Comparative study on the fatigue behaviour of SCC and VC

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Abstract. Continuous cyclic loading on concrete constructions involves a progressive cracking mechanism, leading to significant changes of the material properties during the lifetime of the structure. Gradually, irreversible damage is inflicted and the carrying capacity is affected, which may cause structural collapse at a stress or strain level much lower than in case of a single static load. This so-called fatigue phenomenon is well-documented in literature for traditional, vibrated concrete (VC), but this is not the case for self-compacting concrete (SCC). Given the fact that this latter concrete type is already used worldwide in many types of structures, including cyclically loaded ones, a good knowledge and understanding of the static and fatigue material behaviour is crucial. Up till now, it is unsure whether SCC performs better, worse, or equally under fatigue loading conditions. Therefore, in this study, destructive four-point bending tests are performed on large beams, made from VC and SCC, both statically and cyclically (at different loading rates). A comparison of the deflection, strain, crack pattern and crack width evolution of the different concrete types is made. The results reveal some significant differences regarding concrete strain and crack width development during the cyclic tests.

Introduction

The substantially different composition of self-compacting concrete (SCC), compared to vibrated concrete (VC), affects various material characteristics. For instance, the higher content of fine particles (e.g. by adding fillers) influences the whole microstructure, making the interfacial transition zone of SCC denser and consequently increasing the compressive and tensile strength, opposed to VC with similar w/c ratio [1]. Furthermore, the reduction of coarse aggregates in SCC contributes to a lower stiffness, when comparing to VC of equal strength [1,2]. Additionally, it has been proven that both concrete types demonstrate a different fracture behaviour [2,3].

Based on these observations, the fatigue resistance of both concrete types might be different, as well, since it is governed by a damage process, related to micro-crack initiation, material damage, and fracture behaviour in general. As stated in [4,5], cracking of concrete is determined by the strength of the cement paste, and also by the location and size of the aggregates. Moreover, previous research proves that SCC with equal compressive strength, compared to VC, performs worse in cyclic three-point bending and wedge-splitting tests [6].

Experimental program

Mixtures. Two concrete batches (VC and SCC) with the same cement type and identical aggregate types and sizes were used for the four-point bending test beams. Moreover, there was aimed for a similar compressive strength. Table 1 and Table 2 provide the composition quantities of both mixtures, and their main properties, determined on several control specimens according to the prevailing standards.

Table 1 – Concrete compositions

Composition	VC [kg/m³]	SCC [kg/m³]
CEM III/A 42.5 LA	365	365
Water	175	194
Sand 0/4	726	808
Crushed limestone 2/6.3	652	451
Crushed limestone 6.3/14	434	265
Limestone filler	-	235
Superplasticizer	2.9	8.0

Table 2 – Concrete hardened properties

Properties	VC [MPa]	SCC [MPa]
f_{cm}	49.8 ± 5.0	43.8 ± 1.2
$f_{c,cub,m}$	57.7 ± 1.4	54.5 ± 5.0
$f_{ck} = f_{cm} - 1.64s$*	41.5	41.8
$f_{c,cub,k} = f_{c,cub,m} - 1.64s$*	55.4	46.3
$f_{ctm} = 0.3\ f_{ck}^{2/3}$	3.6	3.6
E_{cm}	38,210	33,082

**s = standard deviation*

Specimens. In order to achieve concrete crushing at ultimate load with the steel rebar deformation remaining fully elastic, the 2.40m long beams are over-reinforced by using three longitudinal bars Ø20mm at the bottom, two longitudinal bars Ø6mm at the top, and vertical stirrups Ø6mm every 55mm (Fig. 1). In addition, the upper part of the geometrical section is narrowed, thus generating larger concrete bending stresses than there would occur in case of a rectangular section.

