Fatigue

Bekaert Design Approach for SFRC SOG and Pavements

Authored by Gerhard Vitt presented by Byron Benson, PE

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Introduction

- Many publications refer to the fatigue properties of SFRC. Results range from good to excellent.
- However, there is no generally accepted methodology available, so far, to quantify the effect of the steel fibers on the fatigue life of a concrete element by using material properties that are derived from a standard beam test.
- Recently, research projects with a special focus on SFRC and SFRC ground slabs were completed:
  - *Fatigue fracture of fibre reinforced concrete in flexure*, IIT Madras, Chennai, India (S. J. Stephen and R. Gettu)
  - *Fatigue Behaviour of Steel Fibre Reinforced Concrete Pavements*, University of South Wales, Sydney, Australia (I. M. A. Al-Damad / S. Foster)
  - *Internal test report*, Wu Han University of Technology, China (Wu Han University / Bekaert)
  - Modellbildung und numerische Analysen zur Ermüdung von Stahlfaserbeton, Ruhr University Bochum, Germany* (Peter Heek / Peter Mark

Introduction

These publications have been used to build a **model that is specific** to:

- ground supported, non-structural pavements and industrial floors only
- SFRC only
- downward forces only
- a range of Dramix® fiber types
- a range of dosages
- a range of concrete strength classes
- a range of load repetitions

NOTE: the model is NOT applicable to

- slab on piles, rafts, elevated structures etc.
- uplift forces
- combined reinforcement (hybrid)

Introduction

But why a fatigue model for Slabs on Ground, after so many years without?

- SFRC is ‘known’ to improve the fatigue resistance of concrete floors and pavements.
- With standard floors and pavements, we haven’t experienced any issues due to fatigue loading.
- However, fatigue is the language pavement designers are speaking.
- So far, we couldn’t really ‘talk’ to them in their language.
- Some recommendations even ask for fatigue design of heavy handling equipment (→TR34).
- Furthermore, handling equipment:
  - has become more sophisticated, heavier and faster,
  - is often guided automatically, following exactly the same path all the time.

