders. The conduct of this competition is supported by a project funded by the U.S. Department of Energy to assess and improve concrete compression fatigue models. The project is led by Tufts University, and the project participants and advisors include the University of Illinois, DNV GL, the Leibniz University of Hanover, Olav Olsen, Seatower, Bintong Engineering, and Wind Tower Technologies.

The motivation for this research project and competition are that the design of wind turbine support structures can be controlled by Fatigue Limit State (FLS) considerations, and that the fatigue capacity (number of permissible cycles for a particular stress range) by one model (or code) can vary from another by an order of magnitude. Existing fatigue models have several shortcomings including that they: (i) do not consider the influence of reinforcing steel; (ii) are unnecessary conservatism in many instances; (iii) rely on the use of Palmgren-Miner's Linear Damage Accumulation Rule and thereby do not consider the effect of order of stressing from variable amplitude stressing; (iv) do not take advantage of new measures for calculating damage accumulation; and (v) do not distinguish between different types of concrete materials. Your participation in this competition would be greatly appreciated, and it will help assess the maturity of our design models and identify where additional work is needed. As with most such competitions, the names of participants will not be associated with their specific predictions. Those whose predictions are closest to what was measured will be asked if they wish to have their names associated with their predictions.

The attached "Competition Invitation" contains the following:
Section 1: Description of the Testing Program
Section 2: Requested Information from Participants
Section 3: Provided Information on Strength and Fatigue Response of Test Cylinders

The other attached documents are:

1. An introduction to fatigue behavior and summary of common fatigue models
2. Two papers that have been published on work completed to date in this project

The due date for submissions is 8 June 2022. You are welcome to only participate in any subset of the elements of the competition, and you are encouraged to forward this invitation to anyone else that you think may be interested in submitting a prediction or following the results of the competition. The results from the competition will start to be released after a subset of test results is available; results are expected to be shared later in June and extend into July. It is not possible to be more precise about when results from all of the testing will be available because the number of cycles to failure for each test (and thereby the time needed to complete each test) is uncertain, and also because the number of repeat tests that will be needed to understand the variability in results is also uncertain; it is expected that we will complete about 7 tests for each case (a specific stress range, type of concrete, and longitudinal reinforcement condition).

This information is also provided on the website that has been created for this competition. This website provides a spot for responding to frequently asked questions. You are welcome to reach out to me directly with your questions and suggestions.

Invitation for Concrete Fatigue Prediction Competition (Attachment to Email)

1. Introduction

Three types of experiments will be conducted on test cylinders that are 4 inches (101.6 mm) in diameter and 8 inches (203.2 mm) in height. These are:

(i) Constant Amplitude Tests (CAT) on Reinforced Concrete (RC);

(ii) Constant Amplitude Tests (CAT) on Saturated Plain Concrete (PC);

(iii) Variable Amplitude Tests (VAT) on Plain Concrete (PC).

- CAT refers to the use of only one stress range (combination of Smax and Smin) over the duration of fatigue testing. For example, an Smax/Smin of 0.80/0.10 would mean that the maximum applied stress (or peak stress) in each loading cycle is 80% of the monotonic strength of the concrete (fcmono), and the minimum applied stress in each loading cycle is 0.10 of fcmono.
- VAT refers to more than one stress range being used over the duration of the fatigue testing. For example, a VAT could consist of the first stage of loading with an Smax/Smin of 0.80/0.10 for a set number of cycles or until a certain condition is reached, and this followed in stage 2 with a Smax/Smin of 0.70/0.05 on the same specimen until failure in fatigue.
- RC refer to cylinders with longitudinal reinforcement. All RC specimens have 4 #3 bars which are 0.375 inches (9.52 mm) in diameter. The corresponding reinforcement ratio is 0.035.

This competition will explore several questions, including:

1. How does the load share change between concrete and longitudinal reinforcement change over loading history, and how does this affect fatigue capacity?
2. What are the positive and negative effects of using longitudinal reinforcement?
3. Is Palmgren-Miners Linear Damage Accumulation Model suitable for calculating fatigue capacity utilization? For example, if higher stress levels occur earlier in the loading history, does this lead to a lower overall fatigue capacity in comparison to if these higher stresses occurred later in the loading history?
4. What is the typical variability in fatigue capacity (# cycles to failure for each stress range), and how is this affected by the presence of reinforcement?
5. Over what length of the test specimen is damage usually distributed?
6. Can the remaining fatigue capacity be estimated by inspecting for visual damage or by strain measurements?

