Damage mechanisms in fiber-reinforced concrete subjected to flexural fatigue through the analysis of cyclic creep curves

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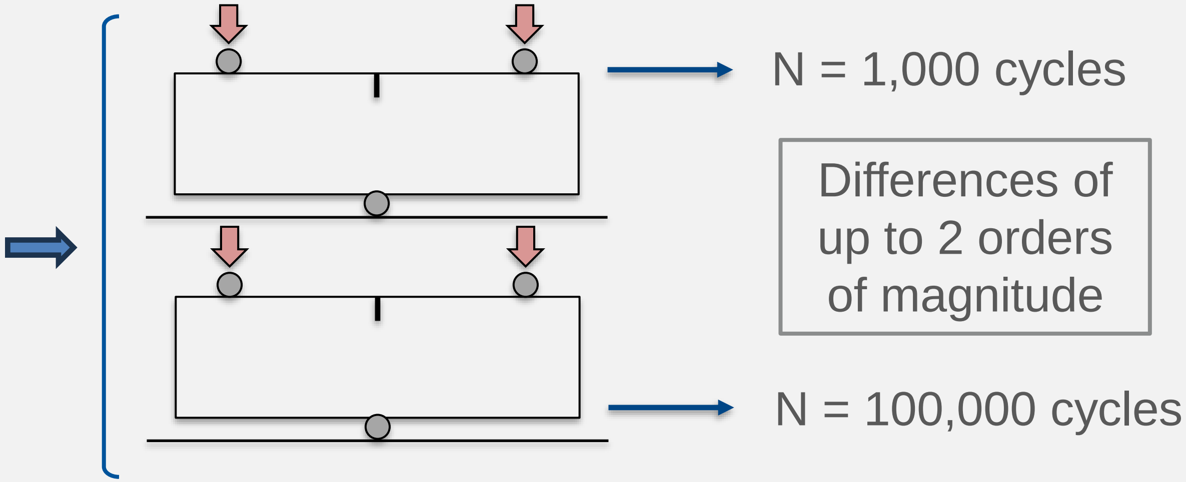
1. INTRODUCTION

- Fatigue in fiber-reinforced concrete (FRC) is an active field of research at present.
- One major issue when studying high-cycle fatigue with constant stress levels is the wide dispersion of results:
  - Two specimens with the same dosage, manufacturing conditions and fatigue load levels

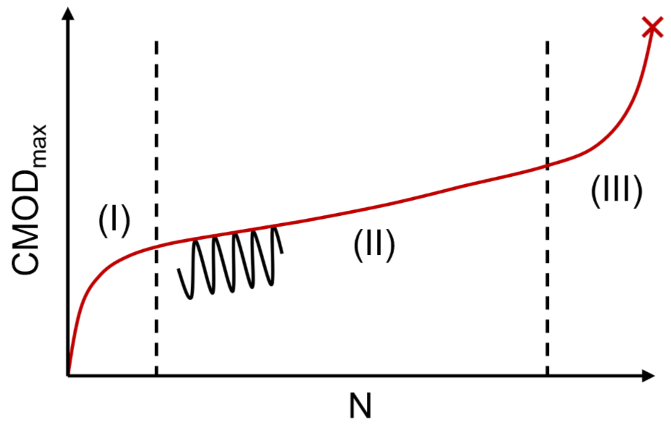


- The practical consequence is that structural codes are very conservative in fatigue design.

1. INTRODUCTION

- This work is focus on flexural fatigue in fiber reinforced concrete.
- In particular, the fatigue creep curves, which represent the maximum CMOD (crack mouth opening rate) at each cycle vs the number of cycles, are analyzed with two goals:

1. Explore the fatigue damage mechanisms in FRC.
2. Look for damage parameters that have a good correlation with fatigue life. This way, it would be possible to adjust expressions to predict fatigue life, therefore reducing the scatter of the results in equal specimens.



2. EXPERIMENTAL PROGRAM

Materials and specimens

- 3 series of SFRC with different fiber contents.
- Fibers → hooked-end, 30 mm long
- Concrete mixes:

Material	Series A1	Series A2	Series A3
Cement	400.0		
Coarse aggregate	538.2		
Fine aggregate	847.1		
Filler	448.8		
Water	160.0		
Superplasticizer	16.0		
Nanosilica	20.0		
Steel fibers	23.6	47.1	78.5
w/c ratio	0.4		
Fibers (% vol. conc.)	0.3%	0.6%	1.0%

- Prismatic specimens of 75x75x300 mm with a notch of 12.5 mm (h/6).
- 16 specimens per series.
- Curing → 1 year in climatic chamber at 20°C and 95% humidity.

2. EXPERIMENTAL PROGRAM

Concrete characterization

- Slump flow in fresh concrete → between 770 mm (series A1) and 650 mm (series A3)
- Tests prior to fatigue campaign:
  - Compressive strength → 106.7 ± 2.2 MPa
  - Modulus of elasticity → 45.4 ± 0.9 GPa
  - 3-point bending tests:

Series	f_{LOP} (MPa)	σ_{ult} (MPa)
A1	7.36	8.78
A2	8.35	11.78
A3	10.45	19.65

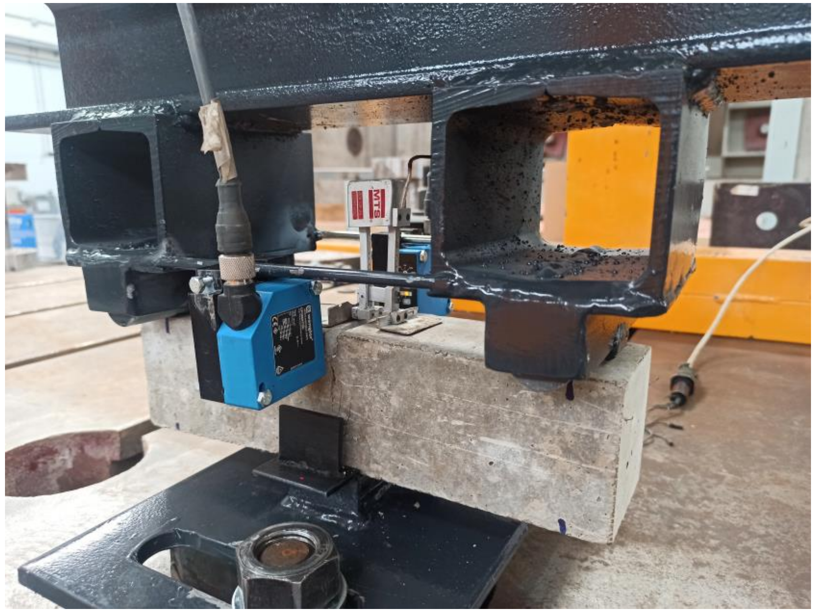
→ $\sigma_{ult} > f_{LOP}$
(strain-hardening behavior)

