FATIGUE CAPACITY OF CONCRETE SUBJECTED TO PARTIALLY LOADED AREAS

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Abstract

The compressive strength of concrete at bearing areas is increased due to the confinement of surrounding concrete and reinforcement. In these partially loaded areas, local crushing and transverse tension forces must be considered. Design codes propose criteria for the concentrated resistance force for static loading but not specifically for dynamic loading. In this study, 102 concrete specimens were tested statically, and 22 concrete specimens were tested dynamically. The effect of steel fibers on the fatigue performance of concrete and the effect of submerged specimens in water were investigated. To simulate a wind turbine foundation, the tested specimens were confined in one direction by applying threaded bolts, while the load was free to spread in the other direction. As expected, transverse reinforcement and fibers increase both the static and fatigue capacity. The static capacity increased with a factor of 1.4-2.0 depending on the environmental condition. Most design codes do not consider the environmental condition, i.e., the reduced fatigue capacity due to the water submergence of concrete structures. Based on the experimental result, a new environmental factor was proposed for a partially loaded area subjected to cyclic loading, which can be taken in the DNV design code's formulation.

Keywords: *Fatigue capacity, Partially loaded area, confinement, Steel fiber reinforced concrete*

INTRODUCTION

The process of fatigue is known as a progressive deterioration of the material, which would eventually lead to failure at different stress levels. Understanding fatigue in concrete is complicated, and the investigation of this phenomenon traced back long before it was scientifically documented. Albert [1] conducted the first scientific investigations in 1837, questioning the reason behind the failure of conveyor chains at loads below the characteristic strength. In recent years, there has been a high investment to transit to clean and renewable energies, and off/onshore seems to have a great potential for wind turbines (WT). As the world's global economy keeps growing, the development of wind turbines is playing an important role. When the wind turbines are subjected to wind forces, large aerodynamic loading would occur, which has the potential to cause complex dynamic vibrations leading to resonance. A consequence of this phenomenon is that the foundation of the structure would suffer from fatigue. The occurrence of cyclic loading in WT is often caused by a variety of wave loads such as wind, water, and earthquake. In such cases, the load is seldom a sinusoidal wave with a certain stress amplitude. Rather, such loads are messy, mixed with several other wave loads, and resemble a stochastic behavior. For simplification, such loads can be decomposed into several sinusoidal loads with specific features. Therefore, a linear damage accumulation law (Eq. 1), known as the Palmgren-Miner rule, was proposed [2]. The hypothesis states that with I different stress blocks in a spectrum, each contributes to the damage accumulation with n_i cycles over the number of endurable cycles for the same stress block (N_i).

$$D = \sum_{i=1}^{I} \frac{n_i}{N_i} \leq 1 \tag{1}$$

Among all the well-established standard codes, *DNV-OS-C502* is the only design code that takes the environmental condition into account by different multiplication factors for structures in water or air. However, the water content of the specimen is not considered, meaning that the aired and sealed structures are considered equal, which is not correct. Another drawback of the design codes is that they base the characteristic concrete strength on the 28-days cylindrical compressive strength; however, the strength will continue to rise after 28-days as the fatigue life determination is a long-term process.

A typical foundation design for onshore WT is a circular spread footing, as shown in Figure 1. To simplify the foundation's behavior, a small piece of it is considered for separate simulation. It is assumed that the boundary conditions are fixed in the loading direction, which prevents axial deformation, and the boundary condition in the radial direction is set to be free.

This study tends to give further insight into the capacity of fatigue life of these foundations under the cyclic loading over the partially loaded area. As none of the standard codes mentions the effect of the partially loaded area that are subjected to cyclic load on fatigue performance, the result could give an insight into the validity of the current design method for non-cyclic loads. In addition, the effect of splitting reinforcement in concrete for both static and dynamic loads is investigated.