2. Competition Testing

This section presents the necessary information on the testing plan, and what information is requested by those who wish to participate in the competition. You are welcome to submit answers to any subset of questions that you wish (i.e. you don’t have to participate in all elements to participate). Section 3 of this document provides results from monotonic and Constant Amplified Tests (CATS) that are relevant for this competition.

The competition consists of three types of tests.

1. Constant Amplitude Tests (CATs) on Reinforcement Concrete (RC)
2. Constant Amplitude Tests (CATs) on Plain Saturated Concrete (PC)
3. Variable Amplitude Tests (VATs) on Plain Concrete (PC)

2.1 Constant Amplitude Tests (CATs) on Reinforced Concrete (RC)

The value of Smax = 0.80 and Smin = 0.05 in these tests, and the loading frequency is 1 Hz.
In these tests on Reinforced Concrete (RC), the load associated with a particular Smax level is equal to Smax x (Pmax), and for Smin is Smin x (Pmax), in which the Pmax stands for maximum monotonic strength of the RC specimen. The predictions being asked of participants in this competition are to be provided in the provided spreadsheet, and they are presented below in Figure 1.

The first of the three parts for the requested predictions are the Number of Cycles to Failure (Nf). At least 7 tests will be conducted to obtain the measured number of cycles to failure. Participants are asked to estimate the Minimum, Average, and Maximum of the measured number of cycles to failure. Tests which were observed to fail prematurely due to a boundary condition failures or other obvious reason for disqualification will not be included. The average strain at failure for the last time that the peak load was sustained is also asked to be predicted.

The second of the three requested predictions are for the strain and the portion through the testing that there was the first visible damage. This is to the average for all tests in this series that were not disqualified, and an example is provided in Figure 1 below the requested information.

The third request information is for the portion of the peak load and valley load taken by the concrete at four different points through the loading history. Those points are 10 cycles into the loading, at 10% of the total number of cycles of loading at failure (Nf) through the loading history, at 50% of Nf, and at 10 cycles before Nf.

1. Constant Amplitude Tests (CATs) on Reinforced Concrete (RC)

Smax (ratio)	Smin (ratio)	Freq (Hz)	Reinforcement	Number of Cycles to Failure (Nf)			Strain at Failure
				Minimum	Average	Maximum	
0.8	0.05	1	4 #3 bars				

Notes: Minimum is the lowest number of cycles to failure (Nf) from all legitimate test results
Average is the mean number of cycles to failure (Nf) from all legitimate test results
Maximum is the largest number of cycles to failure (Nf) from all legitimate test results
Legitimate tests are all of those that did not fail due to a boundary condition or similar reason; a much lower or higher than average number of cycles to failure is not a reason for disqualifying the test result

	Average
Ratio of (Number of Cycles to First Visible Damage, Nv) /(Number of Cycles to Failure, Nf)	
Strain at which the first visible damage shows up	

An entry of 0.60 would suggest that visible first visible damage occurs at 60% of the measured Nf
e.g. If Nf turns out to be 12312, then an entry of 0.60 would predict that first visible damage at 0.6(12518) = 7511 cycles

	Cycle Number (Values in Green Cells are Averages)			
	Ni = 10 cycles	Ni/Nf = 0.1	Ni/Nf = 0.5	Ni = Nf - 10
Portion of Peak Load Taken by Concrete				
Portion of Valley Load Taken by Concrete				

Ni = Number of Cycles
An entry of 0.85 would imply that 85% of the loading is taken by the concrete
The "Portion of Load" will be calcluated as (Load - Asfs)/(Load) where fs is calculated from the measured strain over the height of the cylinder and the fs-εs relationship that was presented in Figure 2 of the competition description.

Figure 1: Description of CATs on RC with Requested Predictions

2.2 Constant Amplitude Tests (CATs) on Saturated Plain Concrete (PC)

The value of Smax = 0.80 and Smin = 0.05 in these tests, and the loading frequency is 1 Hz, which is the same as for the CATs on RC. The requested information from participants is the same as in the first part for CATs on RC, predictions should be provided in the attached spreadsheet, and these are described in Figure 2.