2. EXPERIMENTAL PROGRAM

Flexural fatigue tests

- High-cycle fatigue at constant stress levels.
- 12 tests per series.
- The stress levels were between 16% and 80% of the average σ_{ult} of each series:

Series	σ_{max} (MPa)	σ_{min} (MPa)
A1	7.02	1.40
A2	9.42	1.88
A3	15.72	3.14

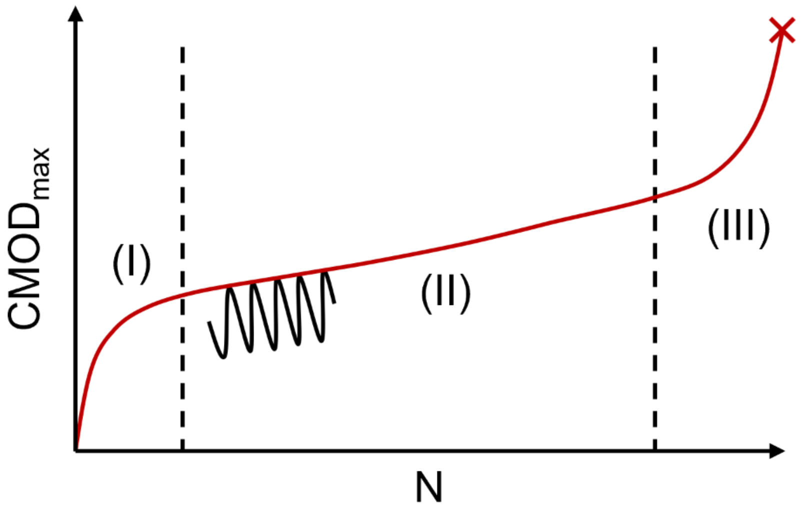


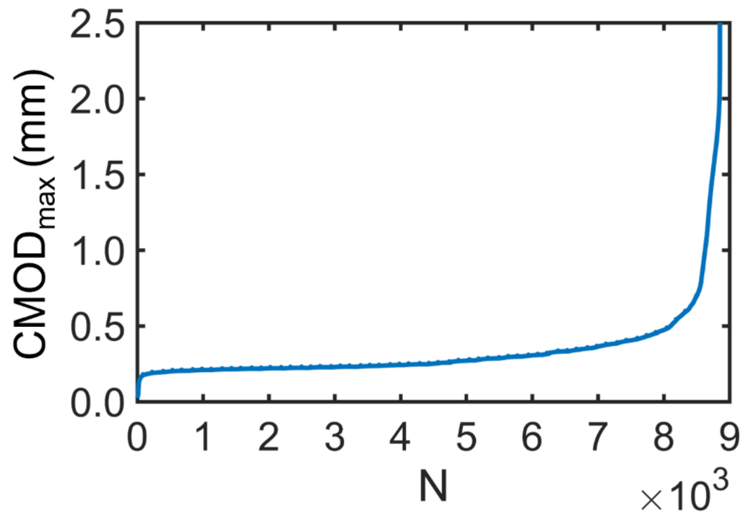
- Parameters measured → load, CMOD, relative displacement and N

3. RESULTS AND DISCUSSION

Fatigue creep curves

- Fatigue creep curves (or cyclic creep curves) represent the maximum CMOD at each cycle versus the number of cycles.
- They provide information on the evolution of fatigue damage in the elements.
- Example of fatigue creep curve in fiber-reinforced concrete subjected to bending fatigue:



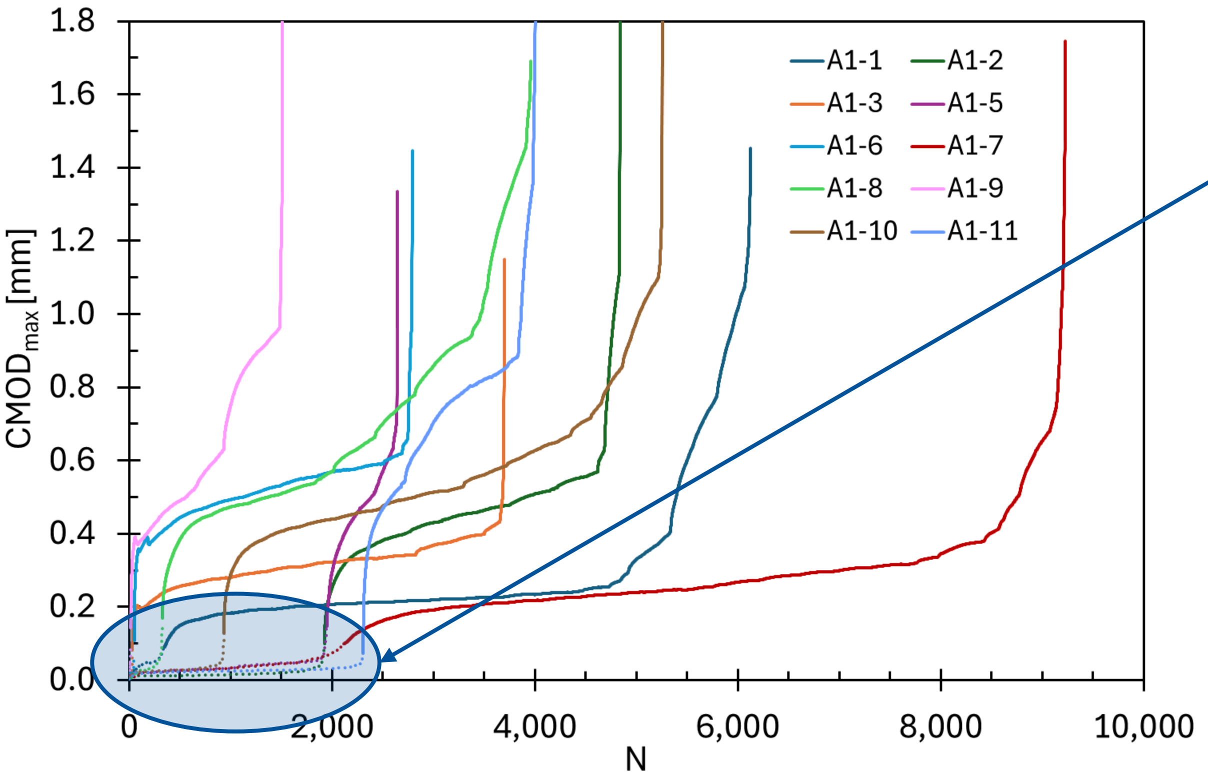


3. RESULTS AND DISCUSSION

Fatigue creep curves

- Fatigue creep curves in series A1 (0.3% fibers):

Specimen	N
A1-1	6,121
A1-2	4,838
A1-3	3,696
A1-4	43
A1-5	2,642
A1-6	2,791
A1-7	9,226
A1-8	3,956
A1-9	1,512
A1-10	5,263
A1-11	4,015
A1-12	48