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Basis of the Design Model

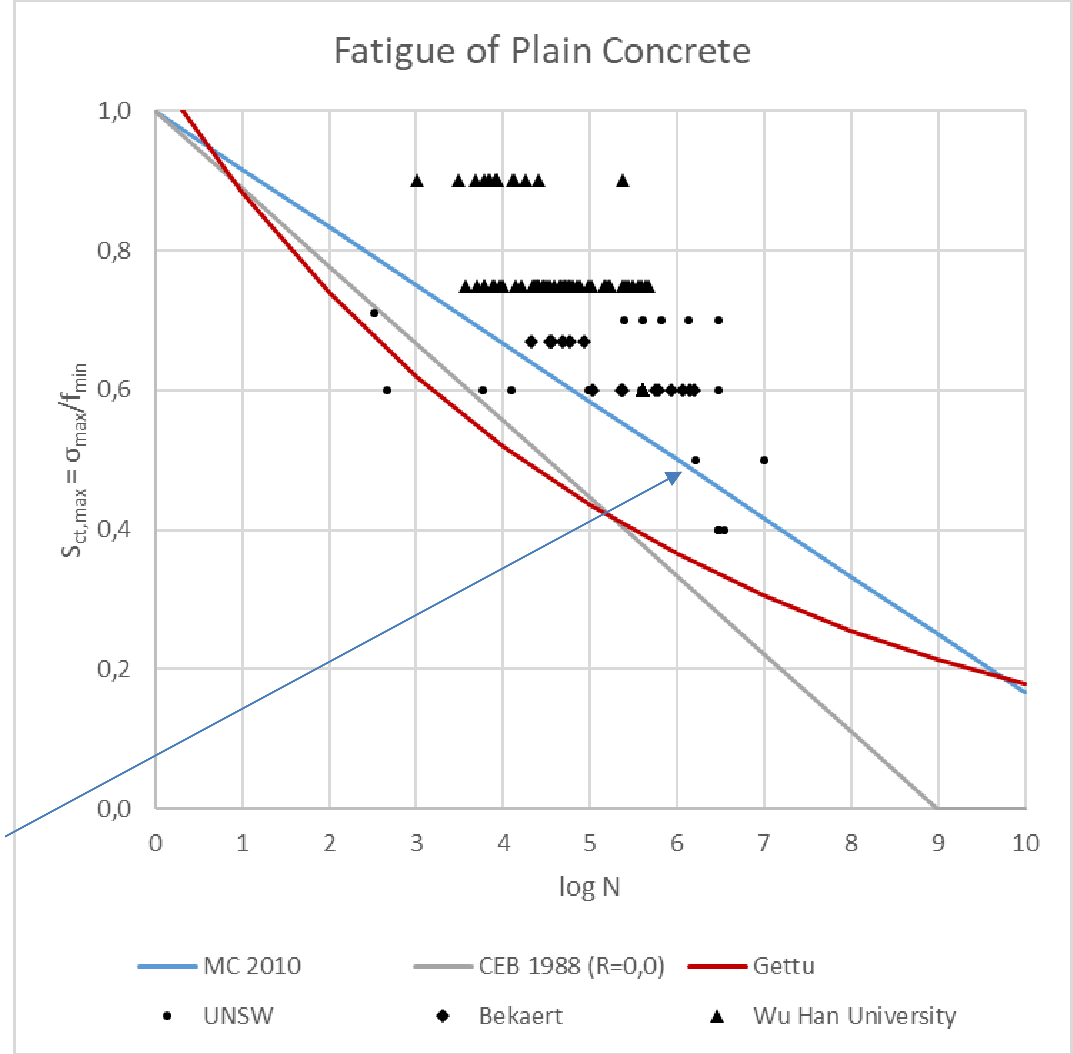
Fatigue of Plain Uncracked Concrete

- Comparison between
  - Model Code 2010 approach
  - CEB 1988 approach for R = 0.0
  - Approach suggested by IIT (Gettu): EN 14641
  - Test results
    - UNSW (Foster, repetitions till 1st crack): RDP
    - Wu Han University (repetitions till 1st crack): RDP
    - Bekaert (own lab tests, repetitions till 1st crack): EN 14651
- The Bekaert design model uses the Model Code 2010 approach before cracking.
- Stress Ratio SR = $\frac{\sigma_{applied}}{\sigma_{static}}$

$$SR_{c,fat} = S = 1 - \frac{\log_{10} N}{12}$$

-OR-

$$N = 10^{12\cdot(1-SR_{c,fat})}$$



Fatigue of SFRC: IIT, Stephen and Gettu

- EN 14651 beam test
  - pre-cracked, fatigue loading at 5 Hz
  - 6 specimens for each configuration
- One fiber type
  - Dramix® 3D 80/60BG
- One concrete mix
  - ~40 Mpa (6,000 psi)
    Different dosages
  - 0, 10, 30, 45 kg/m³ (0 – 76 pcy)
- Different stress levels
  - 50, 60, 70, 80, 90 % of f_{R1}

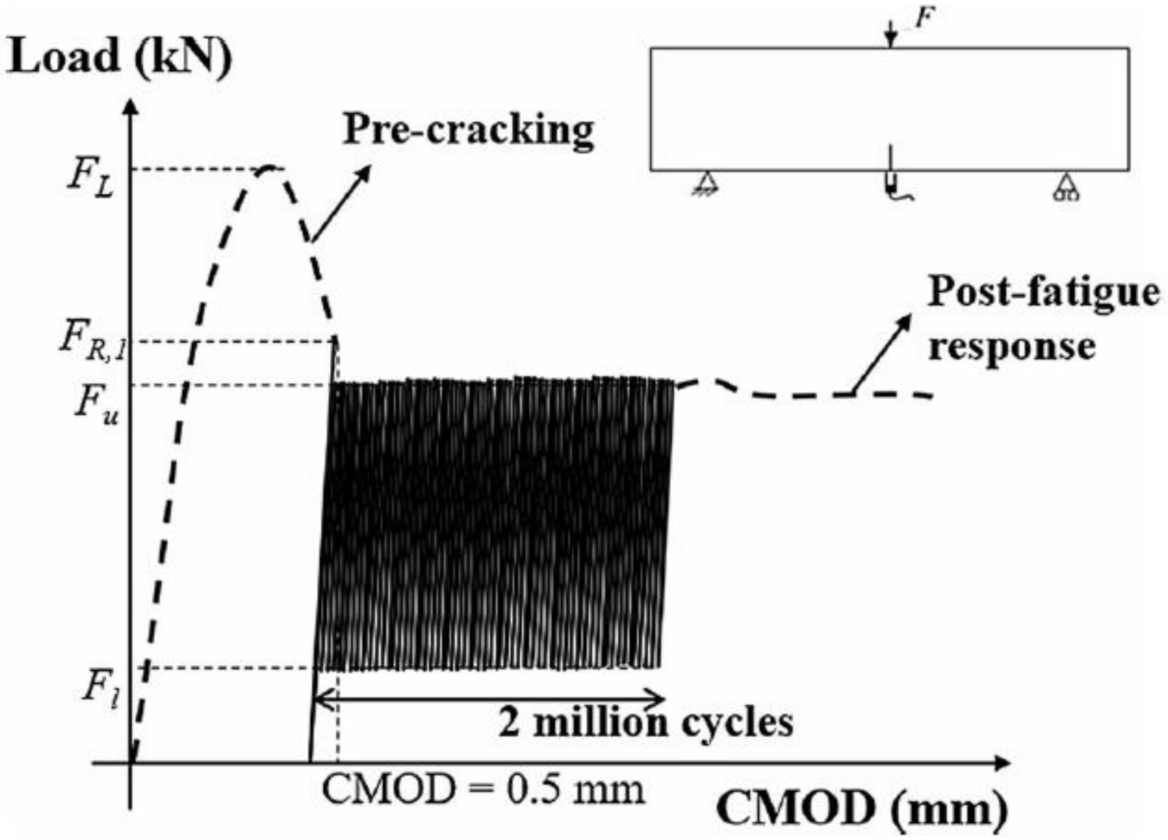
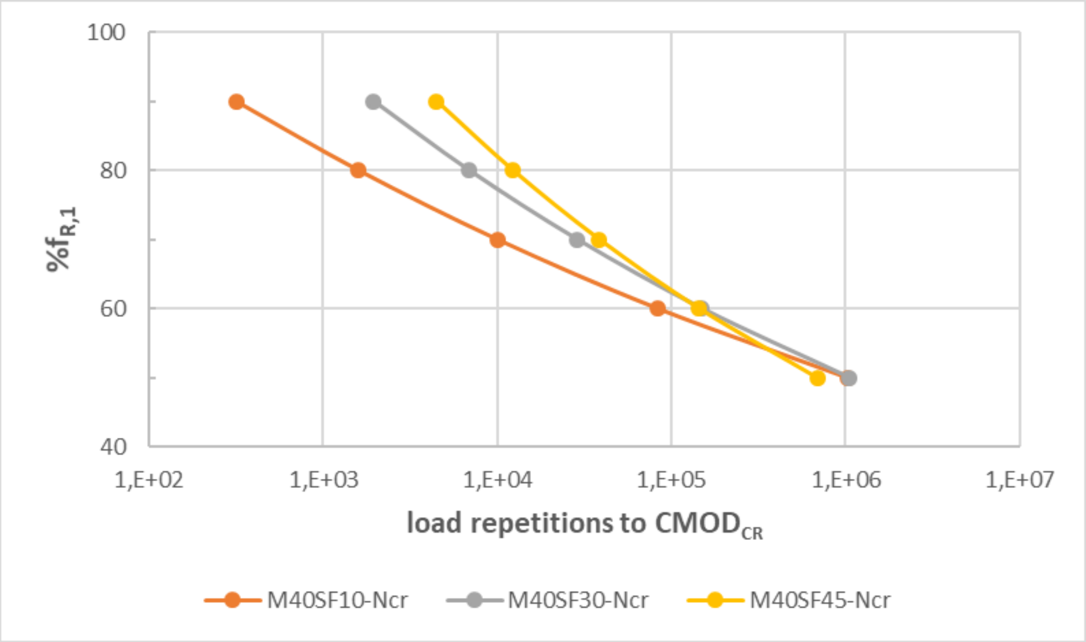
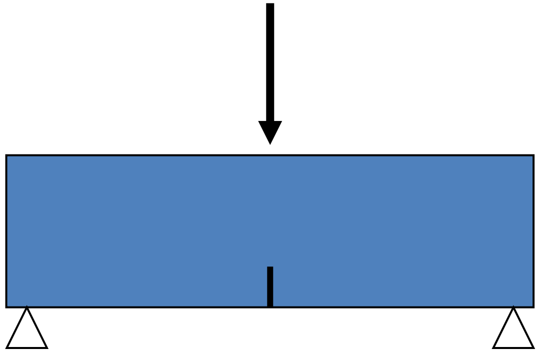