2. Constant Amplitude Tests (CATs) on Saturated Plain Concrete (PC)					
Smax	Smin	Freq	Number of Cycles to Failure (Nf)		
(ratio)	(ratio)	(Hz)	Minimum	Average	Maximum
0.8	0.05	1			

Figure 2: Description of CATs on Saturated Plain Concrete (PC) and Requested Predictions

2.3 Variable Amplitude Tests (VATs) on Plain Concrete (PC)

The loading plan is described in 错误!未找到引用源。 1.

- Test 1d is a test in which the higher stress ratios are applied first (Stage 1) where Smax/Smin = 0.80/0.05. This is followed in Stage 2 where Smax/Smin = 0.70/0.05. The transition from Stage 1 to Stage 2 loading is made at the cycle in which the peak strain (εmax) is equal to about 1.2 x ε′c = 1.2 x 0.0027 = 0.0032. The “d” implies a decreasing magnitude in the maximum applied stress from Stage 1 to Stage 2.
- Test 1i is a test in which the lower stress ratios are applied first (Stage 1) where Smax/Smin = 0.70/0.05. This is followed in Stage 2 where Smax/Smin = 0.80/0.05. The transition from Stage 1 to Stage 2 loading is made at the same number of cycles of loading as Stage 2 of Test 1d. The “i” implies an increasing magnitude in the maximum applied stress from Stage 1 to Stage 2.
- Tests 2d and 2i are the same as 1d and 1i but that the transition from Stage 1 to Stage 2 in 2d is made when the peak strain (εmax) is equal to about 0.75 x ε′c = 0.75 x 0.0027 = 0.0020.

Table 1 Plan for Variable Amplitude Tests (VATs) on Plain Concrete (PC)

		Stage 1				Stage 2		
Case	Freq. (Hz)	Smax	Smin	εmax	N_εmax	Smax	Smin	N_to failure
1d	1	0.80	0.05	≈1.2ε'c	*N1d*	0.70	0.05	*N1*
1i	1	0.70	0.05		N1	0.80	0.05	
2d	1	0.80	0.05	≈0.75ε'c	*N2d*	0.70	0.05	*N2*
2i	1	0.70	0.05		N2	0.80	0.05	

The requested predictions from participants in described in Figure 3.

3. Variable Amplitude Tests (VATs) on Plain Concrete (PC)								
Load Case & Frequency		**Stage 1**				**Stage 2**		
Case	Freq. (Hz)	Smax	Smin	εmax	# Cycles Average	Smax	Smin	# Cycles Average
1d	1	0.8	0.05	≈1.2ε'c		0.7	0.05	
1i	1	0.7	0.05		same as right entry of row above	0.8	0.05	
2d	1	0.8	0.05	≈0.75ε'c		0.7	0.05	
2i	1	0.7	0.05		same as right entry of row above	0.8	0.05	

Figure 3: Description of VATs on PC with Requested Predictions

An example is not used to illustrate the predictions being requested, suppose that you estimate that the fatigue capacity (Nf) for an Smax/Smin case of 0.80/0.05 is equal to 3000 and that the compressive strain at failure is 0.005. You would thereby expect for Case 1d that the number of cycles at which the strain reached 1.2ε′c = 1.2 (0.0027) = 0.0032 is some portion of 3000, let's say 2000 for instance. In this case, the first entry in the top row of the table in Figure 3 would be 2000. Next, let suppose that you estimate that the fatigue capacity (Nf) for an Smax/Smin of 0.70/0.05 is 100000. Since a significant portion of the fatigue capacity was used up in Stage 1 of Case 1d, you may predict that the remaining number of cycles to failure is somewhat less than this, say 40000.

3. Monotonic Response of Concrete and Results from CATs on Plain Concrete

This average monotonic compressive strength (fcmono) of the concrete was measured to be 6000 psi at 55 days after it was cast in July of 2021, as shown in Figure 4. A new set of monotonic tests will be taken at the start of the testing for the competition to update the value for fcmono. The associated strain at peak stress was measured to be 0.0027.