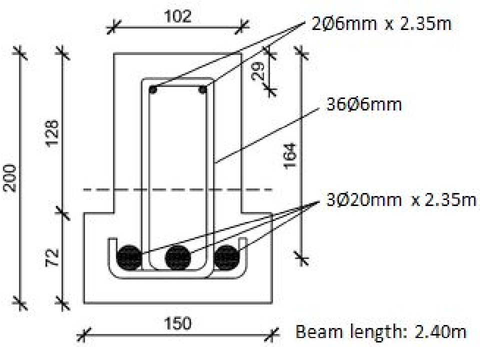


Fig. 1 – Concrete beam cross section

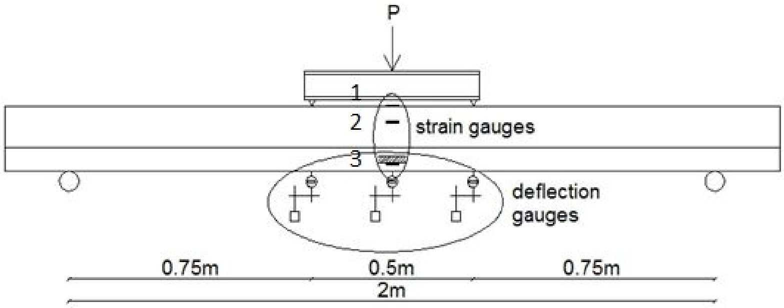


Fig. 2 – Test setup

Test procedure. Fig. 2 depicts the four-point bending test setup, applied for both static and fatigue tests. During all the experiments, the structural behaviour of the beams was registered by means of three strain gauges (N°1 in the middle of the top surface, N°2 along the side of the beam at 5cm from the top, N°3 at the lower side of the middle rebar) and three deflection gauges (at midspan and below the point loads). The crack width evolution was measured using a crack width microscope with an accuracy of 20µm.

Six reference beams (3 VC and 3 SCC) were tested statically, with increments of 5kN up until failure, in order to determine the failure mechanism and the ultimate load P_{ult}. Based on this, the cyclic tests were conducted by applying a sinusoidal load function between a lower and upper limit of 25% and 65% of P_{ult}, 10% and 70% of P_{ult}, or 10% and 80% of P_{ult} with a frequency of 1Hz.

Results and Discussion

Static Tests. All six reference beams failed by pure concrete crushing, as was aimed for. Moreover, VC's average ultimate load of 144kN agrees well with SCC's mean failure load of 143kN, which might be attributed to the similar compressive strength of both concrete types. As regards the average experimental midspan deflection, Fig. 3 shows slightly larger values in case of SCC, with a minimal difference up to a load of 85kN and a deviation of 6% near the point of collapse. Despite this, the crack width progression in Fig. 4 reveals smaller crack widths for SCC, compared to VC. However, it could be observed that SCC generates slightly more cracks, which consequently yields a denser crack pattern. When considering the concrete strain evolution (Fig. 5), it is clear that the strain failure limit of 3.5‰ is (practically) reached for both concrete types (especially SCC). This confirms the concrete crushing failure mode. Furthermore, the strain value for SCC exceeds that in VC with approximately 15% towards the point of failure. In the uncracked state (below 10kN) the deviation is minimal. These findings correspond with those, extracted from the deflection curve in

Fig. 3. The strain measurements in the reinforcement steel yield nearly identical, linear stress-strain curves (Fig. 6) for both VC and SCC, demonstrating that no plastic rebar deformation occurs during the loading process, as could be expected.