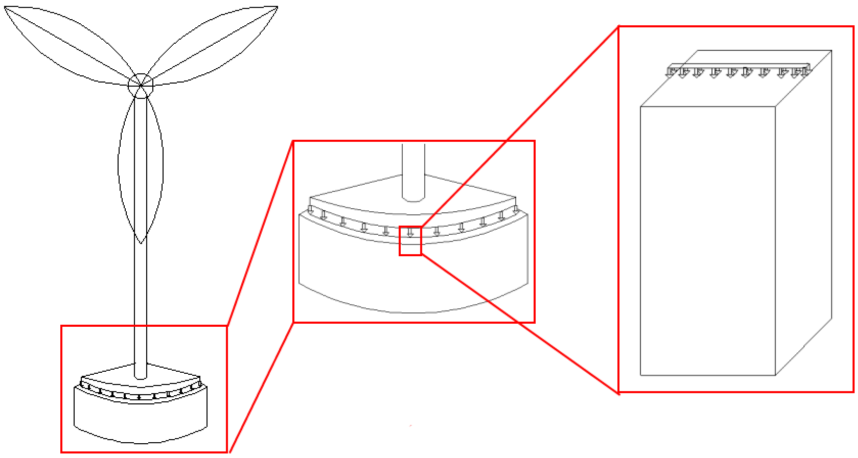

Figure 1. Simplification of test specimen and loading

Partially Loaded Area

Failure under partial loaded area can be caused by both the crushing of the concrete below the loaded area and tensile failure of the bursting region [3]. In a case where a load surface is smaller than the whole surface, the surrounding concrete gives an increase in the total compressive strength. Because of the dispersion of force below the loaded area, bottle-shaped compressive stress trajectories as well as the corresponding deviation stresses perpendicular to the trajectories occur within the block. Consequently, transverse compressive stresses result in the confined region immediately below the loaded area, and transverse tensile (bursting) stresses arise in the bursting region further away from it. Several researchers (e.g. [4], [5]) investigated the linear elastic stress distribution of partially loaded area. The standard codes such as *Eurocode 2* and *fib model code 2010* do not consider cases where the loaded area is smaller than the loaded specimen only in one direction (see Figure 2). *Eurocode 2* (similar to *fib model code*

2010) and *DNV-OS-C502* proposed their own empirical formula based on the tension ring that leads to enhancement of compressive strength. The multiplication factor of the increased loading capacity for *Eurocode 2* and *DNV-OS-C502* is $\sqrt{\frac{A_{c1}}{A_{c0}}}$ and $\sqrt[3]{\frac{A_{c1}}{A_{c0}}}$, respectively. A_{c0} is the loaded area, and A_{c1} is the maximum design distribution area with a similar shape to A_{c0}.

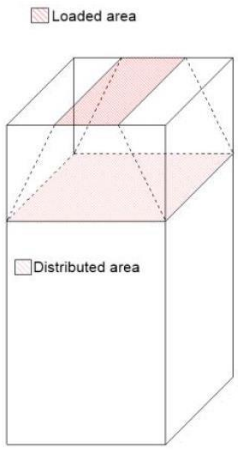

Figure 2. Loaded area smaller in only one direction

EXPERIMENTAL PROGRAM

Proportioning and Specimen Size

The concrete was aimed to have a strength class of B30 in accordance with *Eurocode 2*. The foundations of WT are made of high-strength concrete; however, since the available hydraulic jack has limitations at 1000 kN static pressure and 700 kN dynamic pressure, the strength class was decided to be B30. The cement is a standard Portland cement containing around 18% fly ash. The concrete proportioning is presented in Table 1. Due to the representation of part of the WT foundation and practical reasons in relation to the fatigue testing, the size of the specimen was chosen 210 ×210 ×525 mm.

Table 1. Concrete proportioning

Material	kg/m^3
Norcem Standard Fa	289
Free water	187
Absorbed water	12
Årdal 0/8 *mm*	1050
Årdal 8/16 *mm*	810

Reinforcement, Threaded Bars, and Steel Fibers

The necessary reinforcement was calculated according to *NS-EN-1992-1-1*. Six Ø6 splitting bars were needed to bear the tension force. In addition, four Ø10 vertical bars were used to support the stirrups. In the specimens with splitting reinforcement (WSR), six stirrups (Ø6) were used, and the specimens without splitting reinforcement (NSR) four stirrups (Ø6) were used in the lower part of the specimen. The stirrups were placed with 80 mm center distance in both categories. In the two top layers of specimens with splitting reinforcement, the stirrups that are perpendicular to the wider part of the load surface act as splitting reinforcement; therefore, only two more splitting bars are added. The schematic of reinforcement arrangement is illustrated in Figure 3. The Ø6 reinforcement has a yield strength of

500 MPa with corresponding strains at approximately 2500 $\mu m/m$. The modulus of elasticity was assumed 200 GPa.

In order to prevent the specimens from deforming parallel to the wider line-load, the threaded bars with the yield strength of 640 MPa and ultimate limit strength of 800 MPa were implemented to prevent any traction forces to occur from the end plates. Twelve threaded bars with a diameter of 16 mm were installed on each specimen and cast as the concrete was poured. After casting and dismounting the frame, the threaded bars were restrained with plates and bolts.