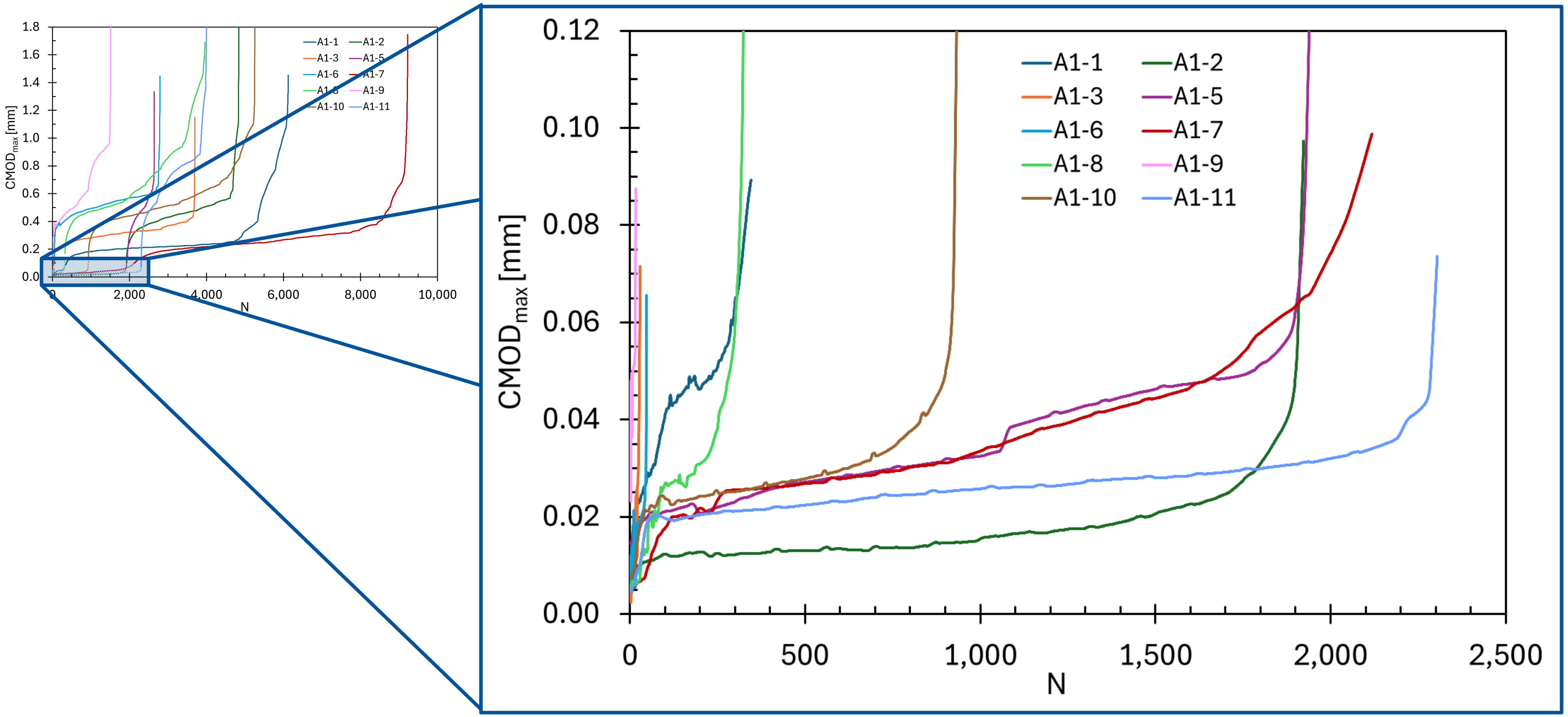


- In all the specimens there is an initial section with a different fatigue behavior from the rest of the curve.
- It is concluded that two different fatigue mechanisms are involved in the A1 series specimens.

3. RESULTS AND DISCUSSION

Fatigue creep curves

- Fatigue creep curves in series A1 (0.3% fibers):



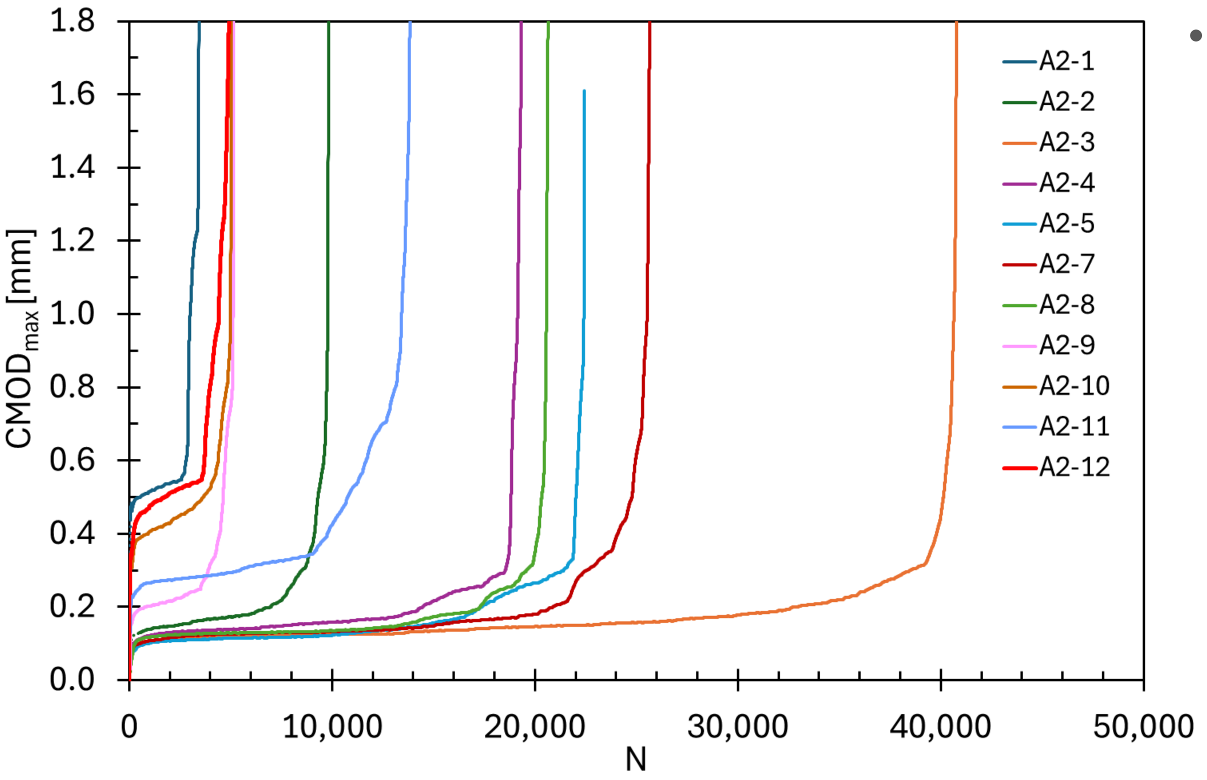
- In the detail view, it is observed that this fatigue section also has the characteristic inverted S-shape.
- However, this mechanism is exhausted in all specimens for low CMODs, less than 0.05 mm.

