Experimental Study of Structural Concrete's Fatigue Capacity

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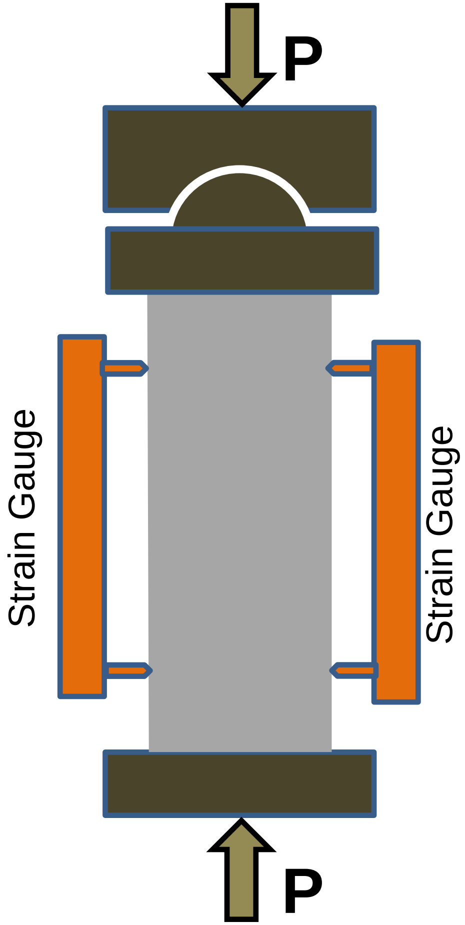

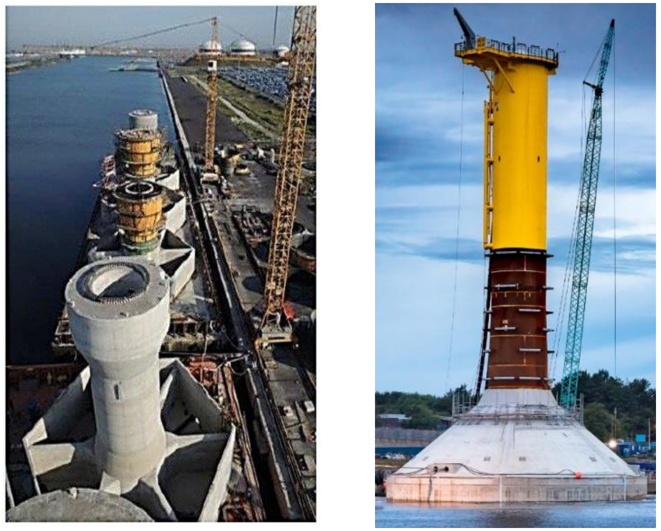

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Outlines:

- Introduction of the project
- Introduction to our team
- Use of concrete in offshore and onshore wind turbine structures and foundations
- Brief introduction of fatigue testing / loading
- Data base and the variation in results
- Guesstimating f’c and its effect on plain concrete results
- Visual crack / damage due to fatigue
- Effect of saturation and longitudinal reinforcement, loading share issue
- 3D Print concrete
- Conclusions and suggestions for future work

Introduction to the Project:

EFFECT OF FATIGUE ON THE CAPACITY AND PERFORMANCE OF STRUCTURAL CONCRETE

U.S. DEPARTMENT OF
ENERGY
Energy Efficiency &
Renewable Energy

Stated Project Goal

This project’s primary goal is to advance innovation in concrete offshore wind support structures (i.e. towers and foundations) by an experimental study that quantifies the effect of fatigue on the strength, stiffness, and durability of marine concretes, and then uses this data to advance models and standards. Currently, the impact of fatigue on structural concrete in standards is treated the same for all concretes regardless of the type of concrete material, and it neglects the benefits of fibers, bar reinforcements, and other effects. This one fatigue model can be conservative by more than a factor of 10 which leaves existing capacity on the table, and does not support simple design solutions that enable higher fatigue stresses to be tolerated. This is a major barrier to the competitiveness of concrete solutions. The new data, models, and standards that this project can deliver will give designers and developers the tools they need to drive innovation, reduce costs, and produce more resilient concrete Offshore Wind Support Structures (OWSS).

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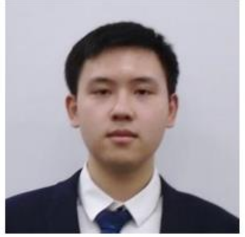
Our Team

Tufts University


Dan Kuchma


Mohsen Minaeijavid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International Concrete Federation (*fib*) Activity Group on Non-Static Loading (Fatigue): Tamon Ueda, Chikako Fujyama, Gyorgy Balasz, Steffen Marx, Carlos Zanuy Sánchez, Morten Anderson, Nadja Oneschkow, Dan Kuchma

Selected Concrete Support Structures for Wind Turbines

Onshore wind turbine concrete towers

Offshore wind turbine concrete fixed base foundations

Offshore wind turbine floating foundations

Concrete anchors for floating Offshore wind turbines

Other possible use of concrete in offshore wind turbine structures

- Concrete has been used in several wind farms to build the ice cones as well as the work platforms of the support structures
- Concrete grout is commonly used to join transition pieces and monopiles.
- Concrete has been used in a similar manner at the interface between monopiles installed by drilling and the surrounding rock, for instance in the offshore wind farm Bockstigen. (Mathern et al., 2021)

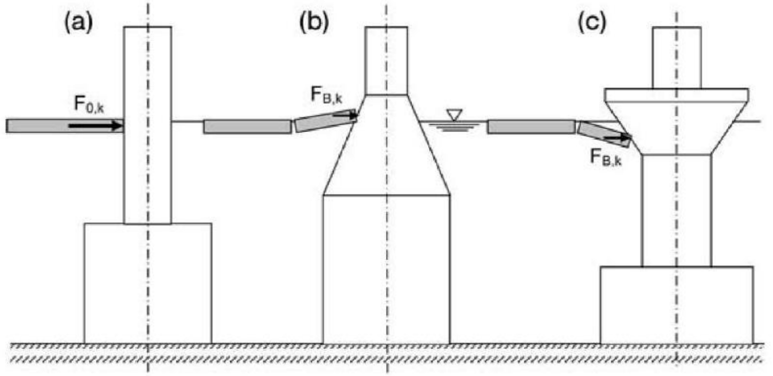
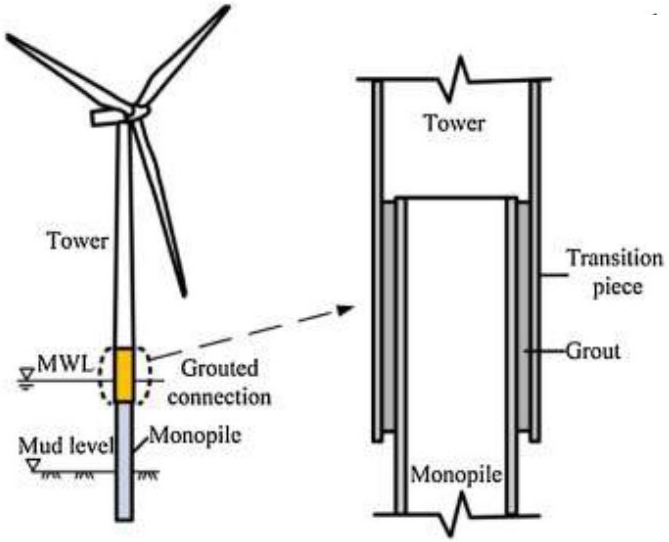
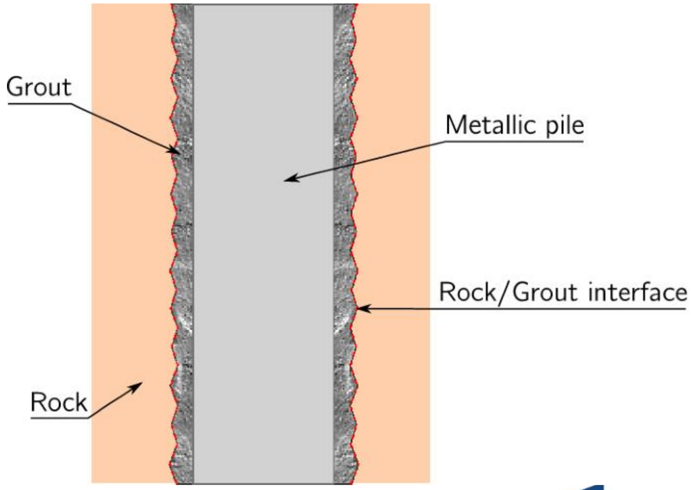
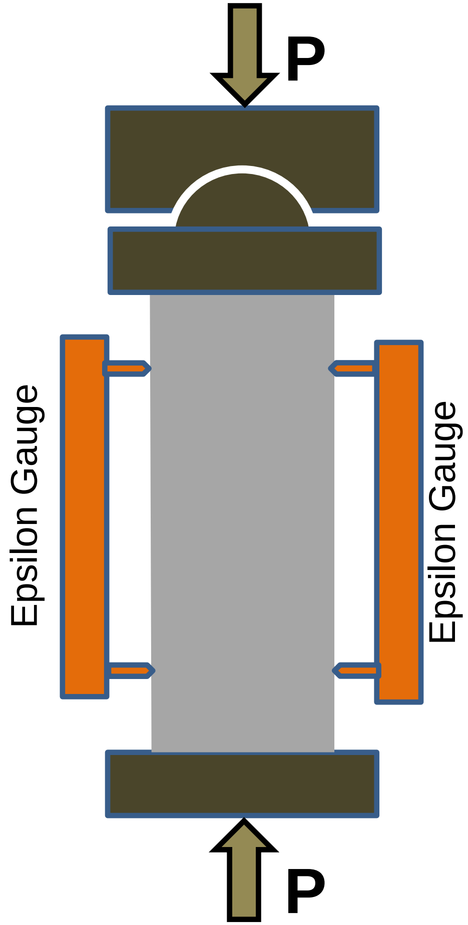


Fig. 2.51 Ice load scenarios for offshore structures: a) vertical surface, b) ice cone, c) inverted ice cone