Steel fiber reinforced concrete (SFRC) is another type of specimen used in this study to compare its performance in cyclic loading that tested in water with other types. The reinforcement arrangement of SFRC specimens is the same as NSR (right schematic in Figure 3). The steel fibers used for this project were of the type *DE50/1.0N* from Mapei with a tensile strength of 1100 MPa. 25 kg/m^3 of steel fibers was added to the almost same concrete composition mentioned in Table 1 with small differences in the volume of aggregate.

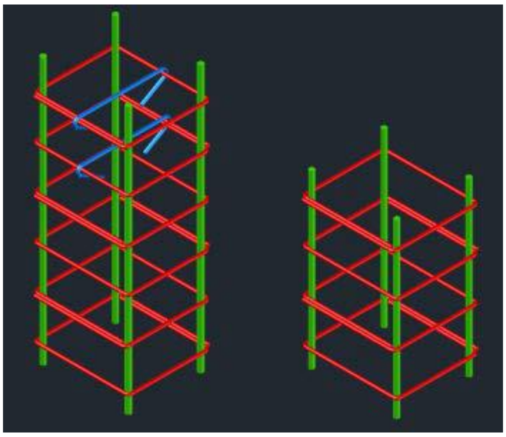

Figure 3. Reinforcement arrangement; (left) with splitting reinforcement; (right) without splitting reinforcement

Testing Setup

A hydraulic jack (MTS) with a static capacity of 1000 kN and a dynamic capacity of 800 kN with a controller (INSTRON 8500) was deployed. A steel bar with a dimension of 70×210×25 mm was placed centered on the top of the specimen. Based on the configuration, the A_{c0} and A_{c1} are calculated 14,700 and 44,100 mm^2, respectively.

Static Testing

Reference Strength:
Static testing of concrete cubes was conducted simultaneously with the fatigue testing to establish a reference strength (average of three cubes' strength) at the time of fatigue testing of the corresponding specimen. Although the reference strength could be useful for short-term fatigue testing, it is less reliable for the long-term due to the strength development as well as drying-out effect. In addition, 28-days compressive strength of cube tests were conducted for each type of specimen.

Static Strength of Specimen:
A 28-days compression test of the beam specimens (same specimens used for the corresponding dynamic test) was conducted. A percentage of the average strength capacity of the beams (average of

three tests) was chosen for the load level of the dynamic test. The load rate for all the static tests was set 0.4 mm/min.

Dynamic Testing

In order to simulate the wind load, a sinusoidal wave load (force-controlled) with a frequency of 1 Hz was applied on the dynamic test. To plot the results in an S-N curve, a minimum of two load levels (short-term and long-term) is needed. E.g., in short-term tests, a higher percentage of the average static load capacity is used; therefore, shorter fatigue life is expected. As the test program tends to simulate the behavior of a WT foundation, the minimum load level was set to 10% of average static capacity for all the fatigue tests to ensure that the specimens are subjected to constant compression. The failure criterion was set as an upper limit of the stroke in the hydraulic jack. At this upper limit, the deformation increases rapidly, and the specimen is not able to support the load anymore.

RESULTS AND DISCUSSIONS

The experimental data regarding the static/dynamic testing of different types of concrete specimens is presented in Table 2.