Fig. 1 Illustration of the test procedure

Fatigue of SFRC: IIT, Stephen and Gettu





- Differences in fatigue performances appear at higher $\%f_{R,1}$.
- Fatigue performances converge at lower $\%f_{R,1}$.

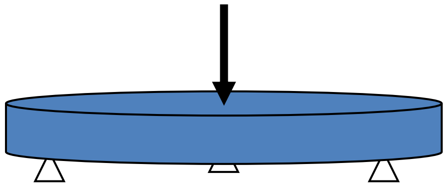
Introduction

- Series A: 5D 65/60 BG
- Series B: 4D 65/35 BG
- Series C: 4D 55/60 BG

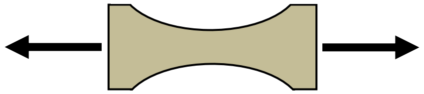
- 30 kg/m³ (50 pcy)

- 40 MPa (6000 psi) concrete, about 55 MPa (8000 psi) at testing
- D_{max} 800 mm (31.5 in)

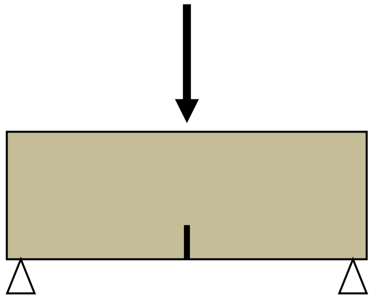
- Tested after 180 days



- 9 panels
  - ASTM C1550
    - uncracked fatigue
      (based on % static mean peak)
    - pre-cracked fatigue at 0.5 mm crack width
      (based on % maximum load)
  - 3 to 4 load levels at a rate of 3 Hz
  - Loaded to failure after 3,000,000 cycles
  - Maximum load level 50% was tested until 10,000,000 cycles



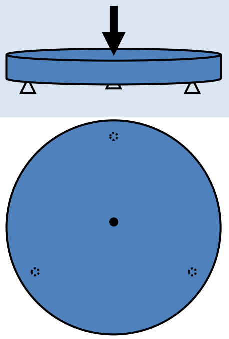
- 6 dog-bones
  - uniaxial tension
  - static testing



- 12 beams
  - EN 14651, ASTM C1609, JCI-S-002
  - static testing

UNSW - Test Setup Small Scale Testing: Round Determinate Panels

Test Type	Max Load	5D 65/60BG	4D 65/35BG	4D 55/60BG
Static	100%	3	2	2
Fatigue, Uncracked	70%	1	2	2
	60%	1	-	-
Fatigue, Pre-cracked	60%	2	3	2
	50%	-		2
	40%	2	2	1



Cracked cross sections

- EN-beam: 15 x 12.5 x 0.9 = 169 cm²
- RDP: 3 x 80/2 x 7.5 x 0.9 = 810 cm²

≈ 5

UNSW - Test Results Small Scale Testing: Conclusions

"The model predicts the number of cycles after cracking of the concrete as presented in Table 5.2, where the fatigue limit equals the number of cycles to crack the concrete plus the number of post-cracking cycles."

$$SR_{f,fat} = S = -0.087\log(N_f) + 1.21 \quad (5.10)$$

-or-

$$N_f = 10^{\frac{S-1.21}{-0.087}}$$

"Equation (5.10) provides a reasonable approximation of the experimental results for the few specimens that were tested; more tests are needed to provide better evaluation of Equation (5.10)."