3. RESULTS AND DISCUSSION

Fatigue creep curves

- Fatigue creep curves in series A2 (0.6% fibers):

Specimen	N
A2-1	3,522
A2-2	10,316
A2-3	40,858
A2-4	19,401
A2-5	22,481
A2-6	1,000,000*
A2-7	26,308
A2-8	20,746
A2-9	5,156
A2-10	5,068
A2-11	14,233
A2-12	5,024



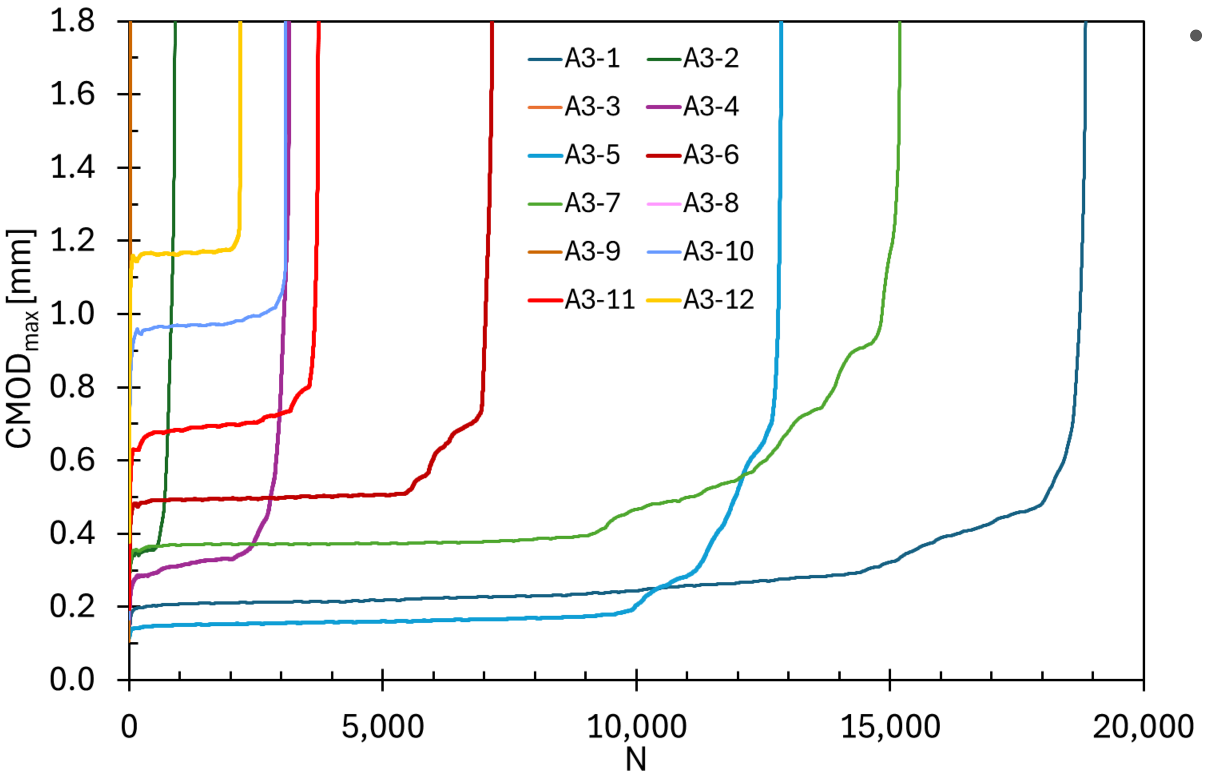
- In some specimens of the A2 series, the initial fatigue mechanism observed in the A1 series also appears, but its extent in very reduced (≈ 50 cycles).

3. RESULTS AND DISCUSSION

Fatigue creep curves

- Fatigue creep curves in series A3 (1% fibers):

Specimen	N
A3-1	18,889
A3-2	918
A3-3	30
A3-4	3,176
A3-5	12,888
A3-6	7,195
A3-7	15,225
A3-8	12
A3-9	31
A3-10	3,090
A3-11	3,743
A3-12	2,219

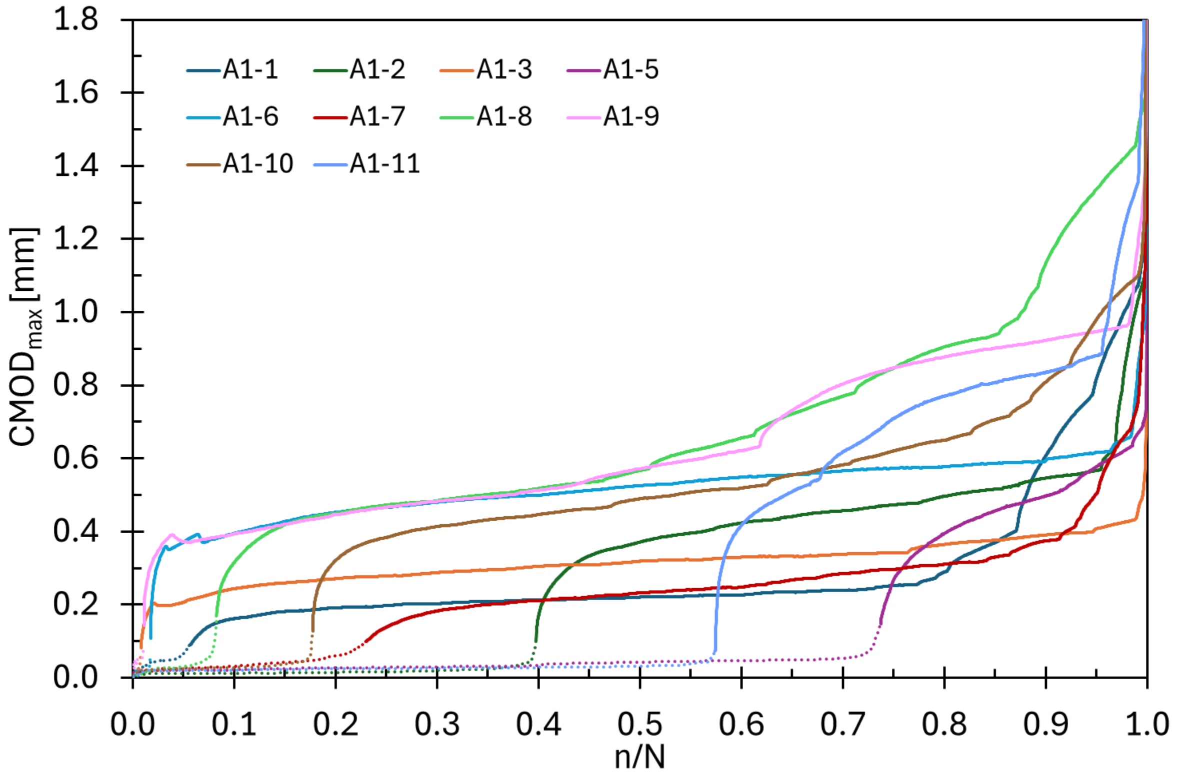


- The initial fatigue mechanism observed in the other series does not appear in the A3 series specimens.