Response of concrete material to static and cyclic loading



f'c = strength of concrete

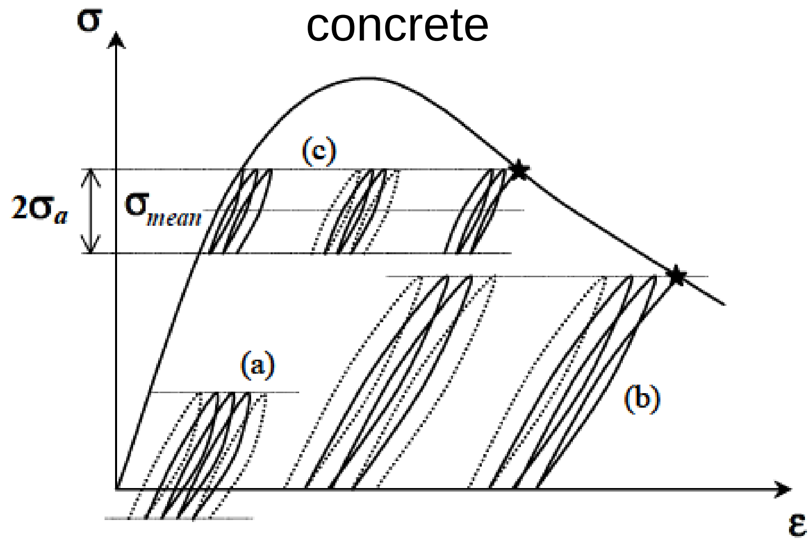


Figure 5.2. *Behavior of concrete under cyclic loading: a) alternate loading; b) repeated loading; c) undulated loading*

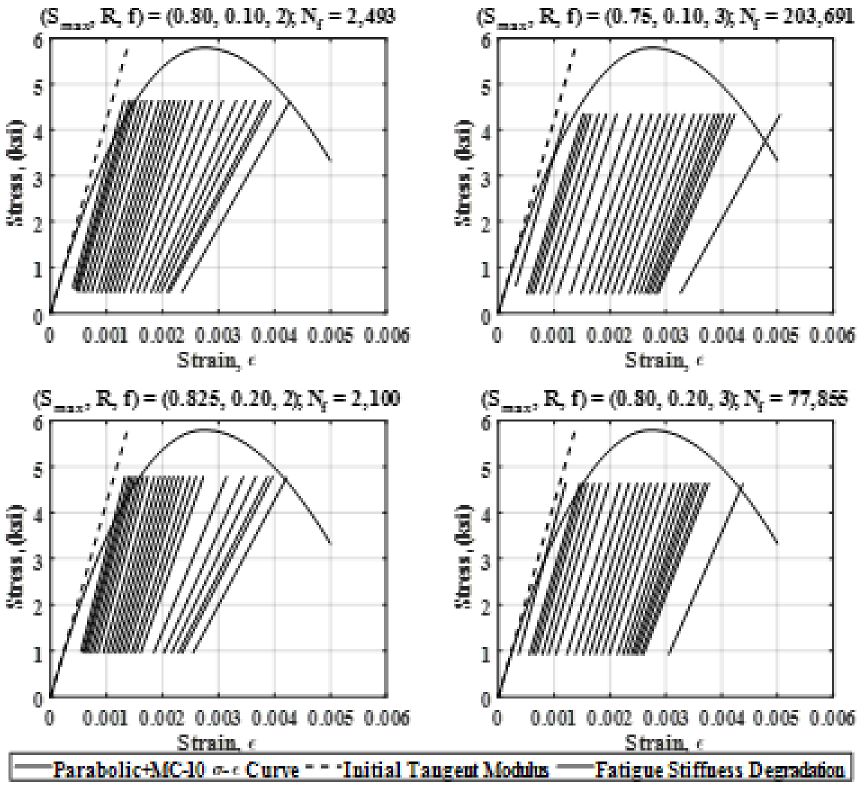
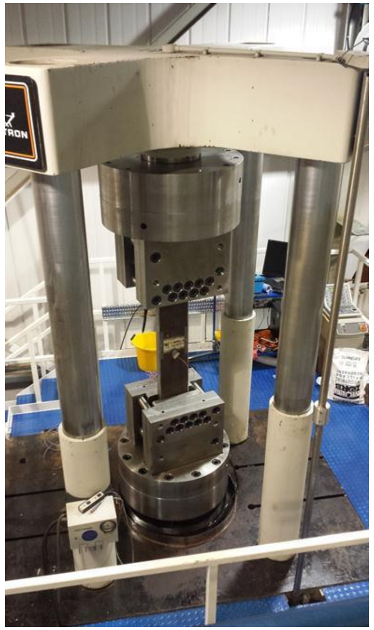
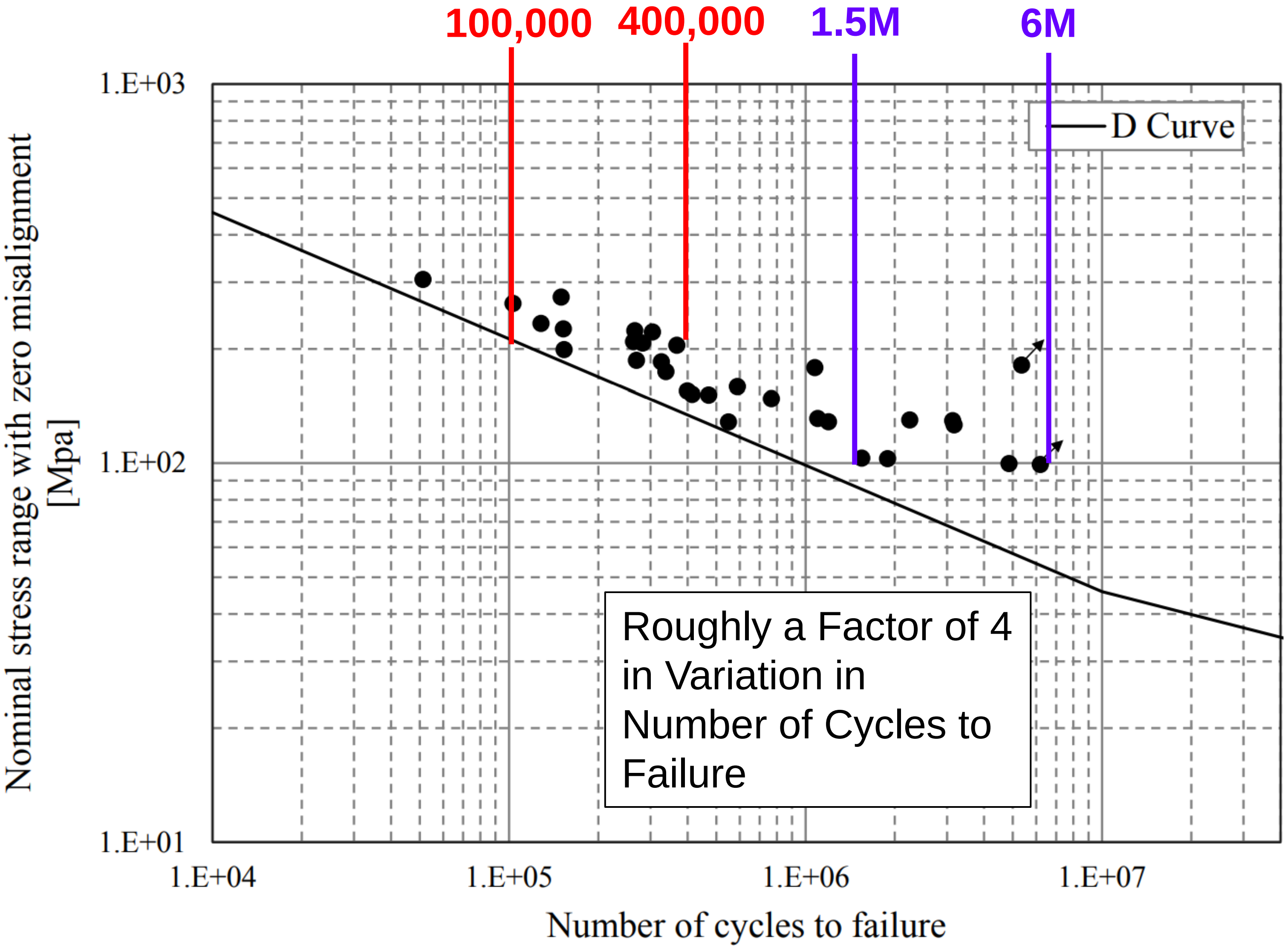


Figure 12: Secant stiffness degradation under fatigue loading for different (S_{max}, R, f) combinations, along with relationship of stiffness degradation to failure (1ksi = 6.89 MPa)

(Viswanath et al., 2021)