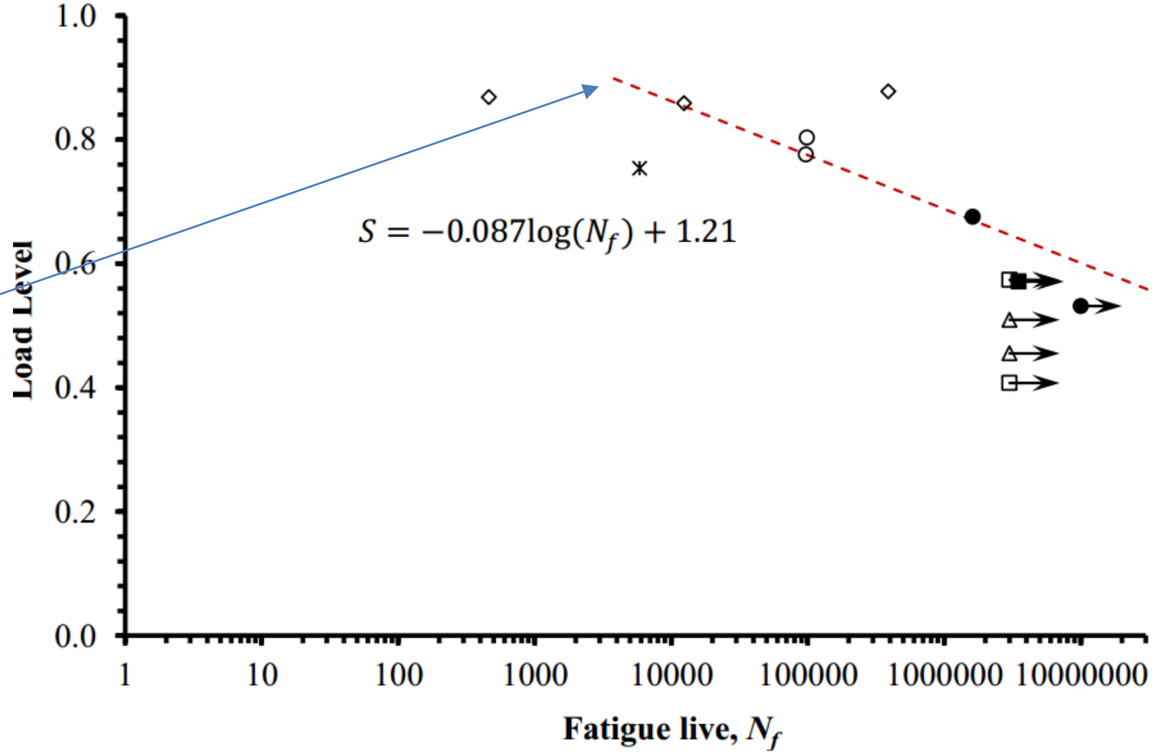


Figure 5.10 – Experimental fatigue lives based on post-cracking peak load capacity.

UNSW - Test Setup Large Scale Tests

- 30 kg/m³ (50 pcy) 4D 55/60BG
- 250 / 200 mm (9.8/7.8 in) slab thickness (plain / SFRC)
- line load contact area = 200 mm x 1000 mm (7.8x39 in)
- k = 0.08 N/mm³ (295 pci)
  (75 individual springs with k = 3.2 kN/mm (18.25 k/in)

- ‘Max load’ in SFRC (200 mm) is based on test load of plain concrete specimen (250 mm)
- Actuator limit 500 kN (112 k)
- 1.25 Hz
  (2.5 Hz: B-CF-C)

Table 6.1 – Test program for pavements.

Specimen ID	Loading span, *S* [mm]	Test type	Slab's thickness, *h* [mm]	Pre-cracked	Fibre content	Max load
A-SP-U	1000	Static	250	No	0	-
A-SF-U	1000	Static	200	No	30 kg/m^3	-
A-CP-U	1000	Fatigue	250	No	0	70%
A-CF-U	1000	Fatigue	200	No	30 kg/m^3	70%
B-SP-U	2300	Static	250	No	0	-
B-SF-U	2300	Static	200	No	30 kg/m^3	-
B-CF-U	2300	Fatigue	200	No	30 kg/m^3	70%
B-CF-C	2300	Fatigue	200	Yes	30 kg/m^3	50%