3. RESULTS AND DISCUSSION

General fatigue creep curve in FRC subjected to bending fatigue

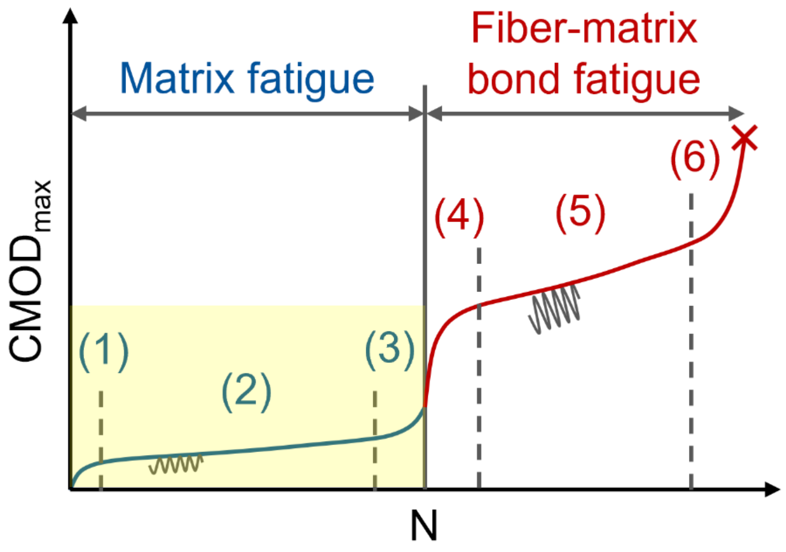
- The specimens of A1 series show the most general case of cyclic creep curves in fiber-reinforced concrete subjected to flexural fatigue:



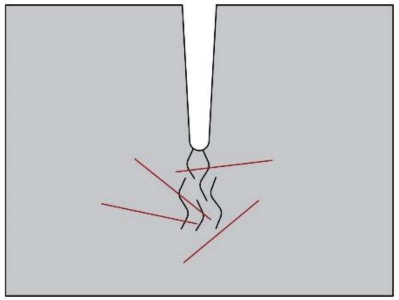
3. RESULTS AND DISCUSSION

General fatigue creep curve in FRC subjected to bending fatigue

- In the general case of fatigue creep curves, two sections can be distinguished, each governed by a different fatigue mechanism:



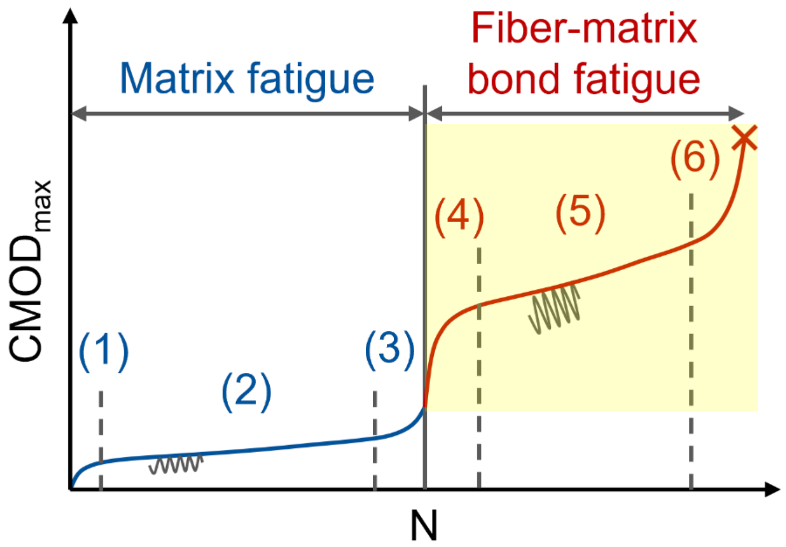
- **Section 1: Matrix fatigue**
  - Scattered microcracks in the environment of the notch.
  - Fatigue loads are resisted by the concrete matrix.
  - Due to the low level of deformations (CMOD<0.05 mm), the fibers are hardly involved.



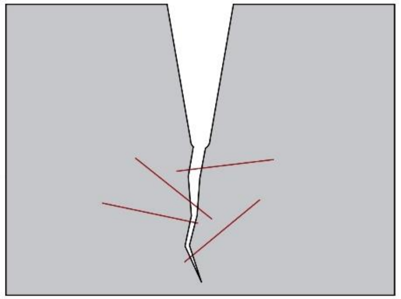
3. RESULTS AND DISCUSSION

General fatigue creep curve in FRC subjected to bending fatigue

- In the general case of fatigue creep curves, two sections can be distinguished, each governed by a different fatigue mechanism:



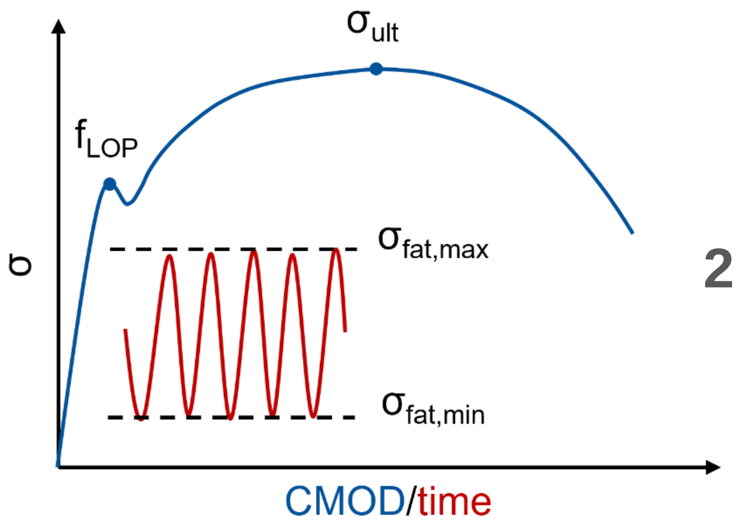
- **Section 2: Fiber-matrix bond fatigue**
  - This section begins when the microcracks converge to form a main macrocrack that breaks the matrix.
  - At this point, fatigue loads begin to be resisted by the bridging forces between the fibers and the matrix.
  - This mechanism is much more ductile than the previous one (higher CMOD).