Table 2. Experimental data

	Avg static beam test	Avg cylindrical strength	Avg partial factor	Avg 28-days cylindrical strength	Number of cycles to failure	Max load level	Increased static strength (%)	Theoretical Max load
WSR in water testing	736.69 (kN)	33.9 (MPa)	1.48	33.76 (MPa)	231	0.85	2.51	0.83
					4749	0.75	1.92	0.73
					5023	0.75	6.64	0.70
					40523	0.65	8.99	0.60
					26040	0.65	11.65	0.58
					61854	0.65	10.17	0.59
					5576	0.72	2.98	0.70
					3664	0.72	2.34	0.70
					12204	0.72	2.34	0.70
WSR in dry testing	618 (kN)	21.6 (MPa)	1.94	20.08 (MPa)	9028	0.84	4.44	0.81
					2004	0.84	7.41	0.78
					6763	0.84	7.41	0.78
					57899	0.76	5.56	0.72
NSR in water testing	505.8 (kN)	33.53 (MPa)	1.03	33.76 (MPa)	2872	0.75	4.98	0.71
					7099	0.75	6.77	0.70
					2595	0.75	3.49	0.72
					21675	0.65	9.45	0.59
					7821	0.65	7.07	0.61
					46407	0.65	7.07	0.61
SFR in water testing	634.7 (kN)	35.94 (MPa)	1.2	34.53 (MPa)	14441	0.74	6.07	0.70
					2132	0.74	5.37	0.70
					5400	0.74	7.82	0.69

Static Results

Partially Loaded Factor:
According to *Eurocode 2* and *DNV-OS-C502*, the formulations allow the compressive strength of a partially loaded area of reinforced concrete to be increased by an amplification factor equal to 1.73 and 1.44, respectively. Since the formulations in both codes require that the transverse tension in the top of the specimens is distributed into the reinforcement, the specimens without reinforcement do not satisfy the requirement. As expected, the NSR specimens did not show a noticeable increase in strength capacity, with an average factor of 1.03. On the contrary, the specimens with splitting reinforcement in the top layers showed an increased capacity of around 1.48 for in-water-tested condition and 1.94 for in-dry-tested condition. Based on the results, it can be concluded that the formulation of *DNV* is more realistic for in-water condition, yet highly conservative for in-dry condition; therefore, the formulation of *Eurocode 2* for in-dry condition is less conservative.

Ductility:
To give an indication of the ductility for different types of specimens, a force-displacement diagram of each type is plotted, in which the area between the displacement and the designated line represents the amount of work (energy) required to make a failure. Linear variable differential transformers (LVDT) were deployed to measure the displacement. Figure 4 shows the average curves of force-displacement for each type of specimen. The result shows that the specimen reinforced with steel fibers has the highest ductility among others, suggesting that the steel fibers contribute to the so-called "crack-bridging" in concrete. Besides, as expected, the WSR specimens are more ductile compared to NSR specimens as they bear more tension in the upper layers of the concrete due to the presence of transverse reinforcement.

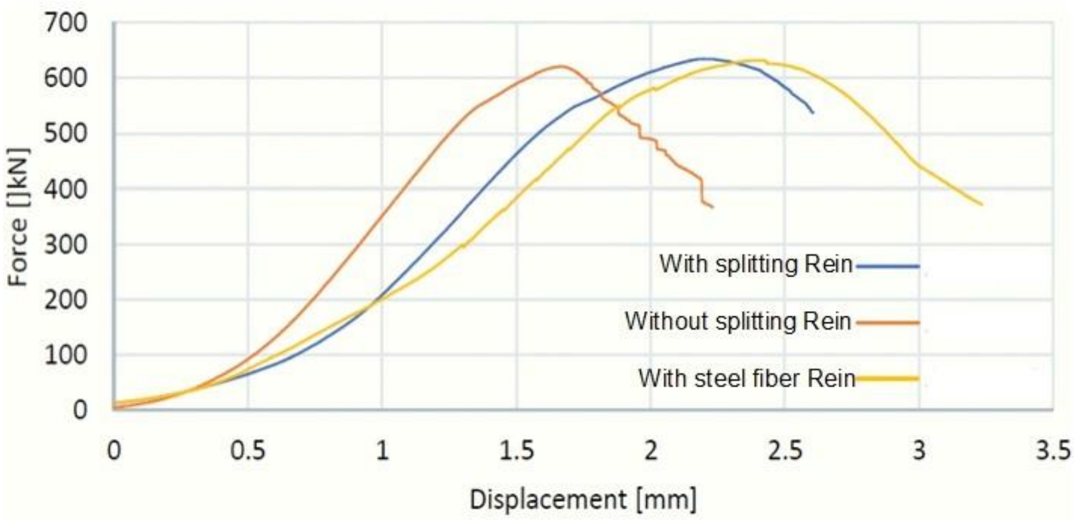

Figure 4. Force vs. Displacement; representing the ductility for different types of specimens