Results from Fatigue Testing of Steel



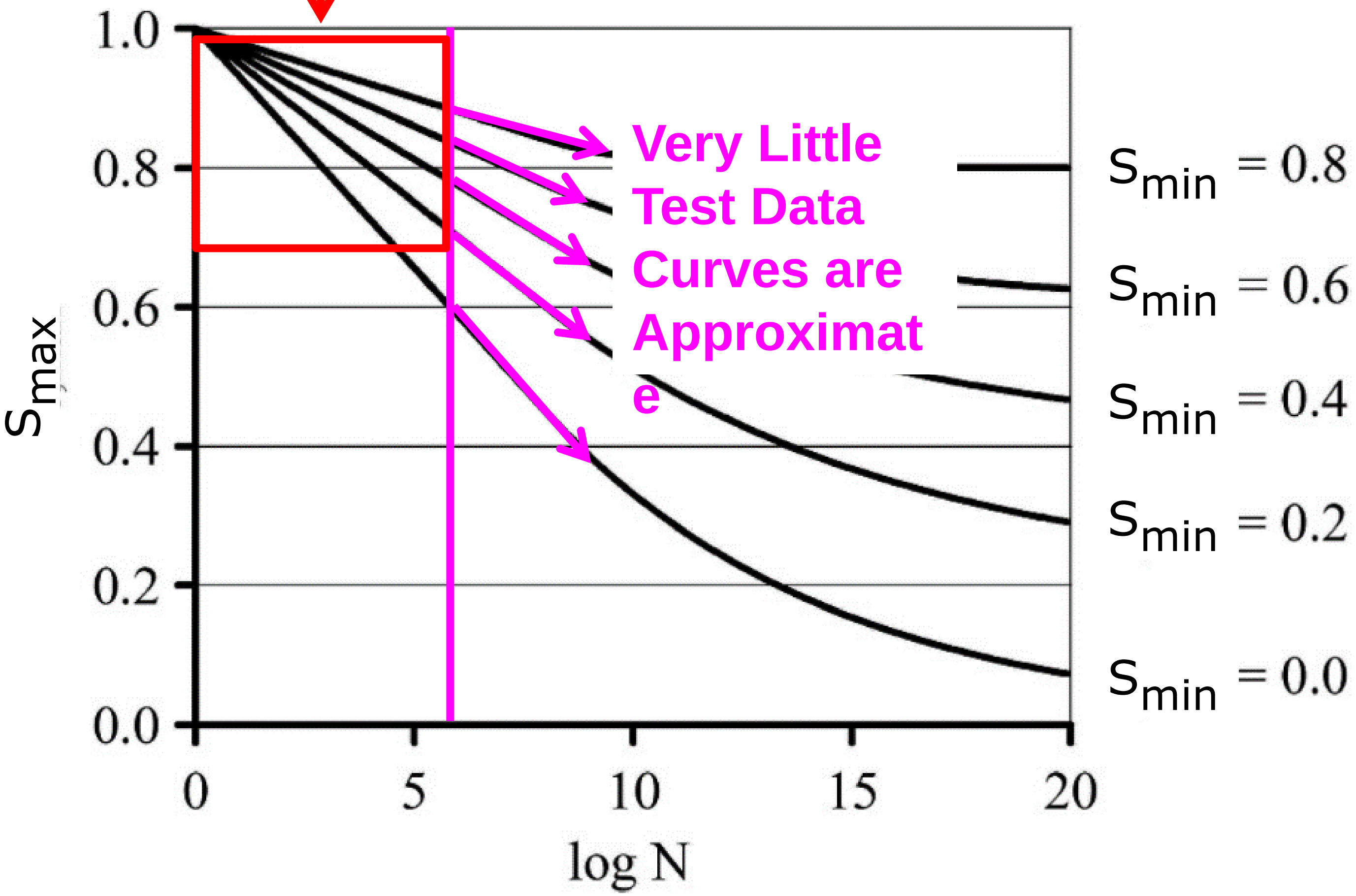


Roughly a Factor of 4 in Variation in Number of Cycles to Failure

Figure 6: SLIC 2 (As welded) test results with zero-misalignment versus thickness-corrected D Curve showing the two suspended tests as failure points

Concrete Fatigue (S-N) Models (Model Code 2010)

Nearly All Test Data



Very Little Test Data Curves are Approximat e

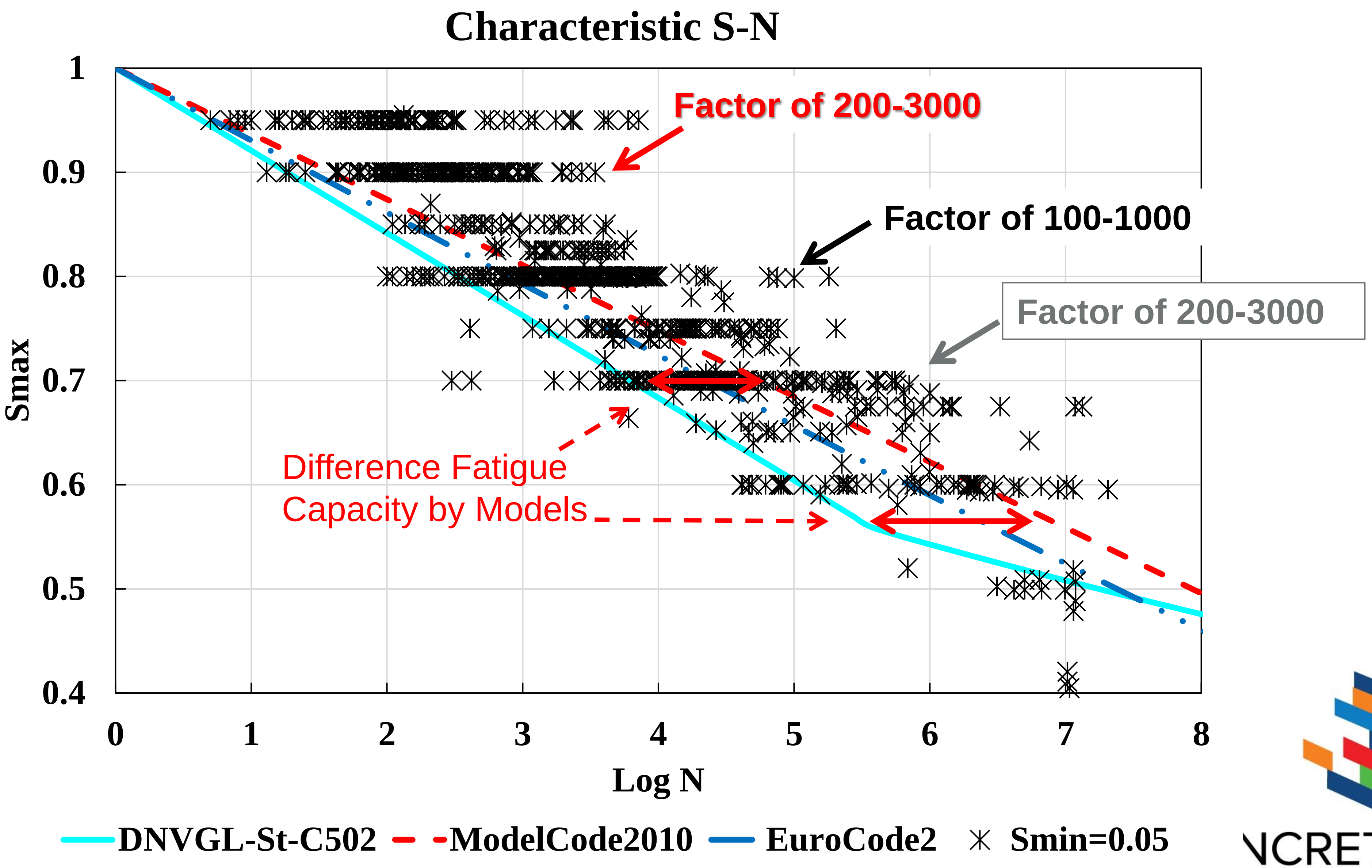
fib Model Code Fatigue Curves

$$S_{max} = \frac{\text{(Max. Applied Stress in Cycle)}}{\text{(Monotonic Stress Capacity)}}$$

$$S_{min} = \frac{\text{(Min. Applied Stress in Cycle)}}{\text{(Monotonic Stress Capacity)}}$$

Concrete Fatigue (S-N) Models and Data Base

Smax=
σmax/strength



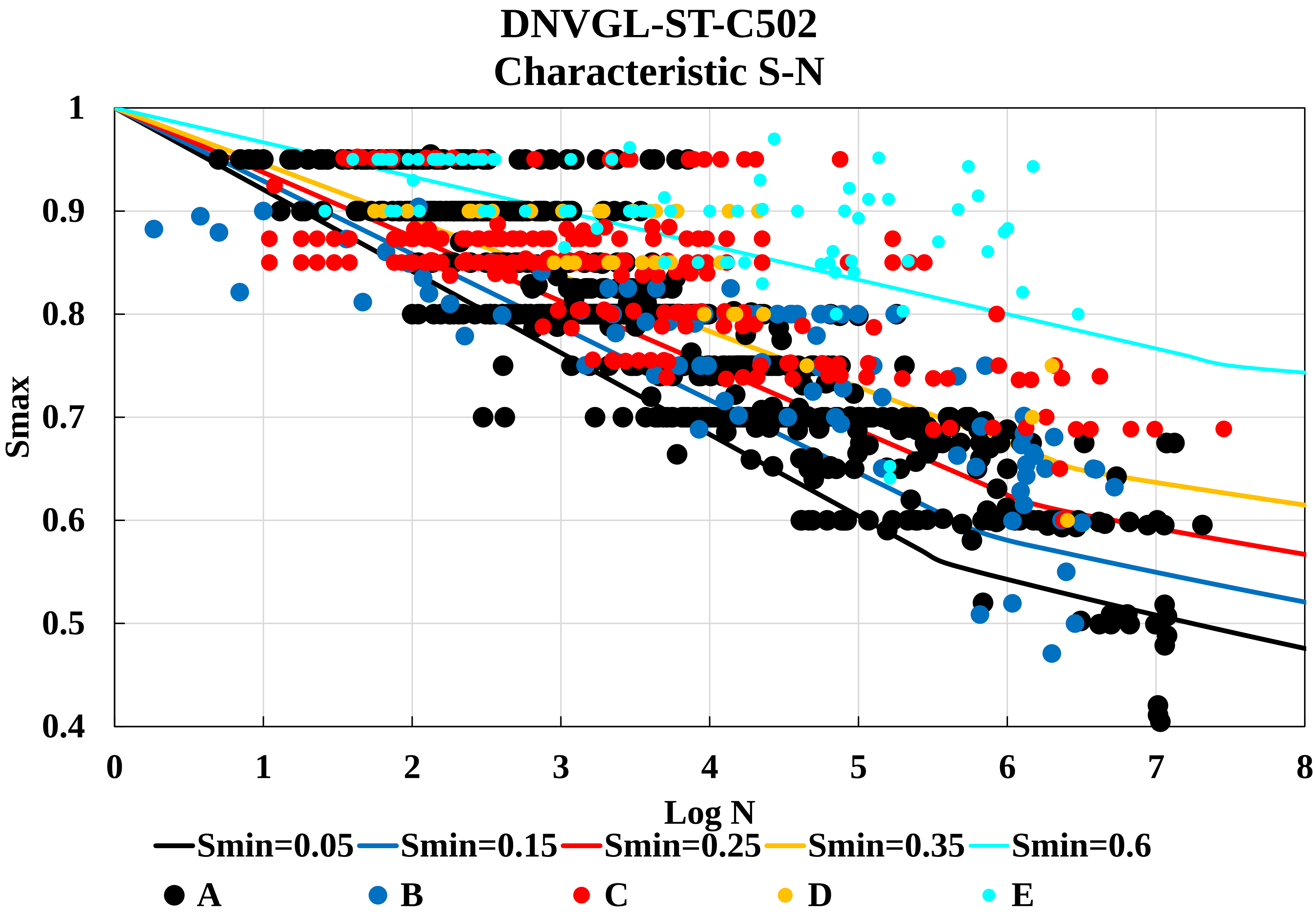
Factor of 200-3000

Factor of 100-1000

Factor of 200-3000

Difference Fatigue Capacity by Models

Concrete Fatigue (S-N) Models and Data Base



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Effect of variation in strength of concrete