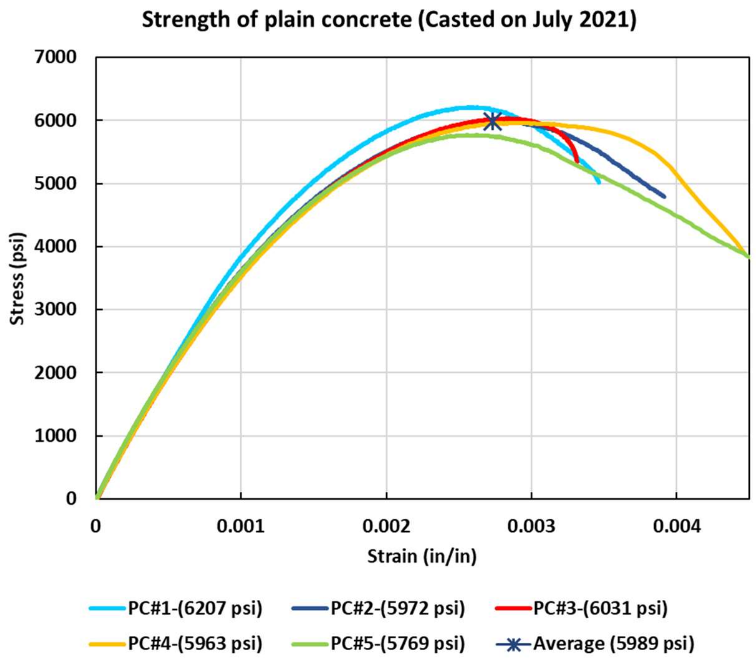


Figure 4 Plain concrete cylinders stress-strain response to monotonic test (at the age of 55 days)

The stress-strain response of the reinforcing steel is given in Figure 5. The average yield strength was measured to be 64 ksi (441 MPa).

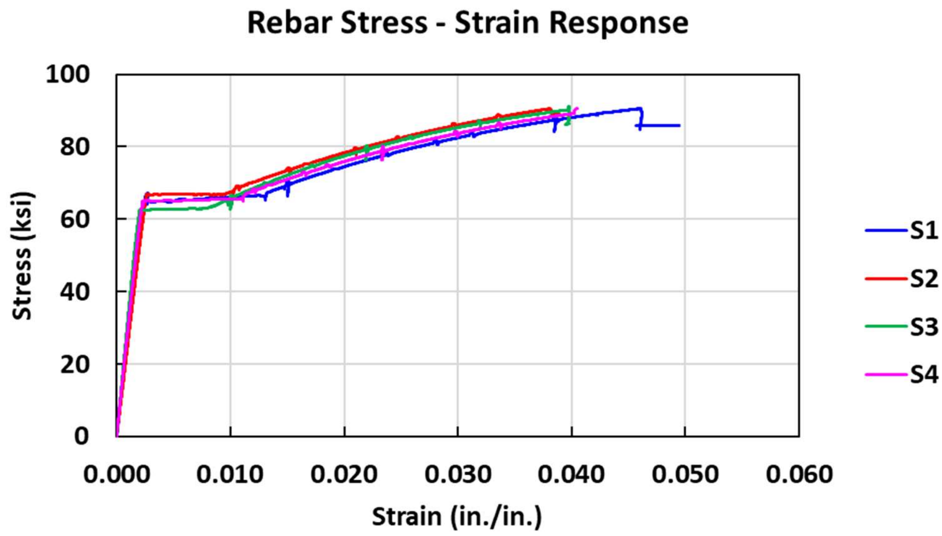


Figure 5 Steel rebar stress-strain response to monotonic test

The measured Number of Cycles to failure, Nf, from the Constant Amplitude Tests (CATs) on Plain Concrete (PC) from this casting are given in Table 2 and Figure 6. There are four test results for both the loading case of a Smax/Sim of 0.80/0.05 and an Smax/Smin of 0.70/0.05.

Table 1 Constant Amplitude Tests to Generate Base Information for Predictions

Name	Maximum stress ratio with respect to f'c; Smax (ratio)	Minimum stress ratio with respect to f'c; Smin (ratio	Loading frequency; Freq (Hz)	Number of cycles to failure; Nf
PC-CAT#1-F1-80-5	0.80	0.05	1	2,860
PC-CAT#2-F1-80-5	0.80	0.05	1	4,790
PC-CAT#3-F1-80-5	0.80	0.05	1	2,875
PC-CAT#4-F1-80-5	0.80	0.05	1	2,529
PC-CAT#1-F1-70-5	0.70	0.05	1	86,220
PC-CAT#2-F1-70-5	0.70	0.05	1	129,355
PC-CAT#3-F1-70-5	0.70	0.05	1	163,164
PC-CAT#4-F1-70-5	0.70	0.05	1	48,232