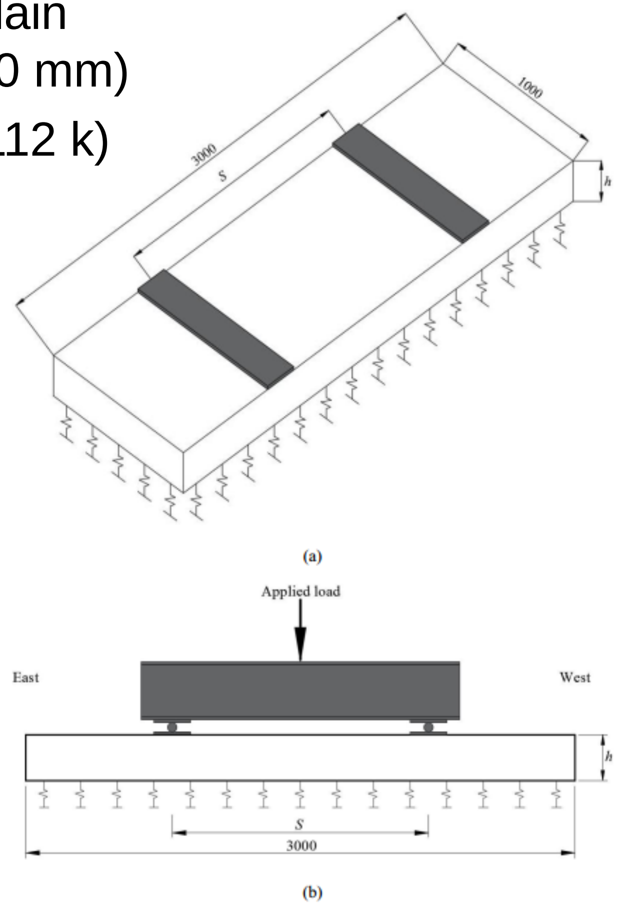


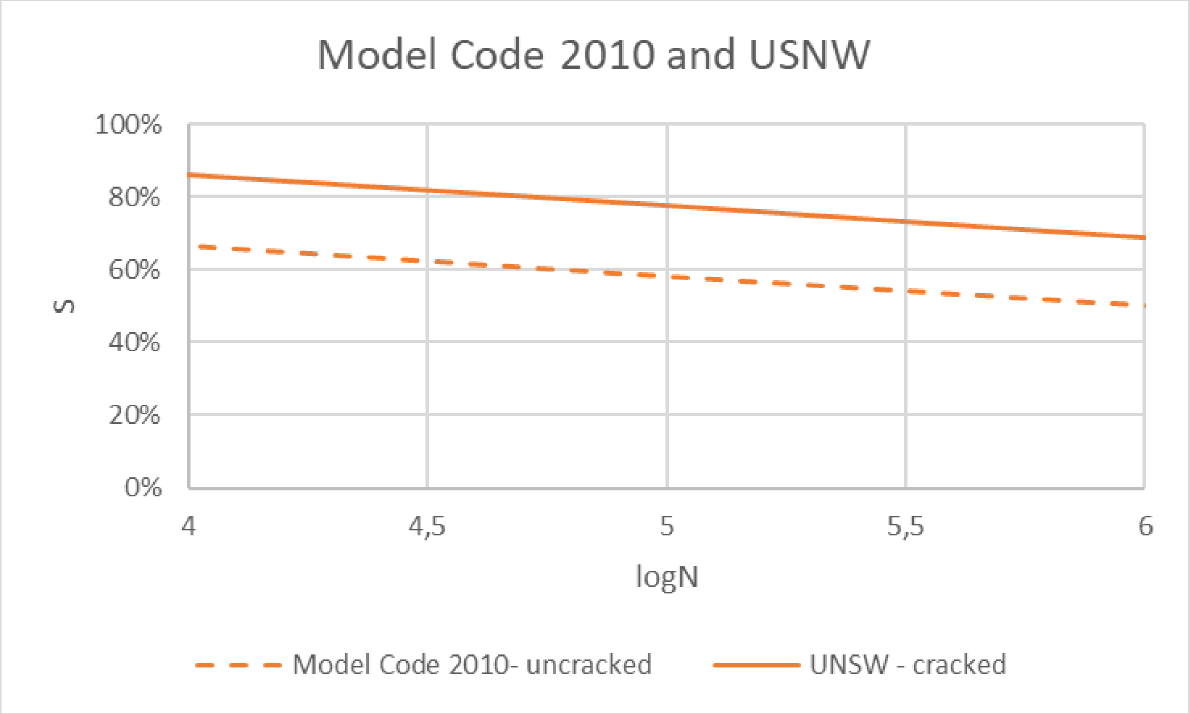
Figure 6.1 – Experimental arrangement and specimen dimensions: (a) 3D configuration of the test set-up; (b) section view of test specimen.

Bekaert Fatigue Model for SOG: Basis of the Design Model

- One model to cover the fatigue behavior of the first crack flexural strength (‘plain concrete’)
- One model to cover the fatigue behavior of the residual flexural strength (‘SFRC’)
- Starting from an uncracked specimen, the total fatigue resistance is the sum of the plain concrete and SFRC fatigue resistance
- The fatigue performance of larger specimens is better than that of smaller specimens
  - Slabs have a better fatigue performance than round determinate panels
  - Round determinate panels have a better fatigue performance than beams
- Generally, fatigue models for concrete
  - are subject to many parameters
  - have significant scatter
  - are usually simplified

Bekaert Fatigue Model for SOG

- Model Code 2010
  - Published, reviewed and accepted
- UNSW
  - The UNSW model is less conservative than the IIT model but provides results which are sufficiently safe
  - Model based on RDP testing instead of beams
  - Backed up by large scale testing
  - Limited number of tests but reasonable and in line with other test results and practical experiences
  - Testing of most specimens was stopped without exceeding the fatigue strength
- The UNSW model for cracked SFRC remains logical when comparing to the Model Code 2010 approach for plain concrete
- A clear difference between plain concrete and SFRC is visible



We mitigate potential model uncertainties by:
- limiting the use of the model to ground-supported pavement slabs with minimum fiber dosages and specific fiber types
- having extensive long-term experience with SFRC pavements with no fatigue issues reported.