Monotonic compressive stress-strain curves

Coefficient of variation = 2%

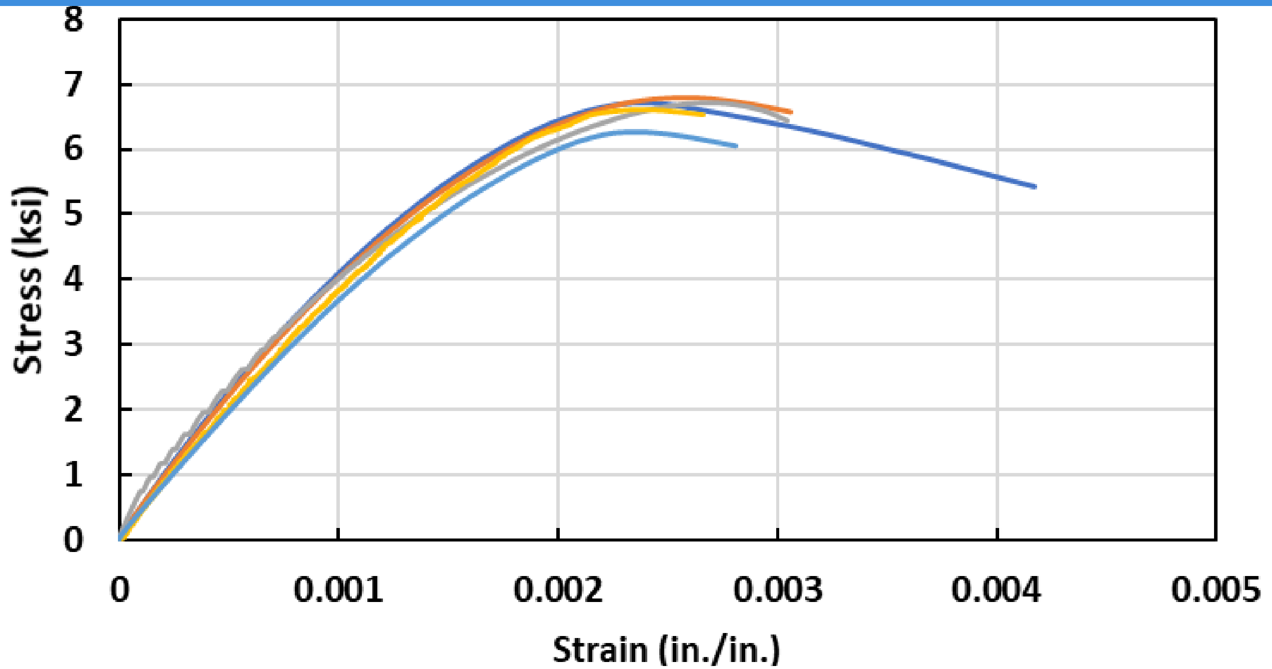
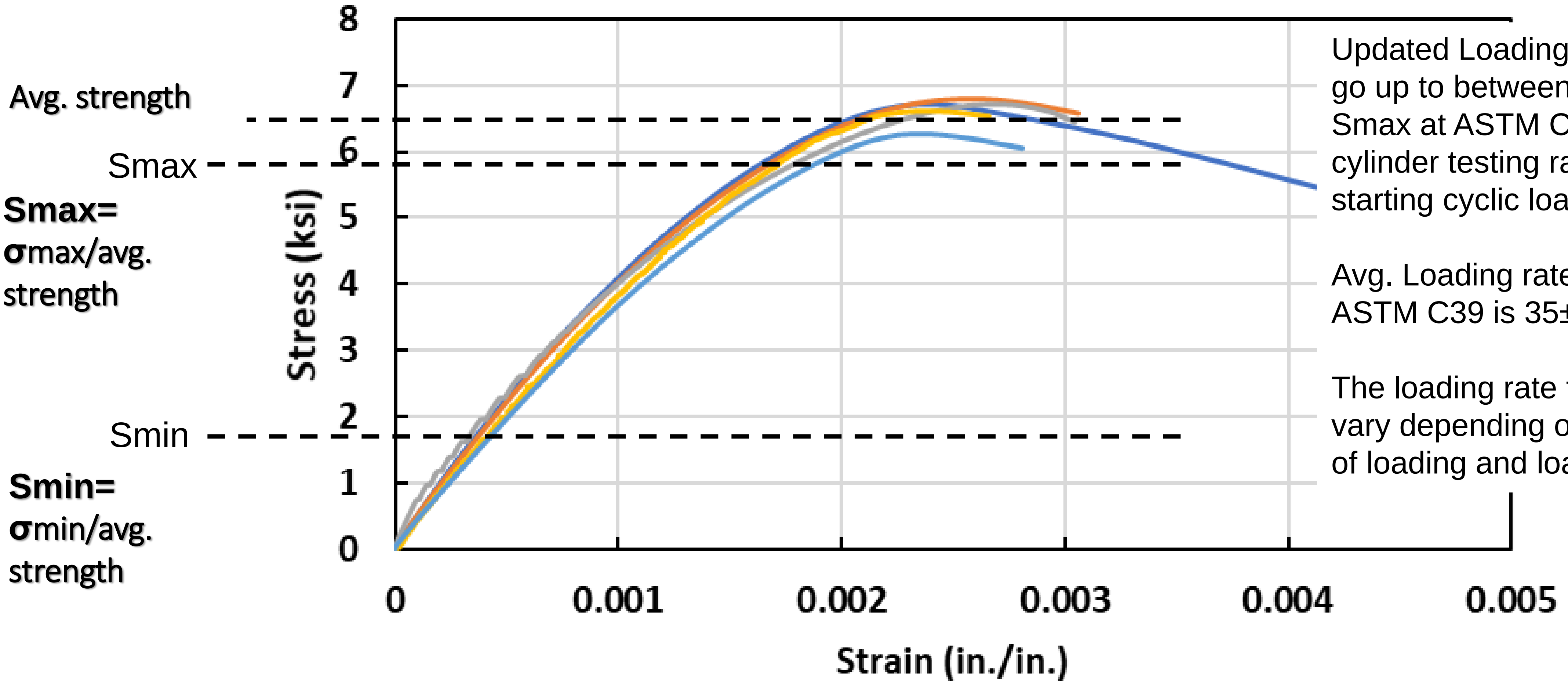


Table 4 change in fatigue capacity of concrete with change in concrete strength

	fcm	Smax	Smin	Y	log Nf	Nf
Example 1	fcm-5% (If fcm 5% lower)	0.84	0.21	0.606	3.25	1,797
	fcm (Planned Smax = 0.80)	0.80	0.20	0.600	4.01	10,208
	fcm+5% (If fcm 5% higher)	0.76	0.19	0.594	4.74	54,996
Example 2	fcm-5% (If fcm 5% lower)	0.63	0.21	0.606	7.53	33,572,059
	fcm (Planned Smax = 0.60)	0.60	0.20	0.600	8.02	104,199,038
	fcm+5% (If fcm 5% higher)	0.57	0.19	0.594	8.51	322,815,611

Effect of variation in strength of concrete

Guesstimating strength of concrete (f’c)



Smax= σmax/avg. strength

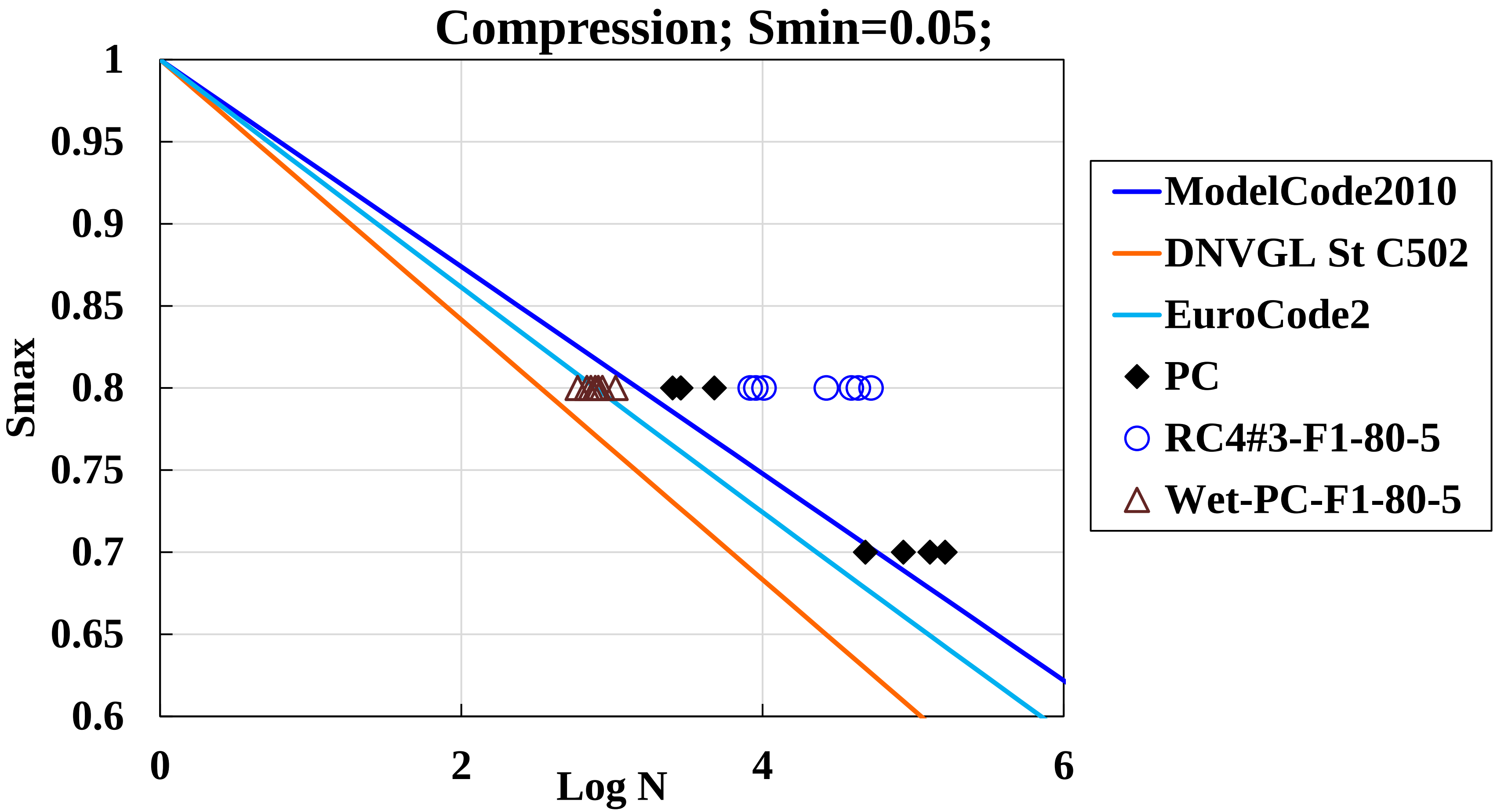
Smin= σmin/avg. strength

Updated Loading Protocol is to go up to between Smean and Smax at ASTM C39 specified cylinder testing rate before starting cyclic loading