Naming guide: Plain Concrete (PC) – Constant amplitude test number 1 (CAT#1) – Frequency of loading (Hz) # (F1) – Smax percent % (80) - Smin percent % (5)

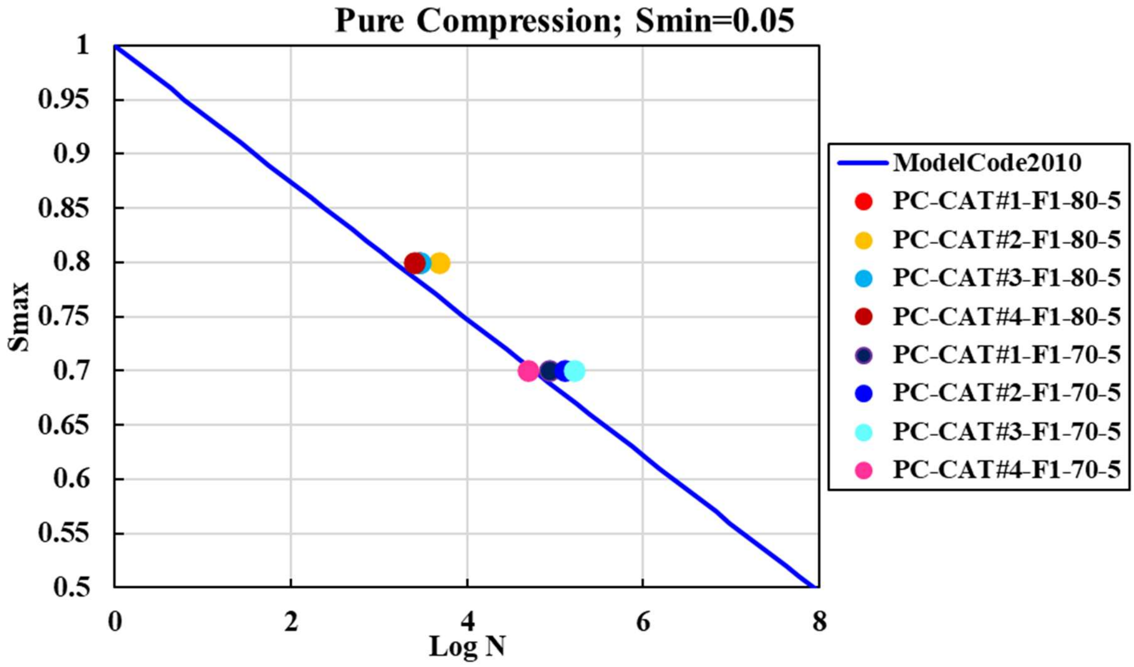
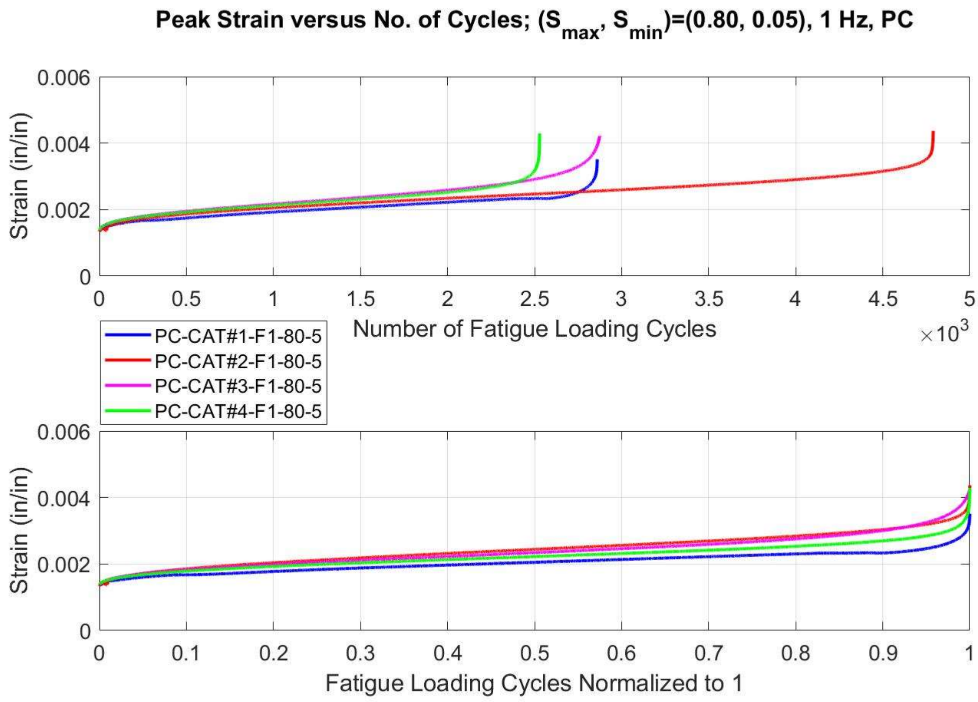