Design Tools and Implementation

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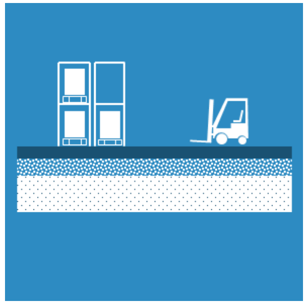
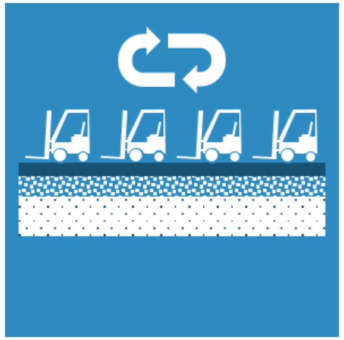
One Design Model, Two Tools



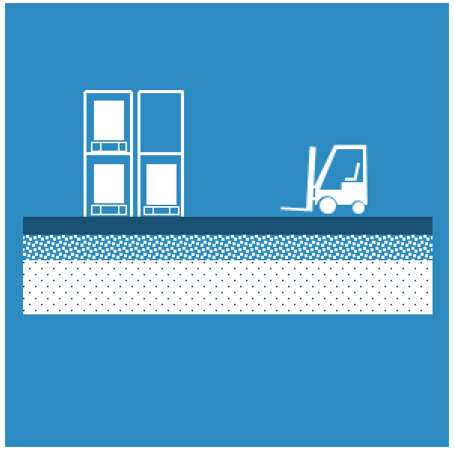
- Slab on Ground
  - Straight forward implementation of the fatigue model in our existing Slab on Ground tool
  - Using equivalent safety factors to unify and simplify the calculation steps
  - Plastic design approach
  - Yield line design approach

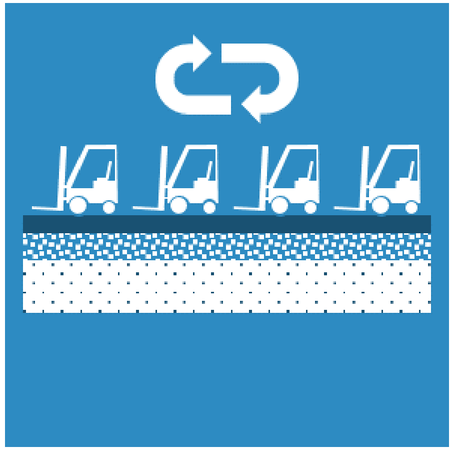


- Slab on Ground - Fatigue
  - Providing the moment capacity of the <u>system</u> for
    - ULS
    - fatigue loading: Modified yield line approach
  - Supporting pavement designers
  - Translating a linear FEA calculation into our fatigue model and a plastic calculation
  - Quasi-plastic design approach
  - ONLY when required by loading and/or project specifications