Crack Pattern:
During the static testing, it was observed that all the specimens followed similar patterns of cracking before reaching failure. Initially, at around 70-75% of the failure load (P_{fail}), vertical cracks appeared in the middle face of the specimen, between the first and second level of threaded bars. This phase often included spalling of concrete cover below the loaded plate. As the load increased towards the failure load, cracks started to form from each plate's corners and propagated down with a small angle toward the edge of the specimen. As shown in Figure 5, even though both types of specimens showed similar crack development, the WSR specimens had the main cracks outside of the threaded bars and reinforcement. The NSR specimens developed the main cracks inside the threaded bars and propagated towards the edge after the third layer where the stirrups were located. Since the specimens with SFR do not have splitting reinforcement in the top layers, they showed a similar crack development as NSR specimens.

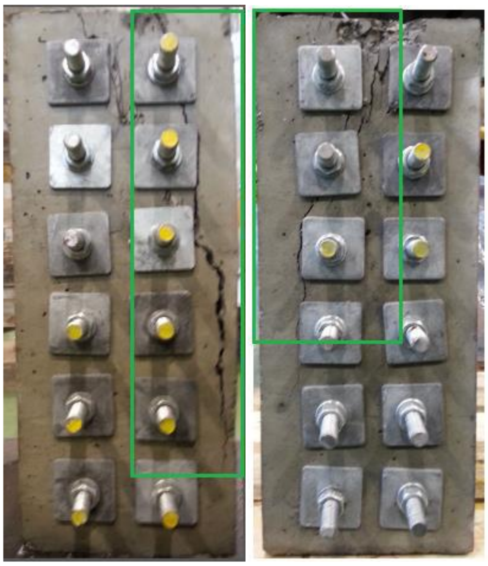

Figure 5. Critical cracks in WSR (left); and NSR (right) specimens

Dynamic Results

The fatigue life of specimens tested in water under different load levels is shown in Figure 6. As expected, the results are scattered significantly. Since the *DNV* takes the environmental effect into account (the environmental factor, C_1, is 10 for structures in water and 12 for structures in dry condition), its formulation is compared with the test results. According to the result, the difference in fatigue life between WSR and NSR specimens is relatively small yet notable. The reason behind extra strength might be the confinement effect from the reinforcement, which gives the concrete some extra cycles before failure.

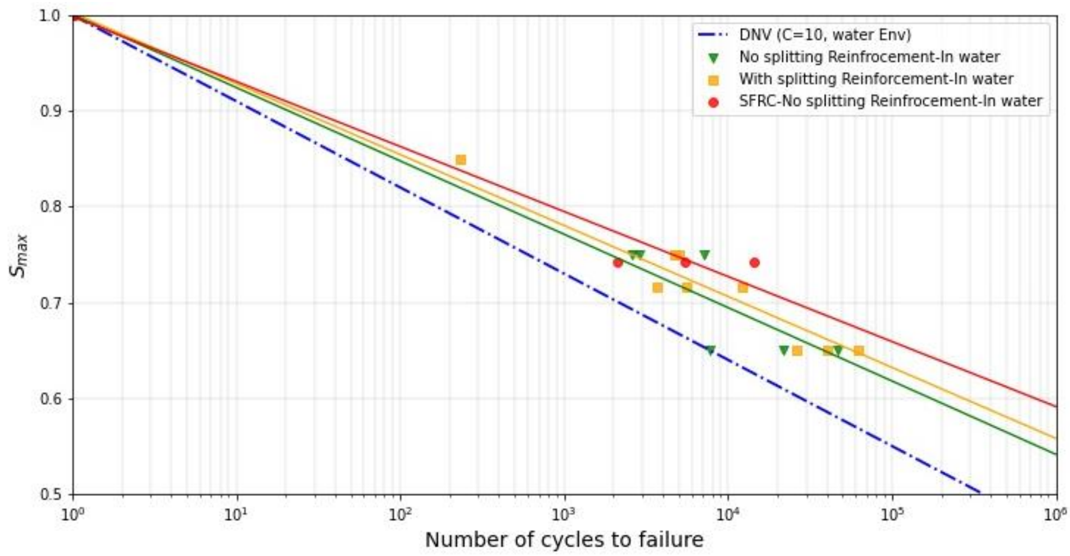

Figure 6. Comparison of experimental data tested in water with DNV's design value in water condition. The regression line is plotted for each set of data

The fatigue life of WSR specimens tested in water and dry condition is illustrated in Figure 7. The difference between the fatigue life of specimens tested in dry condition and water is significant. The specimens tested in dry condition showed up to 20 times higher fatigue life than those tested in water. This might be due to the effect of water content on the fatigue life of concrete specimens, which decreases its performance. This is in agreement with previous research [6]–[8]. Moreover, the formulation of *DVN* for water condition is less conservative than dry condition.