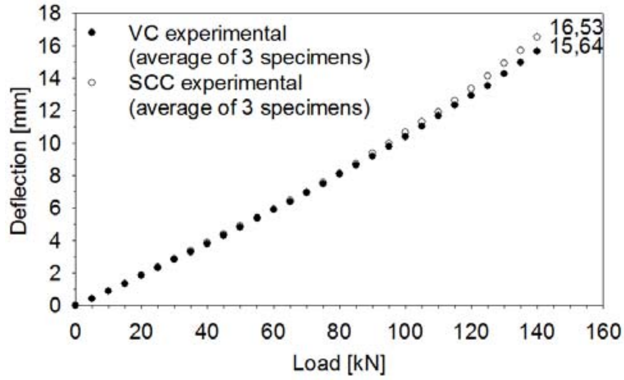


Fig. 3 – Average deflection

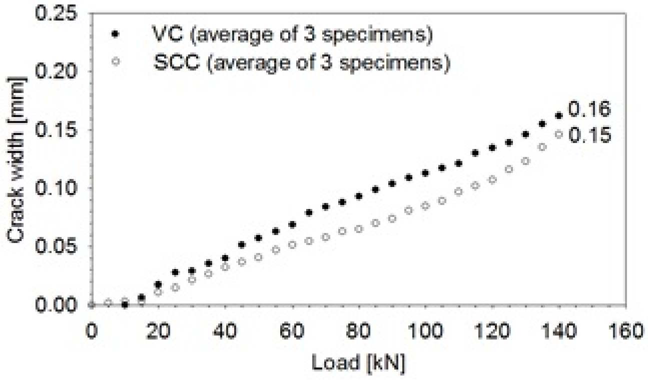


Fig. 4 – Average crack width

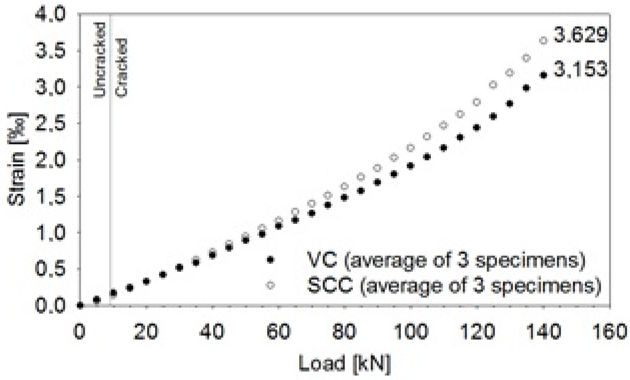


Fig. 5 – Average concrete strain

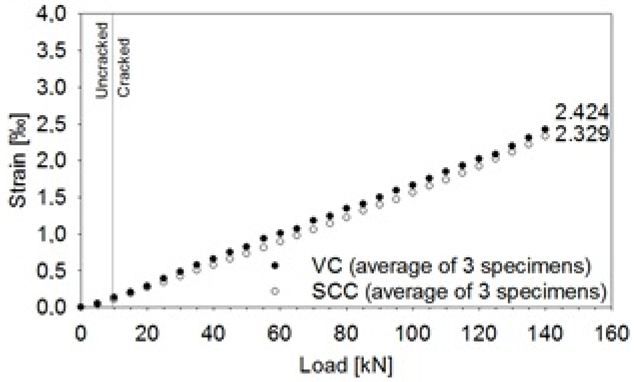


Fig. 6 – Average rebar strain

Fatigue Tests. Table 3 lists the number of cycles to failure of the cyclic tests. Most of the specimens failed due to concrete crushing (CC) of the compressed zone at midspan, except for two beams (VC F1 and SCC F7), which suffered rebar fatigue (RF). Despite some scatter, it is clear that the fatigue life depends on the applied load level: the higher the upper load limit, the least cycles the beams can sustain. However, no clear differences can be noticed between VC and SCC. This is also confirmed by the experimentally determined S-N curves in Fig. 7 (where f_{cc} is the ultimate static concrete crushing stress).

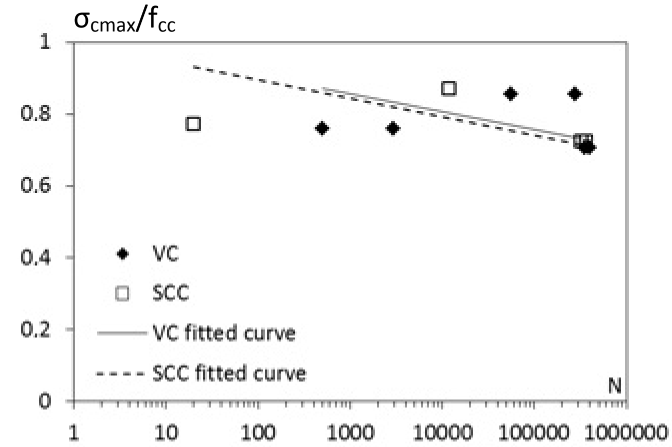
Table 3 – Number of cycles to failure

VC	Load level	# cycles	Failure mode
VC F1	25-65% P_{ult}	404,966	RF
VC F2	25-65% P_{ult}	347,777	CC
VC F3	25-65% P_{ult}	400,000	CC
VC F4	10-80% P_{ult}	2,914	CC
VC F5	10-80% P_{ult}	500	CC
VC F6	10-70% P_{ult}	275,504	CC
VC F7	10-70% P_{ult}	55,968	CC