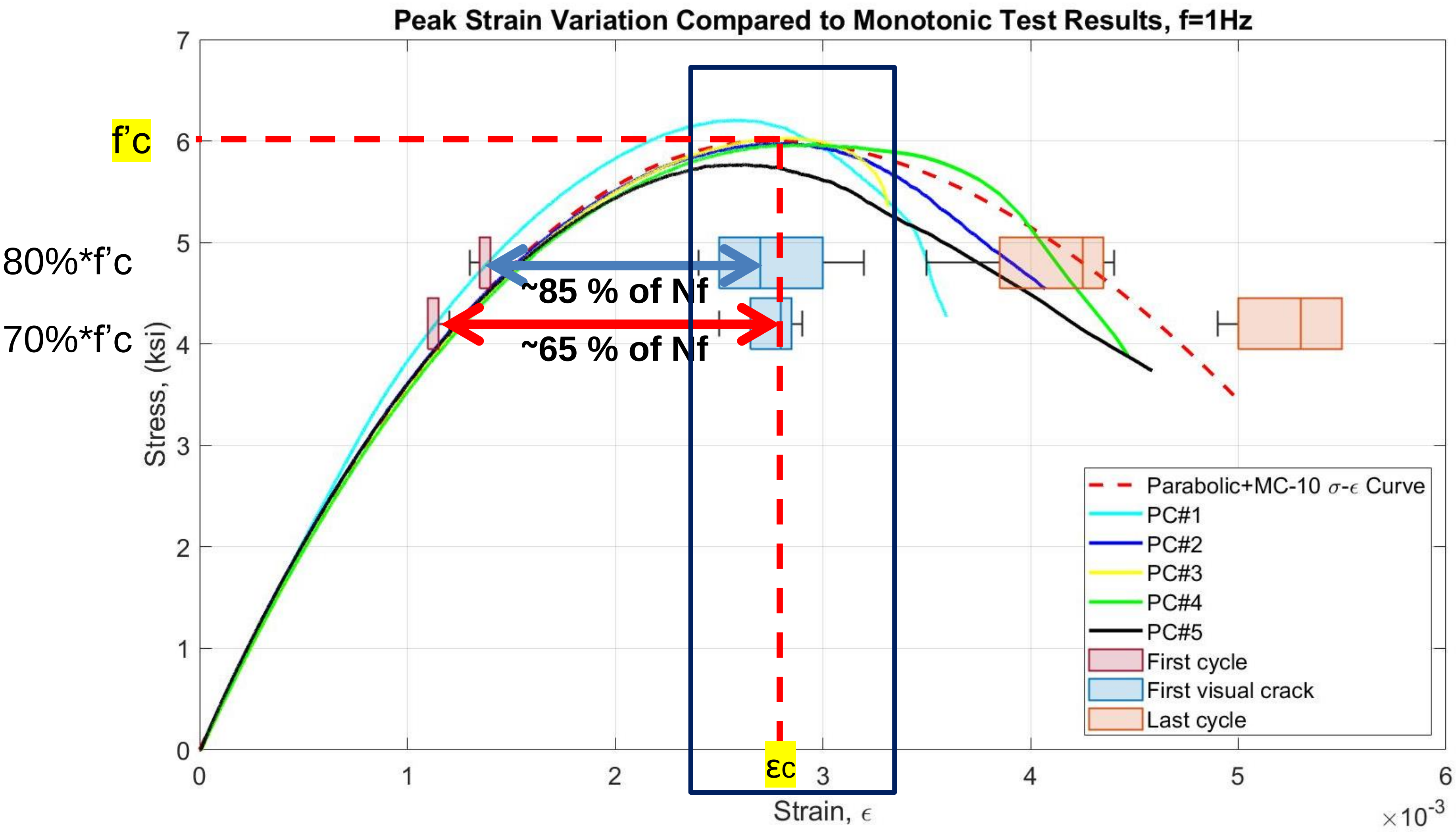
Avg. Loading rate based on ASTM C39 is 35±7 psi/sec

The loading rate for fatigue vary depending on frequency of loading and loading range.

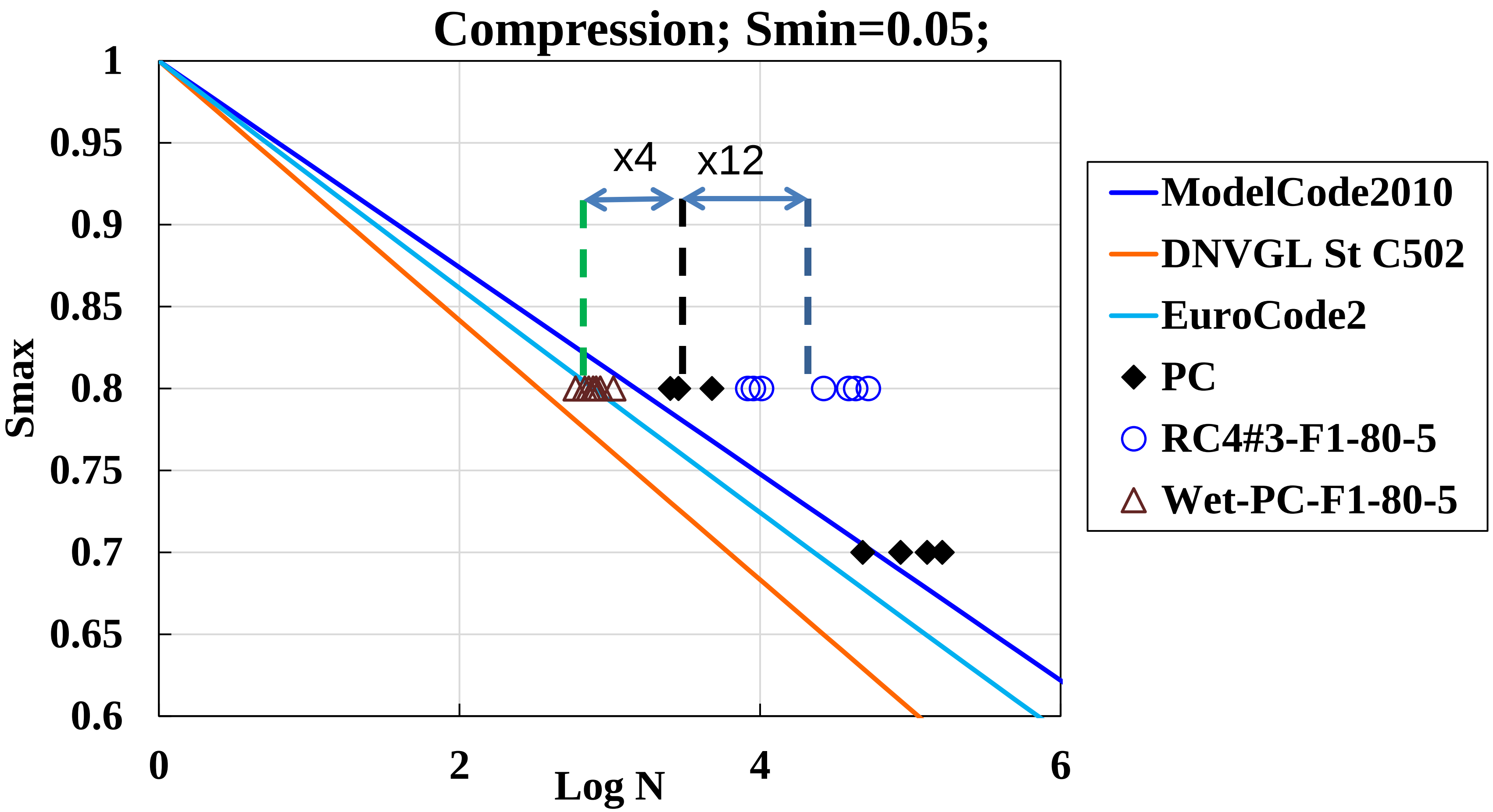
Effect of variation in strength of concrete



Plain concrete testing results (Visual Damage Inspection)