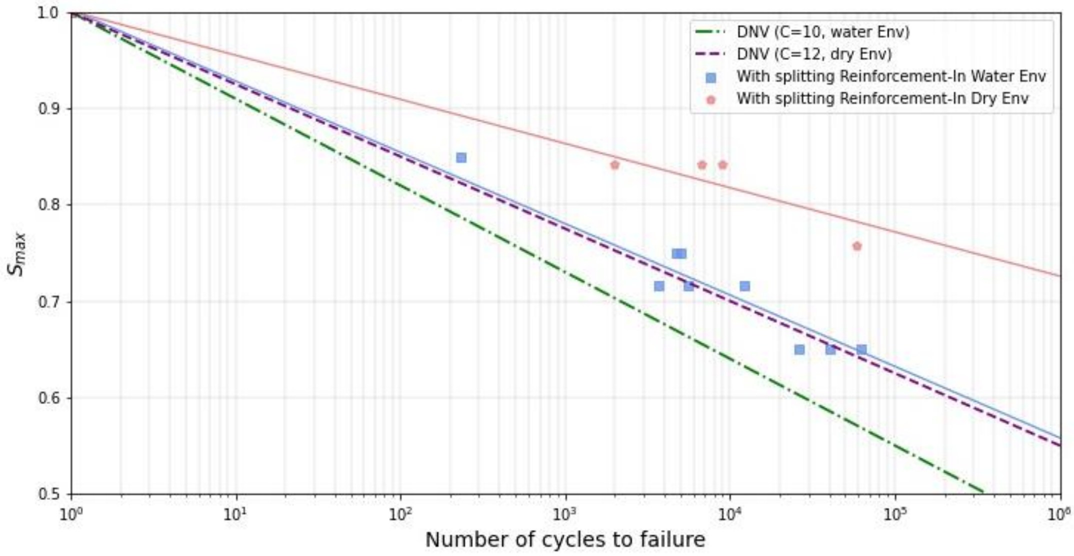

Figure 7. Comparison of fatigue life of WSR specimens tested in water and dry condition with DNV's design value in both conditions. The regression line is plotted for each set of data

The results shown in Figure 6 were based on the static strength conducted prior to the fatigue testing. The most accurate result would be the one with considering the static strength continuously throughout the entire fatigue testing. Since finding the exact static strength at any given time is impossible, an estimation was performed based on the difference between average cubic strength at the time of the static test and the fatigue test. Based on the estimation, a new load level (theoretical load level), which is always lower than the planned one, was introduced. The results are plotted for the theoretical load level in Figure 8. It can be seen that the fatigue capacity is reduced and in some cases crossed the safety line of *DNV* formulation and the rules are not conservative anymore. Based on the experimental result, a new environmental factor (C_1) for the partially loaded area of concrete structures in water condition subjected to cyclic loading can be proposed to estimate the fatigue life with a margin of safety. This value can be taken as $C_1 = 8.6$.