Figure 6 CAT test results on plain concrete

In fatigue testing, it is common to measure and plot the progression of strain at peak stress (Smax) and valley stress (Smin) as a function of the number of loading cycles as well as the normalized number of cycles to number of cycles to failure. This is presented in Figure 7 for when Smax/Smin = 0.80/0.05, and in Figure 8 for when Smax/Smin = 0.70/0.05.

(a)



(b)

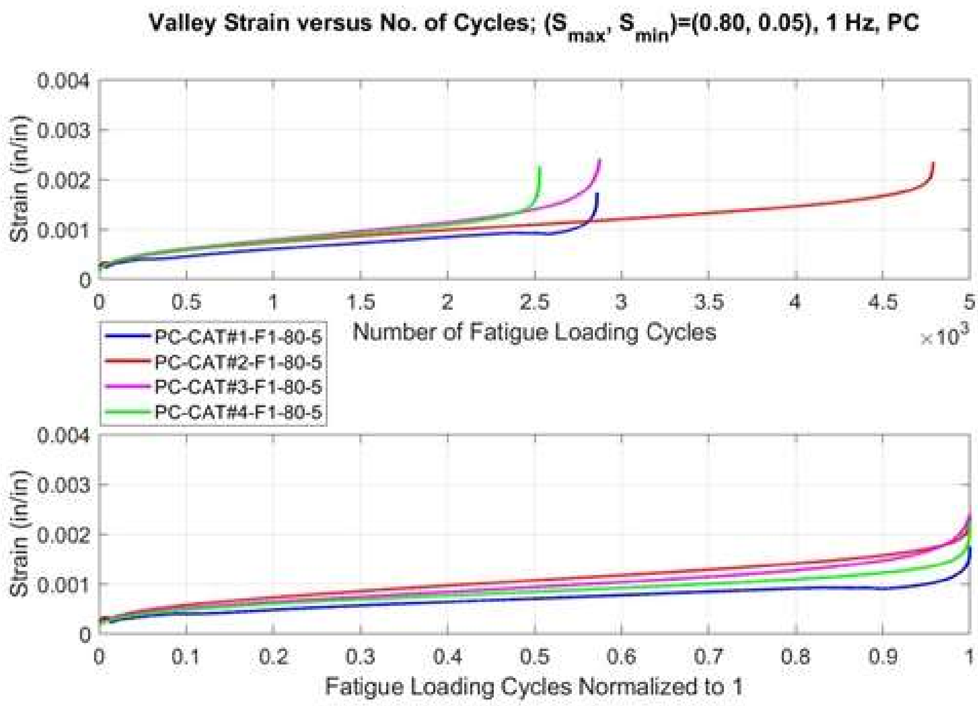
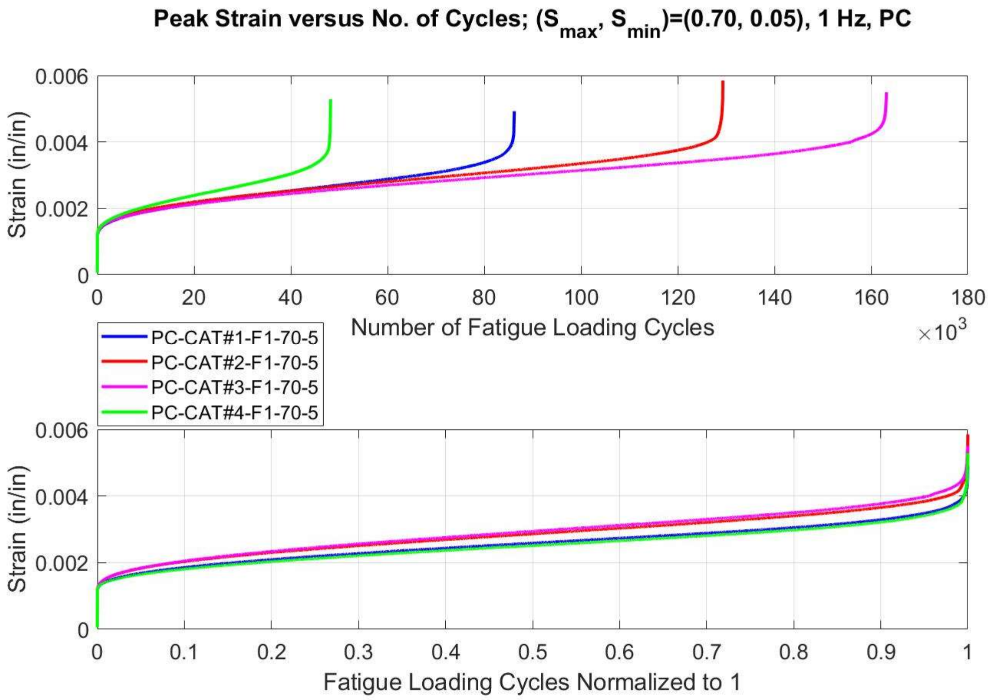