Reinforced and Saturated plain concrete testing results



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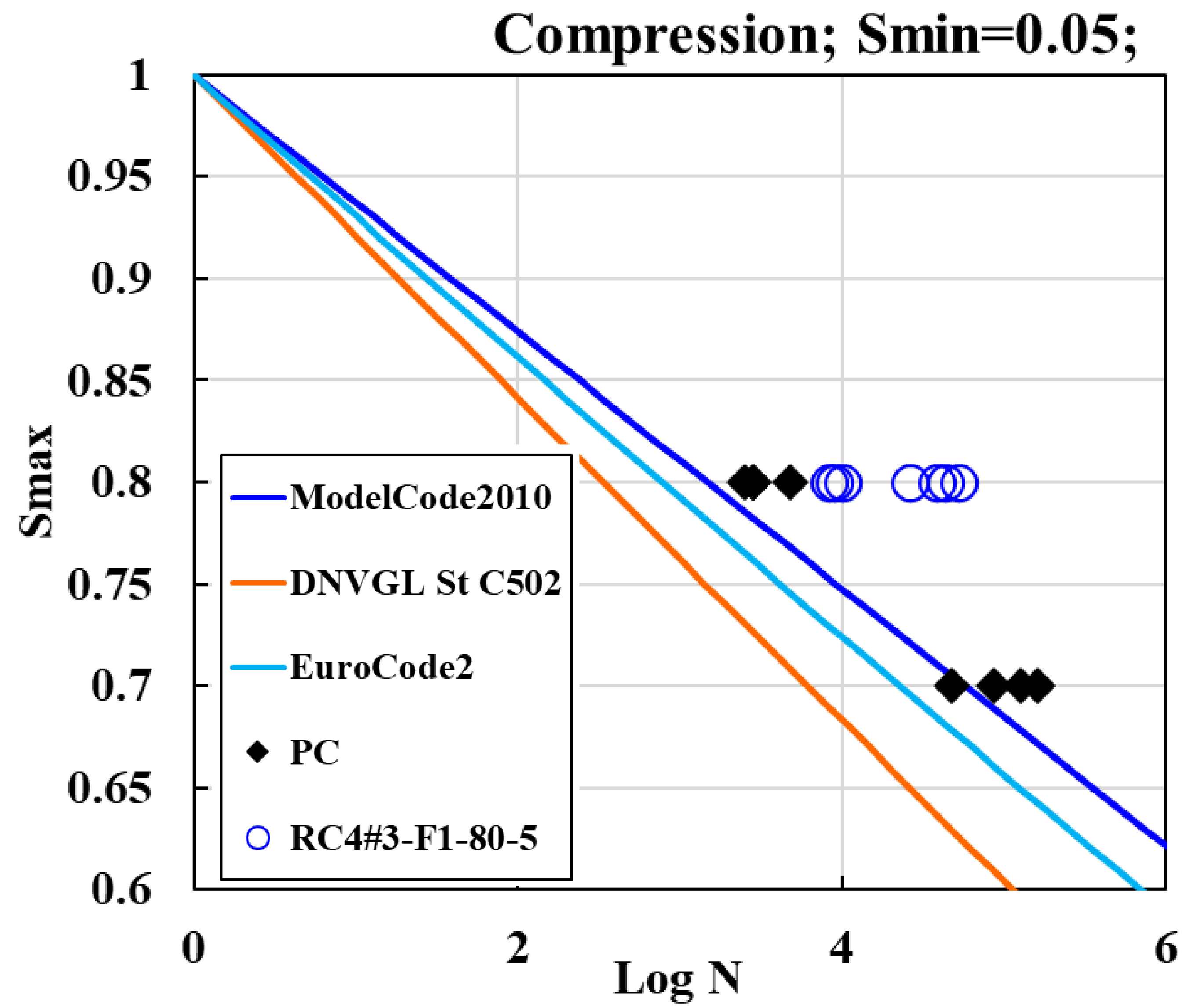
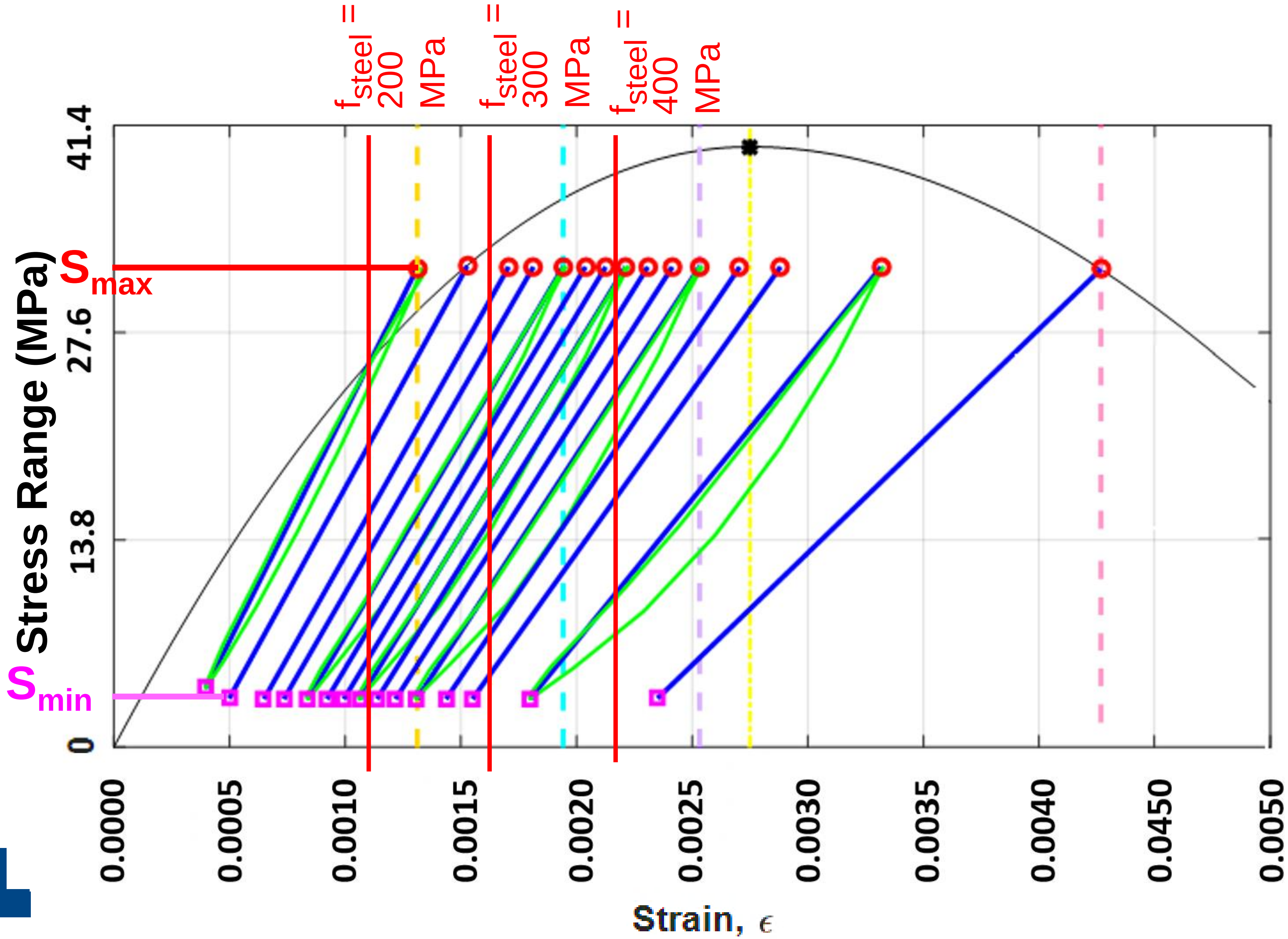
Reinforced concrete testing results

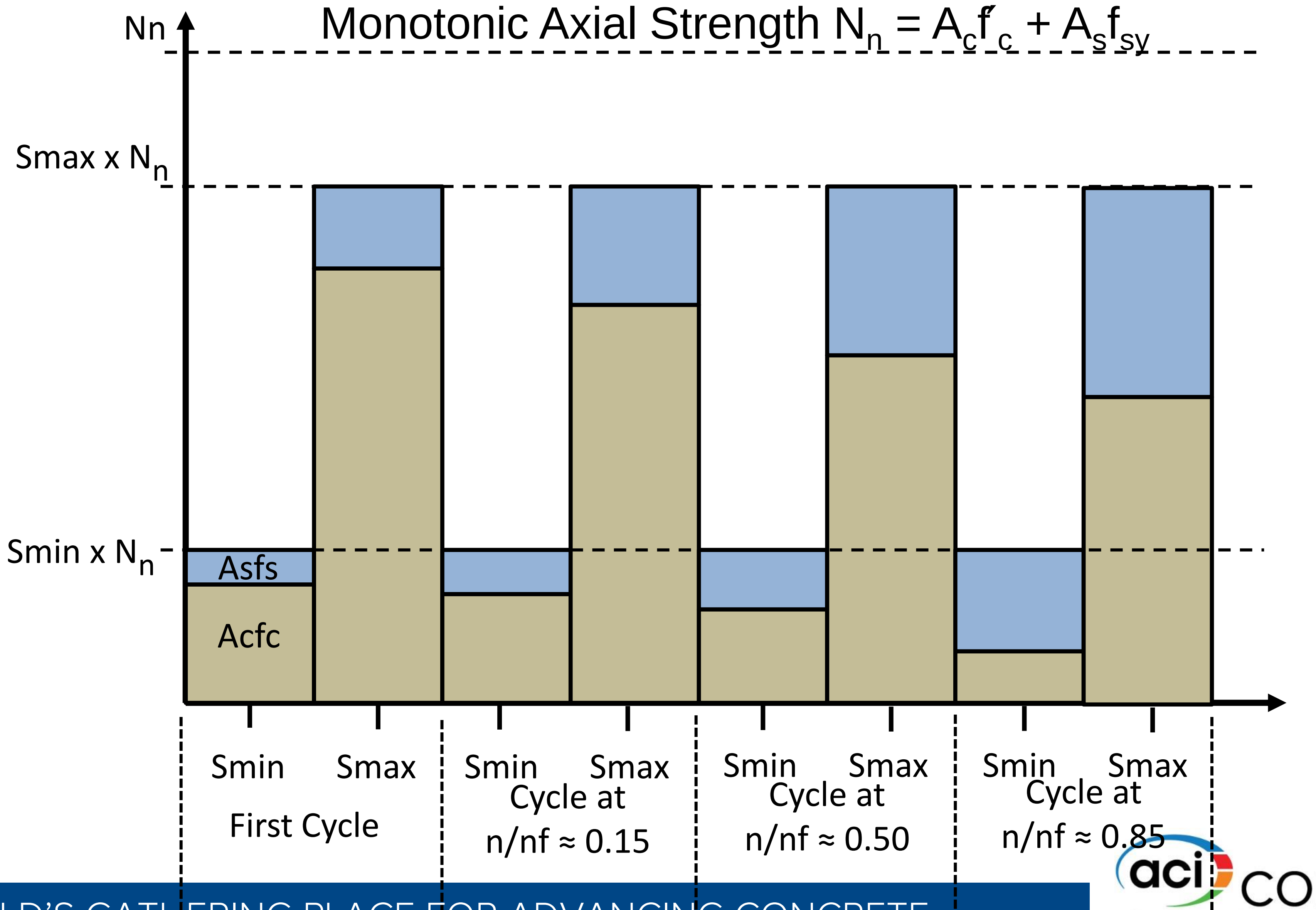


Type	Name	Nf	Ratio MC2010	Ratio DNVGL	Ratio Eurocode
Code	Model Code 2010	1489.5	1.0	4.4	1.9
	DNVGL-ST-C502	336.0	0.2	1.0	0.4
	Eurocode 2	779.5	0.5	2.3	1.0
Dry PC	PC-CAT#1-F1-80-5	2,860	1.9	8.5	3.7
	PC-CAT#2-F1-80-5	4,790	3.2	14.3	6.1
	PC-CAT#3-F1-80-5	2,875	1.9	8.6	3.7
	PC-CAT#4-F1-80-5	2,529	1.7	7.5	3.2
RC	RC4#3-CAT#1-F1-80-5	38,883	26.1	115.7	49.9
	RC4#3-CAT#2-F1-80-5	43,320	29.1	128.9	55.6
	RC4#3-CAT#3-F1-80-5	8,279	5.6	24.6	10.6
	RC4#3-CAT#4-F1-80-5	10236	6.9	30.5	13.1
	RC4#3-CAT#5-F1-80-5	52,576	35.3	156.5	67.4
	RC4#3-CAT#6-F1-80-5	9,024	6.1	26.9	11.6
	RC4#3-CAT#7-F1-80-5	26,535	17.8	79.0	34.0

Reinforced concrete testing results (Load Share)