3. RESULTS AND DISCUSSION

General fatigue creep curve in FRC subjected to bending fatigue

- This general curve is observed when the following <u>two conditions</u> are fulfilled:



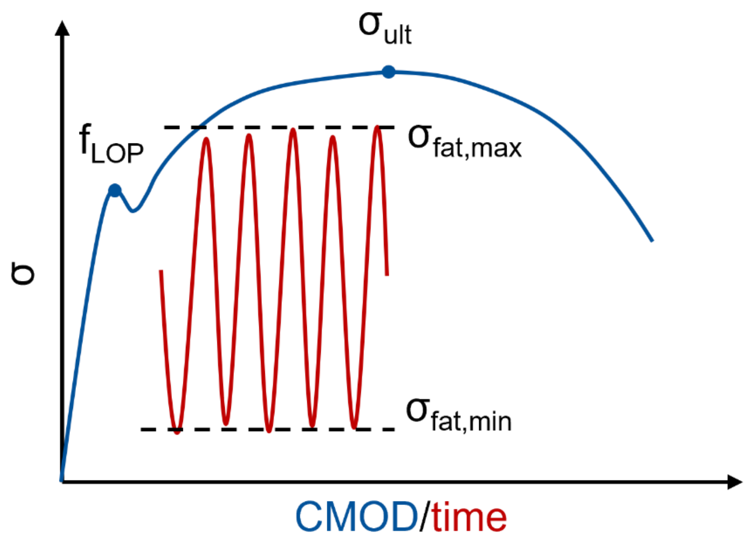
1. **Maximum fatigue stress is lower than first-crack strength ($\sigma_{fat,max} < f_{LOP}$).**
   - First-crack strength is approximately the stress at the limit of proportionality (LOP) in the three-point bending test according to EN 14651.
2. **Strain-hardening flexural behavior is produced ($f_{LOP} < \sigma_{ult}$).**
   - Once the concrete matrix is cracked, the residual stress that fibers can withstand is greater than matrix strength. In other words, the ultimate flexural strength is higher than first-crack strength.

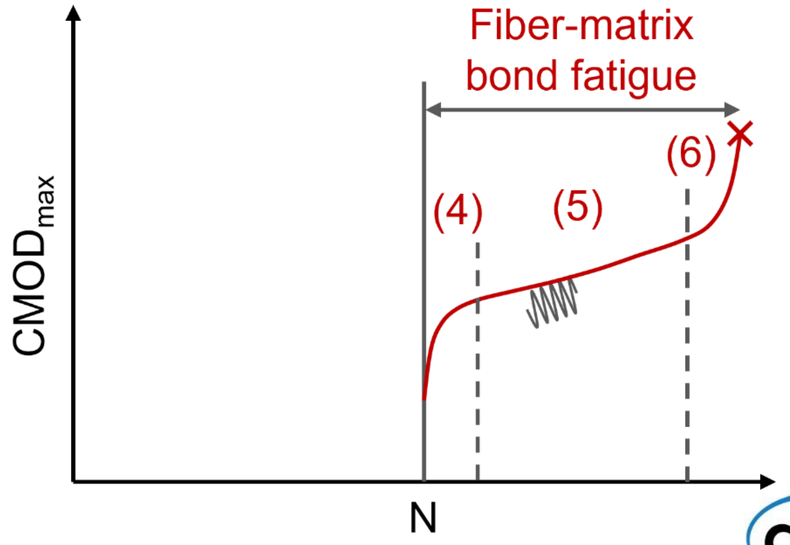
3. RESULTS AND DISCUSSION

General fatigue creep curve in FRC subjected to bending fatigue

- If both conditions are not fulfilled, then only one section of the general curve will be observed. There are two particular cases:

  a. **Strain-hardening occurs, but maximum fatigue stress is higher than first-crack strength ($\sigma_{fat,max}$ > f_{LOP}).**
     - The concrete matrix breaks after the first cycle and only fiber-matrix bond fatigue is observed.





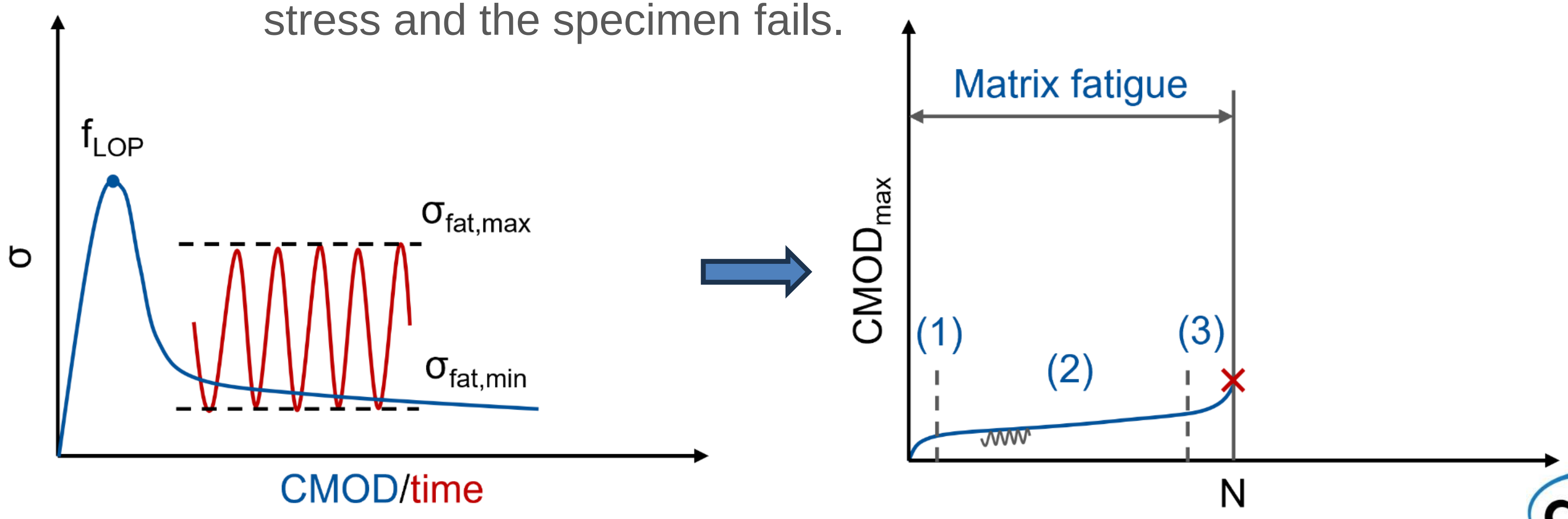
3. RESULTS AND DISCUSSION

General fatigue creep curve in FRC subjected to bending fatigue

- If both conditions are not fulfilled, then only one section of the general curve will be observed. There are two particular cases:

  b. **Maximum fatigue stress is lower than first-crack strength, but there is no strain-hardening ($f_{LOP} = \sigma_{ult}$).**

  - When the concrete matrix breaks after a certain number of cycles, fibers cannot withstand stress and the specimen fails.