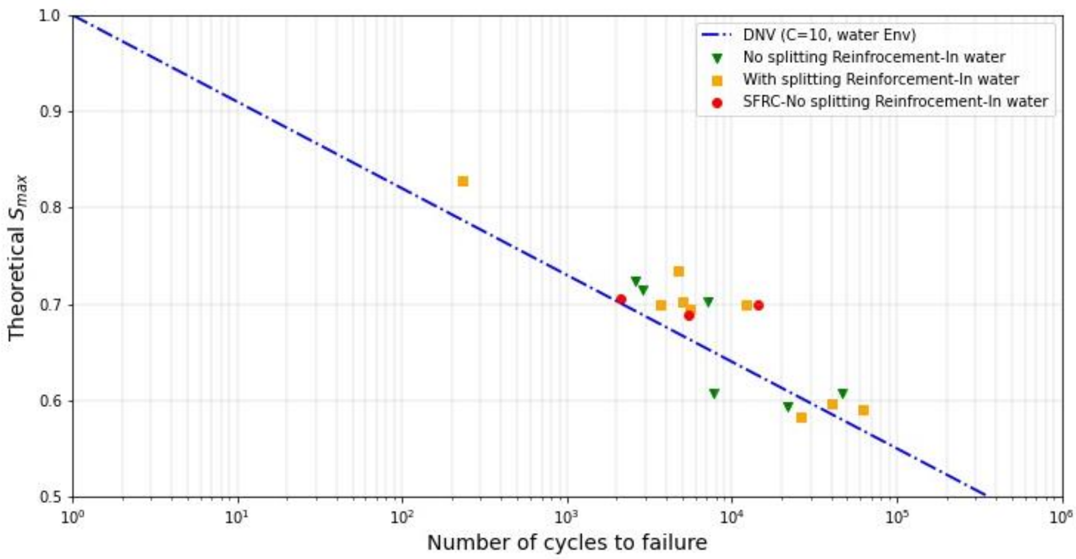

Figure 8. Comparison of theoretical fatigue life of specimens tested in water (based on the strength development) with DNV's design value in water condition

Crack Pattern:
The cracking started with concrete spalling directly underneath the loading plate, followed by small cracks forming in the compression zone. The propagation of cracks and local crushing underneath the loading plate happened slowly throughout the lifetime, but during the last 5% - 10% of its lifetime, crack propagation accelerated. Even though the main pattern is similar between the static and dynamic loading, there are some significant differences as well. For the dynamically loaded elements, local crushing under the loading plate was more severe. In addition, the cracking in the compression zone formed a V-shape spalling, as seen in Figure 9 During the crack propagation phase, the pumping effect of water in the cracks of specimens tested in water was observed. Besides, after fracture, a high rate of erosion damage in the cracks was detected, which might be due to the pumping effect that washed out the particles [8]. Considering the percentages of lifetime after the initial crack, no difference between WSR and NSR specimens was observed. It is concluded that about 85% of the lifetime happened after the initial crack.

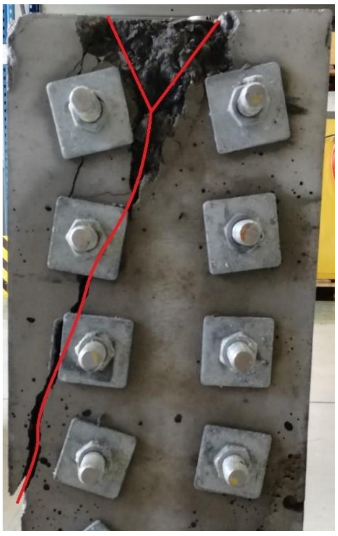

Figure 9. V-shape cracking pattern

Figure 10. At ultimate failure, WSR (left), and NSR (right)

CONCLUSION

Based on the increased strength capacity of specimens subjected to the partially loaded area, the *DNV* formulation is more sensible in terms of taking the partially loaded effect into account for concrete specimens located in water; on the other hand, the *Eurocode 2* formulation is less conservative for concrete specimens located in dry condition.

The C_1 factor in *DNV*'s design code, which takes the effect of dry condition on fatigue life into account, seems to be an appropriate scale yet conservative. However, by considering the effect of strength development after the age of 28-days, the DNV's formulation for water condition is not safe anymore. Thus, a new C_1 factor based on the experimental data was proposed for a partially loaded area subjected to cyclic loading.

Steel fiber reinforcement in concrete is more ductile than concrete with splitting reinforcement. In addition, SFRC with partially loaded areas resulted in a higher fatigue life compared to specimens without splitting reinforcement in the top layers. They also showed to have a slightly higher fatigue life compared to specimens with splitting reinforcement, though they can be considered within the margin of error.

The crack patterns in the dynamic testing showed similarities to the static testing. The presence of splitting reinforcement caused the critical cracks to develop outside of the reinforcement rather than inside for the specimens without splitting reinforcement. Moreover, the phenomenon of pumping effect as a result of opening and closing of the cracks was observed during the dynamic testing, which might increase the rate of erosion in the long term.

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