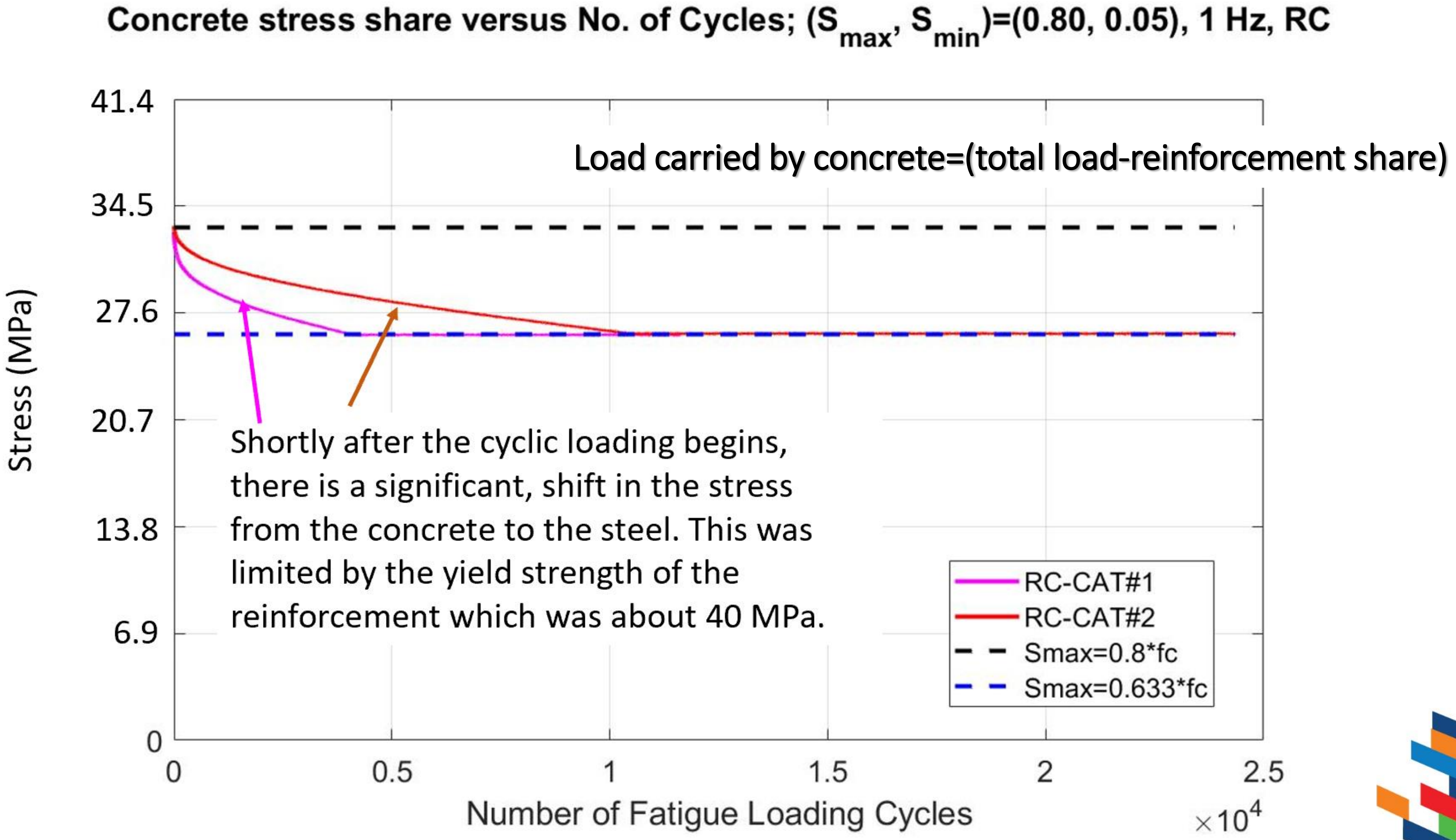


Reinforced concrete testing results (Load Share)



Reinforced concrete testing results (Load Share)

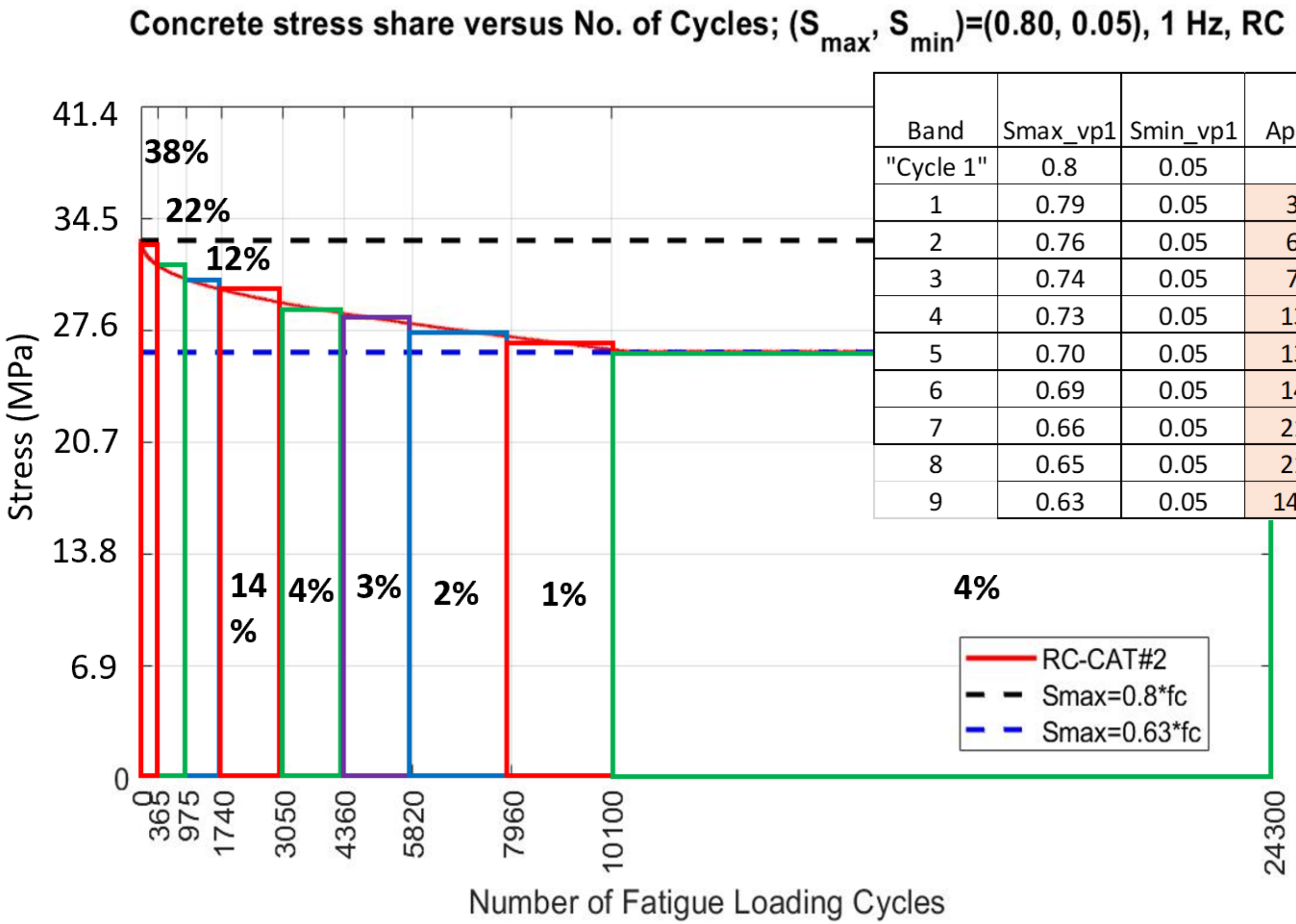
Load carried by concrete


Concrete stress share versus No. of Cycles; (S_{max}, S_{min})=(0.80, 0.05), 1 Hz, RC

Load carried by concrete=(total load-reinforcement share)

Shortly after the cyclic loading begins, there is a significant, shift in the stress from the concrete to the steel. This was limited by the yield strength of the reinforcement which was about 40 MPa.

Reinforced concrete testing results (Cumulative Damage)



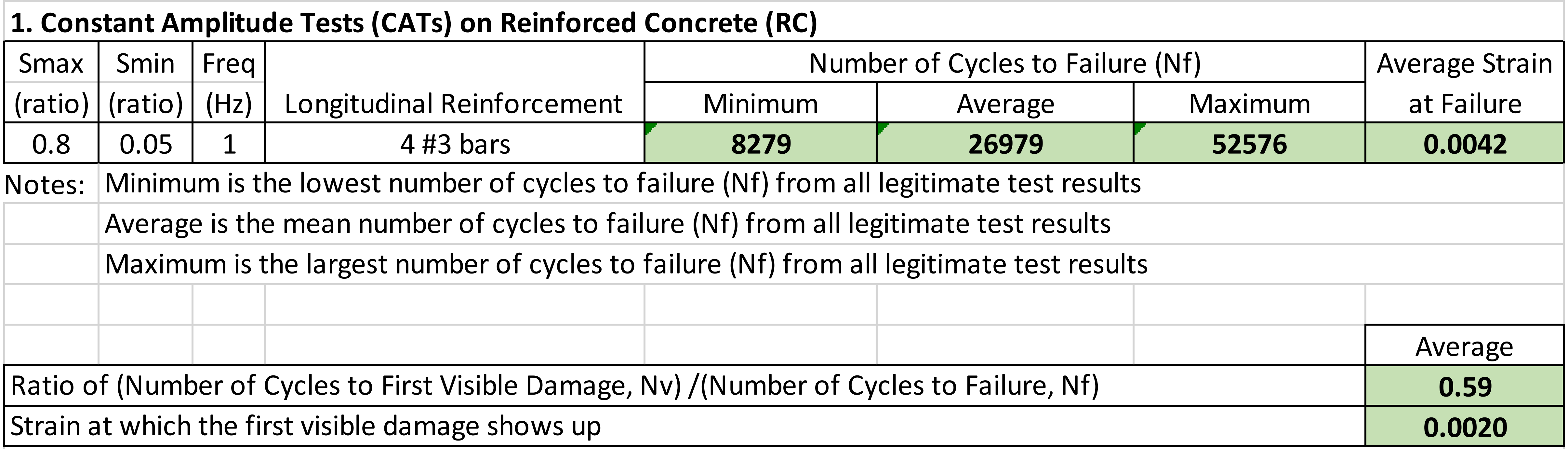
Band	Smax_vp1	Smin_vp1	Applied	Cumulative	Nf Model Code	Utilization	Cumulative Utilization
"Cycle 1"	0.8	0.05	1	1	1490	0.001	0%
1	0.79	0.05	365	365	1926	0.189	38%
2	0.76	0.05	610	975	5554	0.110	60%
3	0.74	0.05	765	1740	12762	0.060	72%
4	0.73	0.05	1310	3050	20091	0.065	86%
5	0.70	0.05	1310	4360	62476	0.021	90%
6	0.69	0.05	1460	5820	98355	0.015	93%
7	0.66	0.05	2140	7960	226005	0.009	95%
8	0.65	0.05	2140	10100	413902	0.005	96%
9	0.63	0.05	14200	24300	651600	0.022	100%

Palmgren-Miner's Rule

$$D=\sum_{i=1}^{k}\frac{n_i}{N_i}$$

- If the catigue capacity is calculated using Palmgren's Miners rule and the Model Code, the first 365 cycles of loading caused about 10 times as much damage as the last 14200 cycles of loading.
- Expressed another way, the first cycles cause 437 more times the fatigue damage as once the reinforcement has yielded.