3. RESULTS AND DISCUSSION

Fatigue life

- According to fatigue creep curves, fatigue life can be divided in two parts:
  - **N_1** → matrix fatigue
  - **N_2** → fiber-matrix bond fatigue

Test No.	A1		A2		A3	
	N_1	N_2	N_1	N_2	N_1	N_2
1	346	5,775	59	3,463	0	18,889
2	1,924	2,914	504	9,812	0	918
3	31	3,665	50	40,808	0	30
4	27	16	57	19,344	0	3,176
5	1,948	694	53	22,428	0	12,888
6	49	2,742	1,000,000*	0	0	7,195
7	2,118	7,108	56	26,252	0	15,225
8	327	3,629	0	20,746	0	12
9	17	1,495	0	5,156	0	31
10	934	4,329	0	5,068	0	3,090
11	2,305	1,710	0	14,233	0	3,743
12	42	6	0	5,024	0	2,219

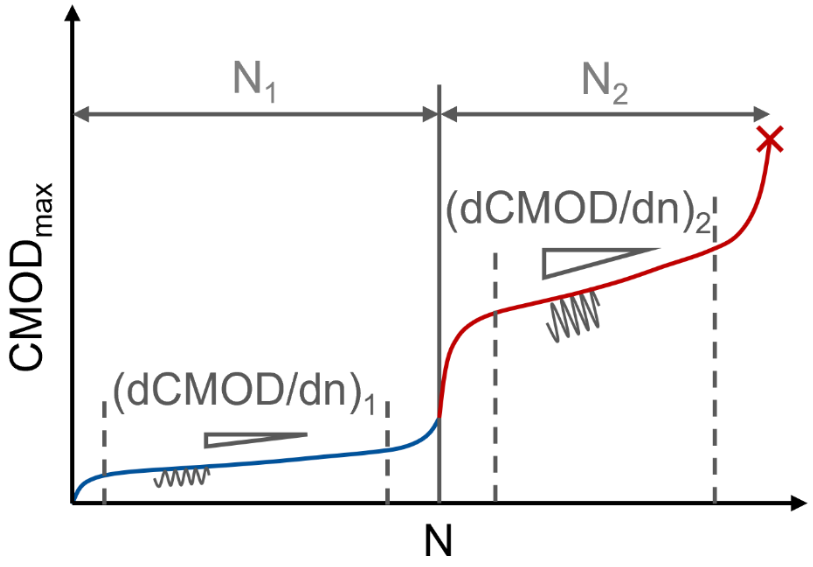
- In series A2 and A3, since the maximum fatigue stress is higher than first-crack strength, matrix fatigue is not expected to occur ($N_1 \approx 0$).

Series	$\sigma_{fat,max} / f_{LOP}$
A1	95%
A2	113%
A3	150%

3. RESULTS AND DISCUSSION

Relationship between CMOD rate and fatigue life

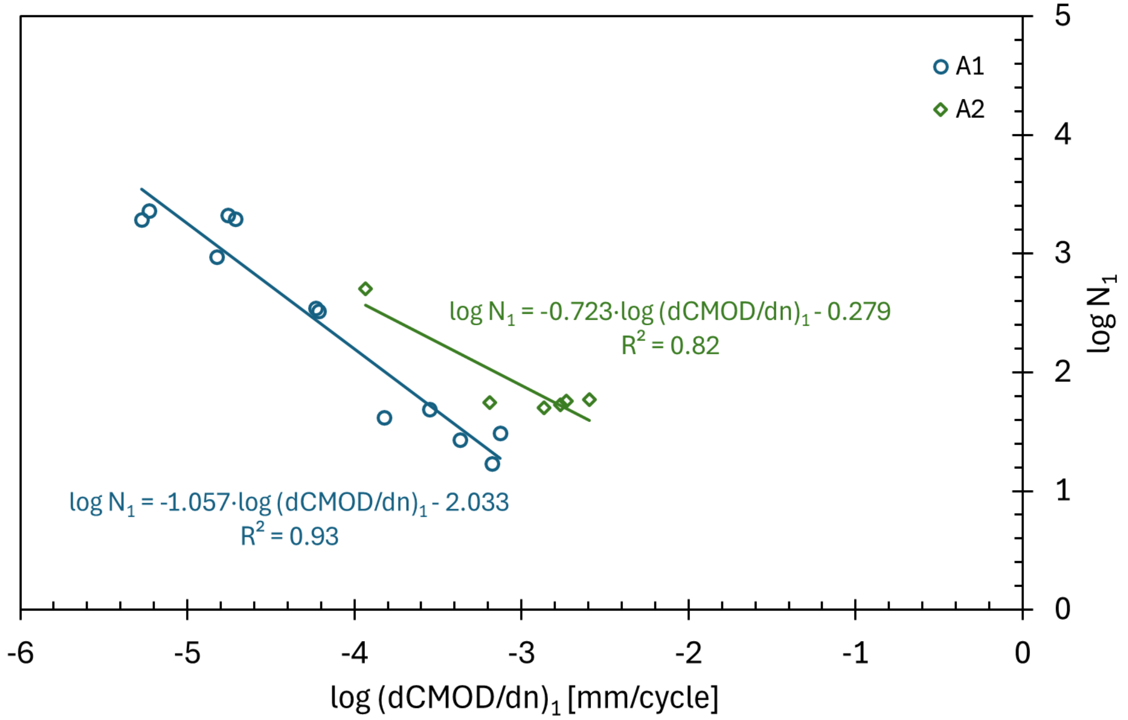
- The CMOD rate (dCMOD/dn) is the slope of the central stage in fatigue creep curves.
- It represents the speed at which fatigue damage is being infringed to the specimen.