VC	Load level	# cycles	Failure mode
SCC F1	25-65% P_{ult}	360,000	CC
~~SCC F2~~	~~25-65% P_{ult}~~	~~2,136~~	~~bad compaction~~
SCC F3	25-65% P_{ult}	88,523	LD*
SCC F4	25-65% P_{ult}	320,000	CC
SCC F5	10-80% P_{ult}	11,842	CC
SCC F6	10-80% P_{ult}	20	CC
SCC F7	10-70% P_{ult}	550,569	RF

**LD = Local Damage*

When considering the deformation evolution during the fatigue experiments, similar curves are found for the vertical displacement (Fig. 8) and strain measurements (Fig. 9). First, a long period of slightly increasing deformation is present, followed by a rapid growth up to failure. Again, the loading range is crucial: the initial (and ultimate) value increases as the upper load limit increases. Comparison of VC and SCC, however, yields conflicting results. SCC overall shows a faster concrete strain increase, but only in case of the highest load level (10-80%) the deflection of SCC is consistently larger than that of VC.



The crack width progression, which also evolves in a gradual increase and a final, short period of rapid growth, is rather stable for VC, while the crack widths in SCC grow faster. Moreover, SCC again produces more cracks, compared to VC. This might be explained by the better bond properties of SCC and the altered development of tensile stresses between the cracks.

Fig. 7 – Experimental S-N curve

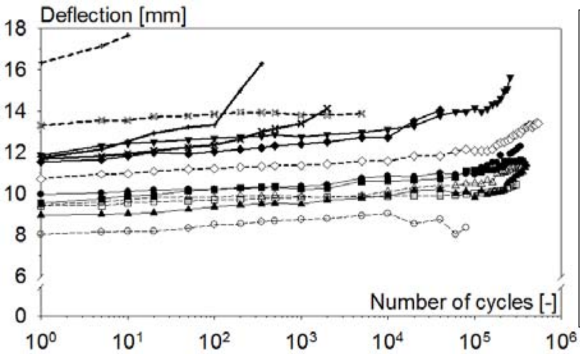


Fig. 8 – Deflection evolution

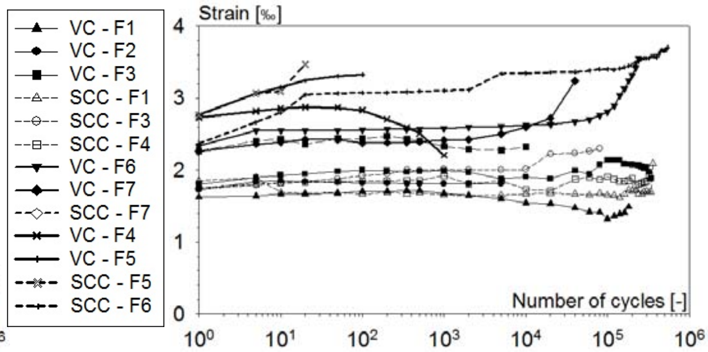


Fig. 9 – Strain evolution

Conclusions

For most tested beams (both statically and cyclically loaded) compressive failure occured. The static ultimate load is similar for VC and SCC and yet the deflection and strain is slightly larger in case of SCC. Regarding the fatigue tests, only the highest load level (10-80%) yields larger deformations for SCC. Also the fatigue life strongly depends on the applied lower and upper stress limits. No consistent relationship, covering the full loading scope, can be found between VC and SCC. When comparing the cracking behaviour of both concrete types, SCC generates, on average, a larger amount of cracks, which are smaller in the static experiments. During the cyclic tests, the fatigue crack propagation in SCC takes place at a more accelerated level.

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