Reinforced concrete testing results (Visual Damage)



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

Smax (ratio)	Smin (ratio)	Freq (Hz)	Longitudinal Reinforcement	Number of Cycles to Failure (Nf) Minimum	Number of Cycles to Failure (Nf) Average	Number of Cycles to Failure (Nf) Maximum	Average Strain at Failure
0.8	0.05	1	4 #3 bars	**8279**	**26979**	**52576**	**0.0042**

Notes: Minimum is the lowest number of cycles to failure (Nf) from all legitimate test results

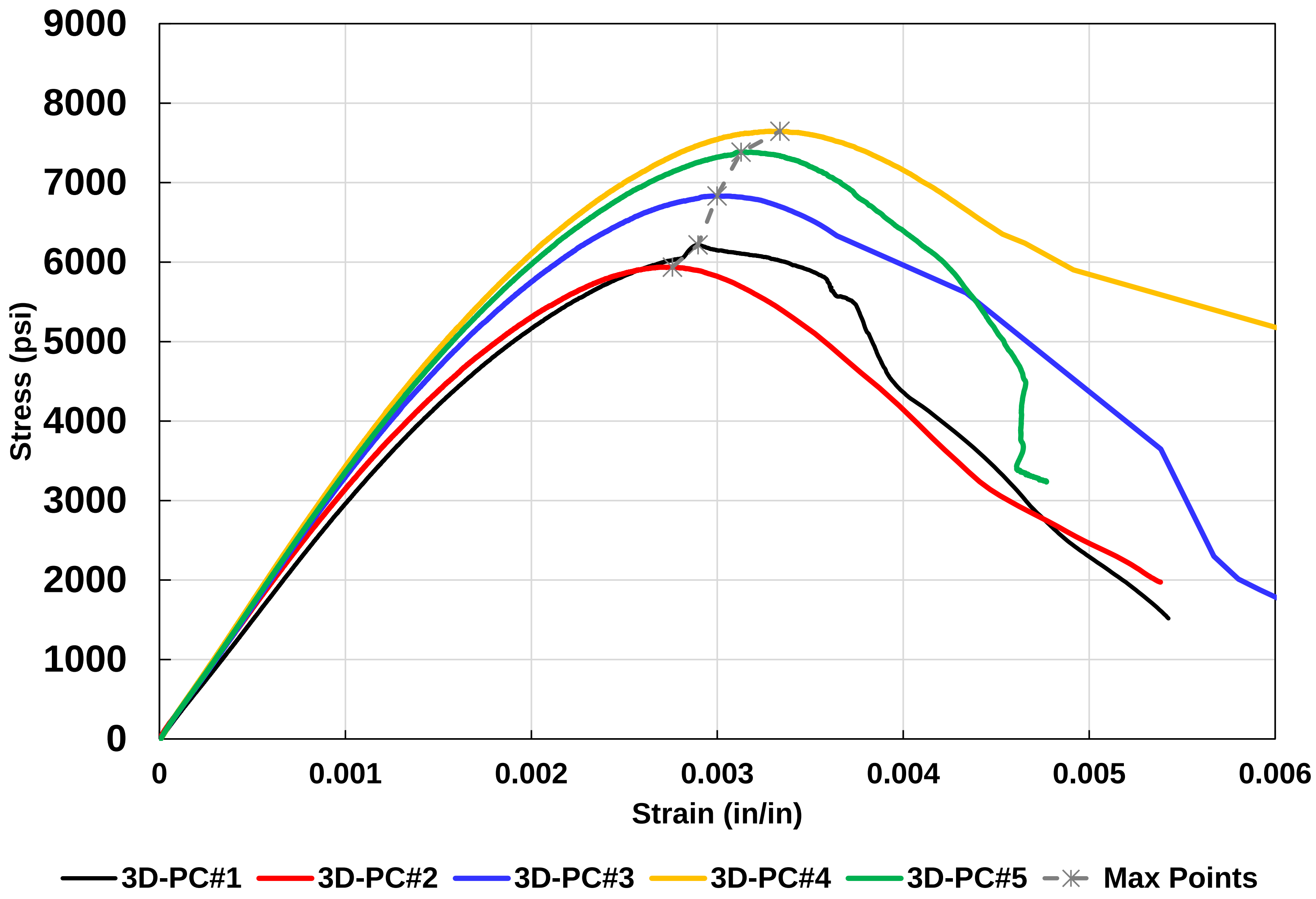
Average is the mean number of cycles to failure (Nf) from all legitimate test results

Maximum is the largest number of cycles to failure (Nf) from all legitimate test results

	Average
Ratio of (Number of Cycles to First Visible Damage, Nv) /(Number of Cycles to Failure, Nf)	**0.59**
Strain at which the first visible damage shows up	**0.0020**

Average of 0.001823, 0.002152, 0.001820, 0.002027, 0.002254 0.002083, 0.002146

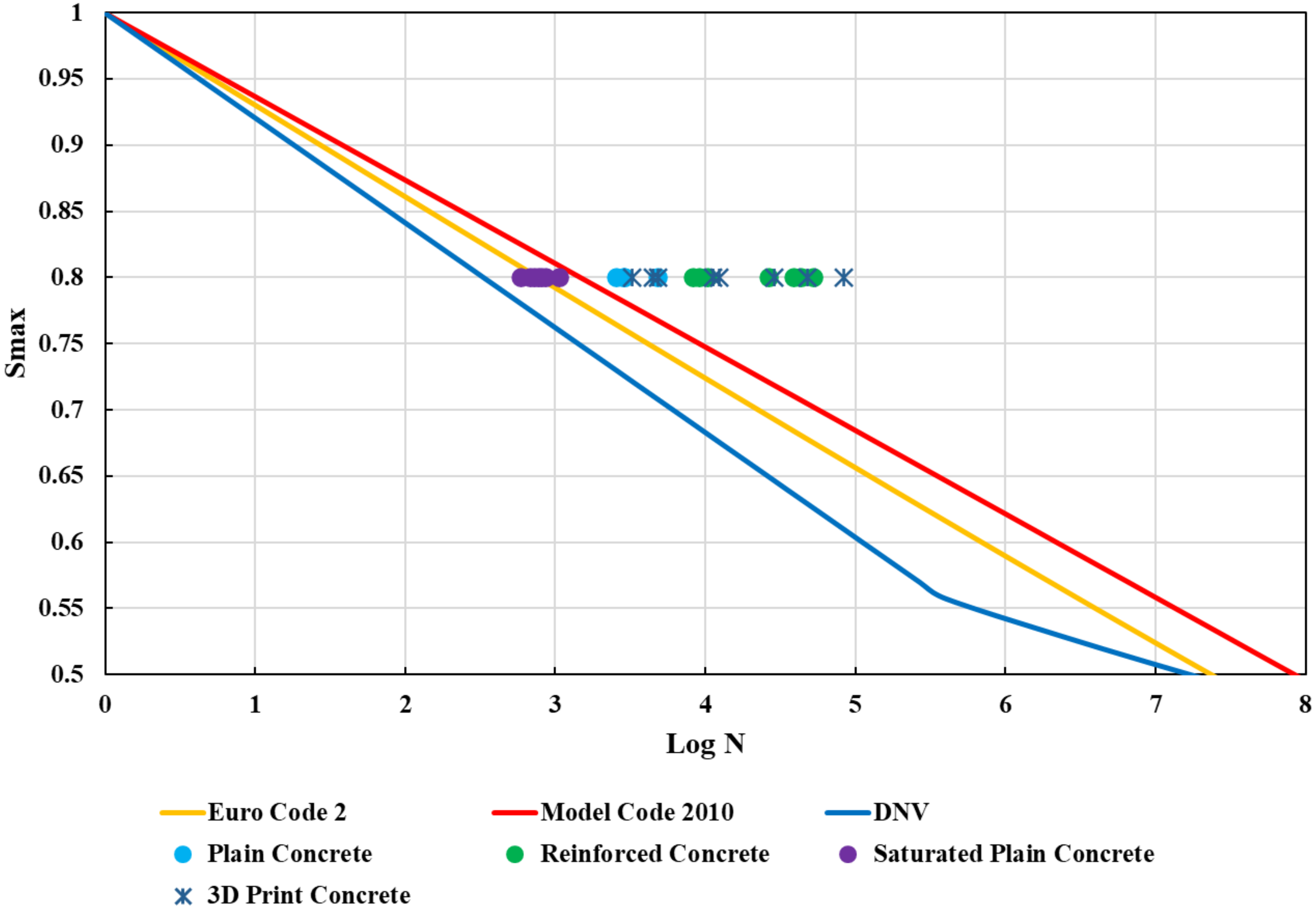
3D Print concrete testing results (Monotonic strength)



Coefficients of variation of strength results is almost 11%.

Coefficients of variation of printed specimens of 17–20% (Le et al.)

3D Print concrete testing results (Fatigue Capacity)



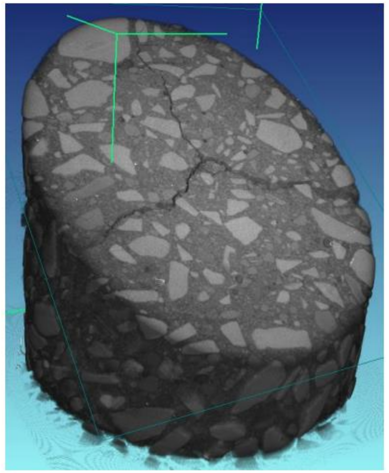
Conclusion and Needs for future investigations

Conclusion:

- Considering the variation of concrete strength in defining the fatigue loading protocol will reduce the fatigue capacity testing results range
- Change in concrete stiffness due to the cyclic loading damage has an effect in load share between concrete and reinforcing steel, and finally on estimated fatigue capacity.
- 3D Print concrete has a considerable fatigue capacity compared to th plain concrete with the same level of strength.

Need for Future investigations:

- Need for a standard for fatigue testing
- Exploring the effect of aggregate size on the fatigue
- X-Ray Microtomography (aka computed tomography) on damaged concrete specimen due to the fatigue loading



Thank you for your attention!

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