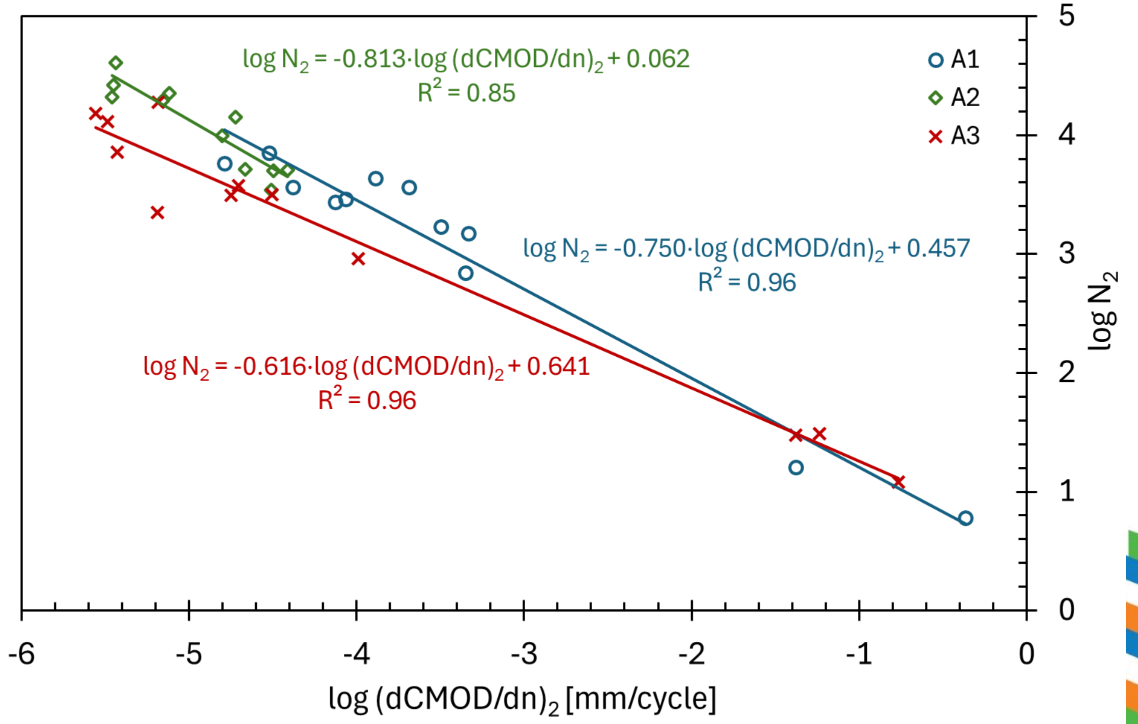


3. RESULTS AND DISCUSSION

Relationship between CMOD rate and fatigue life

- The results show that there is a strong correlation between CMOD rate and fatigue life. Higher dCMOD/dn lead to lower N, and vice versa.





3. RESULTS AND DISCUSSION

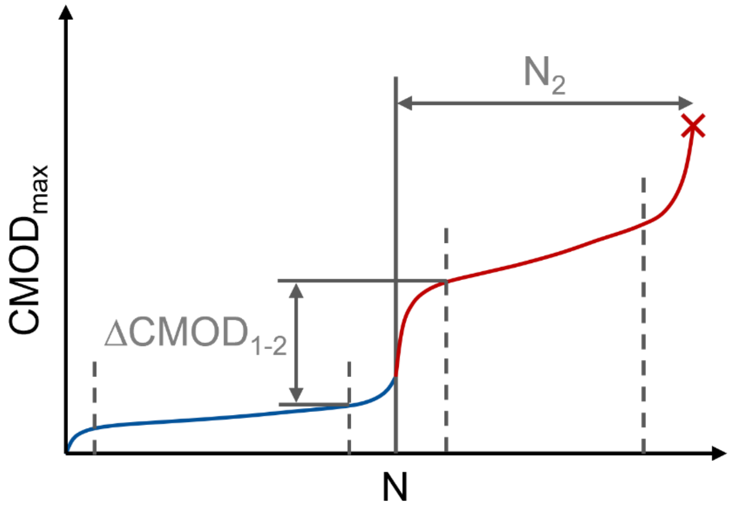
Relationship between CMOD rate and fatigue life

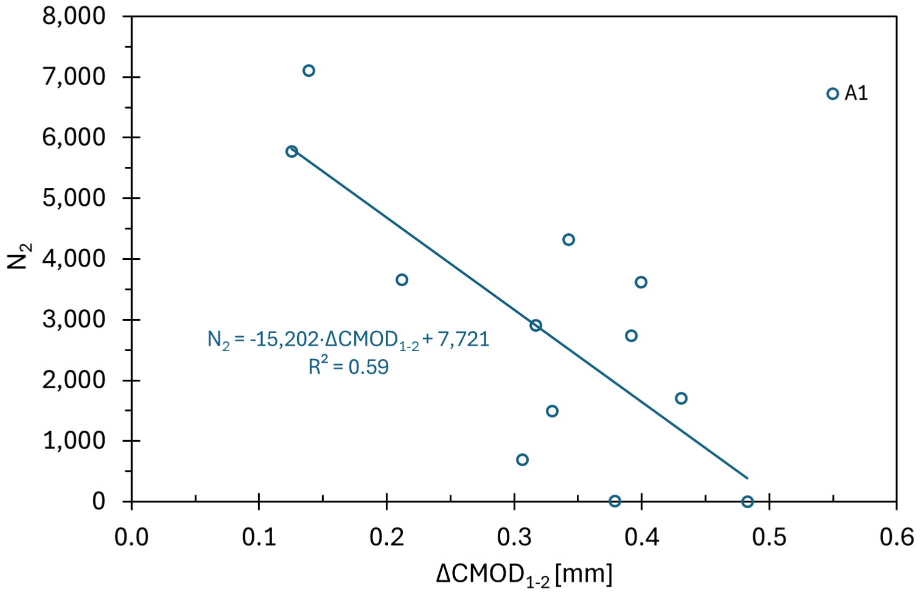
- This relationship is verified independently for both fatigue mechanisms:
  - The CMOD rate of the first section $(dCMOD/dn)_1$ is correlated with the number of cycles of the matrix fatigue (N_1).
  - The CMOD rate of the second section $(dCMOD/dn)_2$ is correlated with the number of cycles of the fiber-matrix bond fatigue (N_2).
- This has several implications:
  - $(dCMOD/dn)_1$ can be used to predict fatigue life until cracking.
  - $(dCMOD/dn)_2$ can be used to predict fatigue life from matrix cracking to the total failure.
  - Apparently, both fatigue mechanisms are independent.

3. RESULTS AND DISCUSSION

CMOD increase between fatigue sections ($\Delta CMOD_{1-2}$)

- In the specimens of series A1, where both fatigue mechanisms occur, it has been found a good correlation between:
  - CMOD increase between fatigue sections ($\Delta CMOD_{1-2}$).
  - Number of cycles of the fiber-matrix bond fatigue (N_2).





3. RESULTS AND DISCUSSION

CMOD increase between fatigue sections ($\Delta CMOD_{1\text{-}2}$)

- Higher CMOD “jumps” between fatigue sections lead to lower number of cycles that fibers can then withstand.
- This is explained by the following:
  - Once the concrete matrix is cracked and fibers start to act, there is a certain value of CMOD at which fiber-matrix bond fatigue is stabilized.
  - This value varies between specimens because it depends on fiber distribution.
  - It is assumed that, the higher this value of CMOD stabilization, the lower the resistant cross-section and then the lower the fatigue life.

4. CONCLUSIONS

- The flexural fatigue behavior of FRC in the most general case consist of two fatigue mechanisms: matrix fatigue and fiber-matrix bond fatigue.
- According to this, the general fatigue creep curve in FRC under bending fatigue is analyzed, stablishing the conditions to observe it and the particular cases that can appear.
- It is found a strong correlation between CMOD rate and fatigue life. This relationship is verified independently for both fatigue mechanisms.
- Other parameters of the fatigue creep curves, such as CMOD increase between fatigue sections, also show a good correlation with fatigue life in particular cases.

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