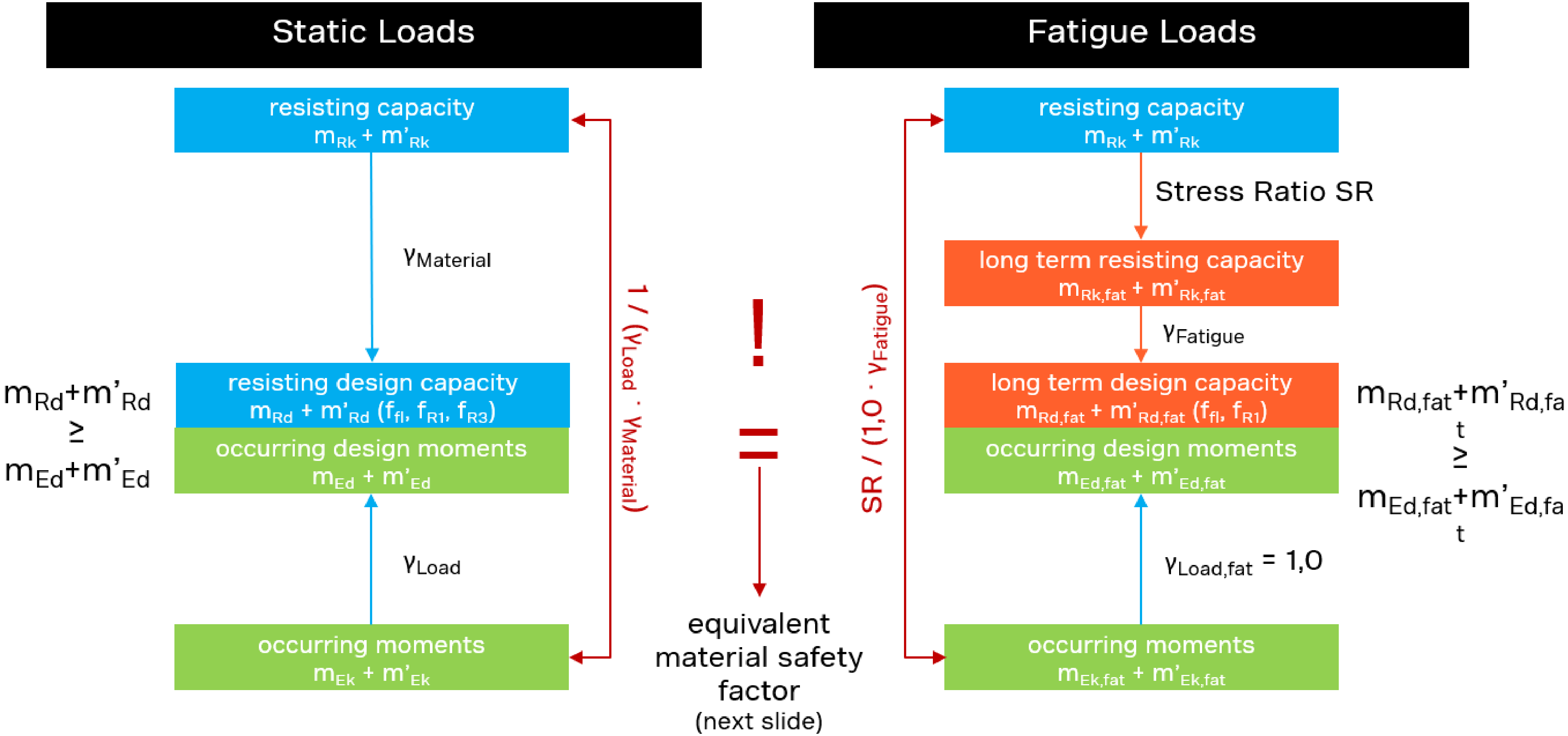
Applicability

- Scope
  - only applicable for ground supported industrial floor slabs and pavements
  - downward forces only (‘wheel loads’)
  - minimum 10^4 and maximum 10^7 load repetitions
  - only for internal users, only for users on “Technical Manager” and “Sales” level
- Fibers
  - DRAMIX®: 5D 65/60BG, 4D 80/60BG, 4D 65/60BG, 4D 65/35BG, 4D 55/60BG, 3D 80/60BG & GG types
  - minimum fiber dosage 30 kg/m³ (50 pcy)
- Concrete
  - C25/30 - C40/50 (3500 – 6000 psi)
  - additional limitations due to the selected fiber type may apply





Implementation in Slab on Ground



Implementation in Slab on Ground

Fatigue Design via Equivalent Safety Factors

- The relevant factors for fatigue design are converted to an equivalent material safety factor
- 'NEW' Equivalent fatigue factor $\gamma'_{Material}$: $\gamma_{Load} \cdot \gamma'_{Material} = \frac{1.0 \cdot \gamma_{Fatigue}}{SR} \Rightarrow \gamma'_{Material} = \frac{\gamma_{Fatigue}}{\gamma_{Load} \cdot SR}$
- The larger of the above factor and the static material safety factor is applied for each material in order to derive the moment capacity m+m' of the system.
- That moment capacity is applied to the bending moments that are determined for all wheel loads.
- All other loads will be calculated with the unmodified static material safety factors $\gamma_{Material,stat}$

	Equivalent Partial Safety Factors	Equivalent Strength Reduction Factors
Residual Strength	$\gamma'_f = \max\left\{\gamma_{f,stat}\,;\frac{\gamma_{fat}}{SR_{f,fat} \cdot \gamma_{Load,stat}}\right\}$	$\phi'_{FRC} = \min\left\{\phi_{FRC,stat}\,; SR_{FRC,fat} \cdot \frac{\gamma_{Load,stat}}{\gamma_{fat}}\right\}$
Flexural Strength	$\gamma'_{ct} = \max\left\{\gamma_{ct,stat}\,;\frac{\gamma_{fat}}{SR_{c,fat} \cdot \gamma_{Load,stat}}\right\}$	$\phi'_{ct} = \min\left\{\phi_{ct,stat}\,; SR_{c,fat} \cdot \frac{\gamma_{Load,stat}}{\gamma_{fat}}\right\}$
Compressive Strength	$\gamma'_{cc} = \max\left\{\gamma_{cc,stat}\,;\gamma_{cc,stat} \cdot \frac{\gamma'_f}{\gamma_{f,stat}}\right\}$	$\phi'_{cc} = \min\left\{\phi_{cc,stat}\,;\phi_{cc,stat} \cdot \frac{\phi'_{FRC}}{\phi_{FRC,stat}}\right\}$

Implementation in Slab on Ground

- **Fatigue design**
  - Fatigue capacity of the system is calculated as a multiple of the first crack moment

$$\Phi_{fat} = max\left\{\frac{f_{ctk,fl}\cdot SR_{c,fat}+f_{R1,m}\cdot SR_{f,fat}}{f_{ctk,fl}};\frac{2\cdot f_{R1,m}\cdot SR_{f,fat}}{f_{ctk,fl}}\right\}$$

$SR_{c,fat}$ = 1 - (log N)/12; $SR_{f,fat}$ = -0.087 log N + 1.21;

N = number of cycles

$$M_{Ed,fat} \leq m_{Rd,fat} + m'_{Rd,fat} = \Phi_{fat} \cdot \frac{f_{ctk,fl}}{\gamma_{fat}} \cdot \frac{b\cdot h^2}{6}$$

  - Fatigue capacity of the system is compared to the maximum elastic moment due to loads relevant for fatigue
  - An optional safety factor for fatigue γ_{fat} may be applied upon request

Large Scale Test Results:

Specimen	Load Span [mm]	Test Type	Thickness [mm]	Pre-cracked	Fibres [kg/m³]	Min load [kN]	Max Load [kN]	≈ f_{fl} [MPa]	≈ f_{R1} [MPa]	Repetitions till 1st crack [#]	Max repetitions [#]
A-SP-U	1000	Static	250	No	-	n/a	1st cr 467,6	5,3	0	n/a	n/a
A-SF-U	1000	Static	200	No	30	1st cr 260	> 476,6	5,3	3,8	n/a	n/a
A-CP-U	1000	Fatigue	250	No	-	82	342	5,3	0	323	323
A-CF-U	1000	Fatigue	200	No	30	81	343	5,3	3,8	1796	> 3.000.000
B-SP-U	2300	Static	250	No	-	n/a	1st cr 215,7	5,3	0	n/a	n/a
B-SF-U	2300	Static	200	No	30	1st cr 175,4	490,4	4,6	3,2	n/a	n/a
B-CF-U	2300	Fatigue	200	No	30	37,5 x2	156 x2	5,3	3,8	98334	2.000.000 +> 1.000.000
B-CF-C	2300	Fatigue	200	Yes	30	35,2	109 (1st cr 165,4)	4,6	3,2	n/a	> 5.000.000

Large Scale Test Results:

1-[log(1796)]/12

-0.087[log(3E6)]+1.21

260k*1.19

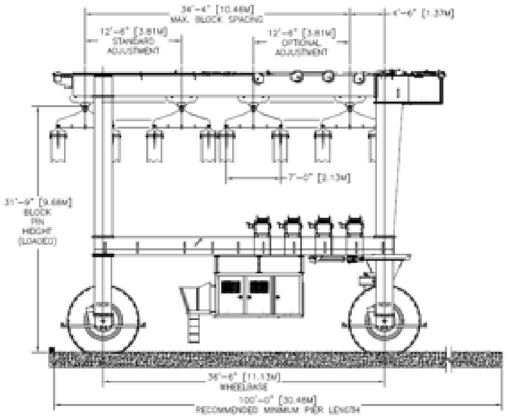
Specimen	# till 1st crack [#]	max # [#]	$SR_{c,fatigue}$ [%]	$SR_{f,fatigue}$ [%]	$\Phi_{fat,1}$ [%]	F at 1st crack [kN]	max $F_{applied}$ [kN]	max $F_{predicted}$ for given # [kN]	$F_{predicted}$ / $F_{applied}$ [%]	Comment
[illegible]	[illegible]	1	100%	100%	100%	299.3	299.3	299.3	100%	
[illegible]	[illegible]	1	100%	100%	172%	260.0	476.6	446.4	94%	actual load capacity is higher: actuator limit was achieved
A-CP-U	323	323	79%	100%	79%	299.3	218.9	236.7	108%	
A-CF-U	1796	> 3.000.000	73%	65%	119%	260.0	343.0	310.0	90%	test was stopped, but more repetitions would have been possible
B-SP-U	1	1	100%	100%	100%	138.0	138.0	138.0	100%	
B-SF-U	1	1	100%	100%	170%	175.4	490.4	297.4	61%	a[illegible]t was achieved
B-CF-U	98334	2.000.000	58%	66%	106%	175.4	156.0	185.7	119%	test was continued with 2x the initial load after 2.000.000 repetitions were applied
continued	98334	> 1.000.000	58%	69%	108%	175.4	312.0	188.9	61%	test was stopped, more repetitions would have been possible
B-CF-C	0	> 5.000.000	0%	63%	87%	165.4	109.0	144.3	132%	test was stopped, more repetitions would have been possible

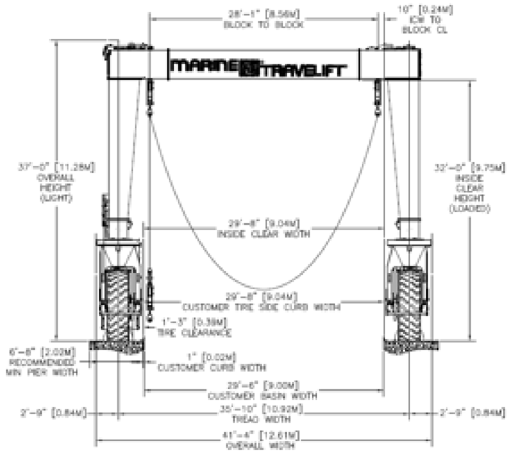
1st crack load factor $\Phi_{fat,1}$:
A factor to estimate the maximum load for the given number of load repetitions, expressed as a multiple of the first crack load.

The model predicts the maximum applicable load very well for all tests where the repetitions were achieved. If tests were stopped at a certain number of repetitions, the model can only provide an indication. This means that ratios above 100% are only overestimating the predicted loads when the test was stopped due to failure.

$$\Phi_{fat,1} = max\left\{\frac{f_{fl} \cdot SR_{c,fat} + f_{R1} \cdot SR_{f,fat}}{f_{fl}}; \frac{2 \cdot f_{R1} \cdot SR_{f,fat}}{f_{fl}}\right\}$$

Design Example SOG:





- 800 kN wheel load, 0,9 MPa
- Bekaert SOG approach
- k = 0,07 N/mm³
- 5.000.000 load repetitions

Slab on Ground

- max $m_{Ed}+m'_{Ed}$ = 124,8 kNm/m
  - γ_Q = 1,2 Load factor
  - φ = 1,2 Wheel impact factor
  - γ_{fat} = 1,0
  - γ'_f (γ_f) = 1,33 (1,2) Fiber reduction factor [fatigue (static)]
  - γ'_{ct} (γ_{ct}) = 1,89 (1,5) Concrete tension reduction factor [fatigue (static)]
- 35 kg/m³ 4D 65/60BG
- C32/40

330 mm

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Large Scale Test Results:

Bekaert