Figure 7 Strain Evolution Plot for plain concrete CAT with (Smax, Smin)=(0.80, 0.05)
a) Peak; b) Valley

(a)



(b)

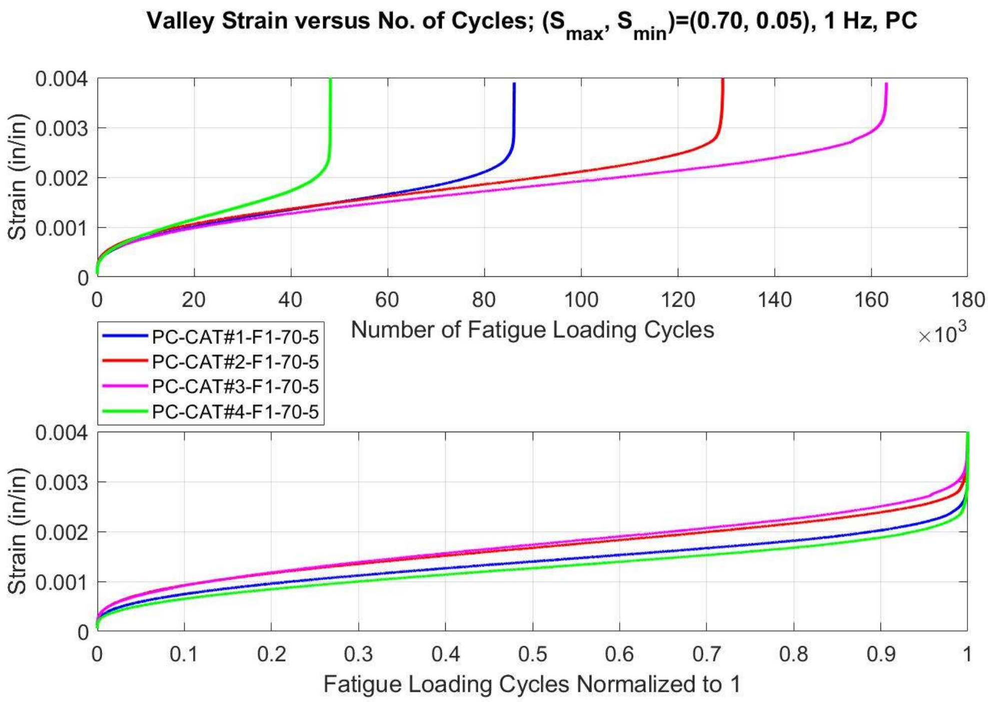


Figure 8 Strain Evolution Plot for plain concrete CAT with (Smax, Smin)=(0.70, 0.05)

b) Peak; b) Valley

The axial strain that is presented in all plots and that will be recorded in the experiments are the average straining over the central 6 inch (152.4 mm) of the height of the cylinder that was measured by two Epsilon clips on gauges. Figure 9 slows the location of one of these gauges and then other is on the opposite size of the test cylinder.

Figure 9 Epsilon axial extensometer