Concrete compression fatigue - Design rules and focus areas for testing

Morten S. Andersen[1], Christian Ertel[2]

[1]DNV GL, Renewables Certification, Tuborg Parkvej 8, 2900 Hellerup, Denmark

[2]DNV GL, Renewables Certification, Brooktorkai 18, 20457 Hamburg, Germany

e-mail: Morten.Sogaard.Andersen@dnvgl.com, Christian.Ertel@dnvgl.com

Morten S. Andersen, Principal Specialist, Civil Engineer from Technical University of Denmark (DTU). Has worked 20 years with design of concrete structures - mainly wind turbine foundations and towers. Has participated in writing design standards for wind turbines with high focus on fatigue performance of concrete.

Christian Ertel, Senior Engineer, Civil Engineer from Leibniz University of Hannover (Germany). Has broad experience in design of wind turbine concrete structures and grouted connections. Experimental investigation and research work on fatigue behaviour of ultra high performance concrete (UHPC).

1. Summery

This paper presents and compare some common fatigue design methods for concrete structures and discuss the factors considered in the individual design methods. Further, some of the background literature for the methods is presented and discussed. In conclusion, this paper summarizes which topics related to concrete compression fatigue should be studied further by experimental tests from the authors point of view in order to optimize the concrete compression fatigue design methods.

2. Introduction

Due to the large cyclic loading, which a wind turbine concrete support structure most often is subjected to, fatigue is often a design driver for these structures. The design rules and guidelines for fatigue in concrete structures have therefore come more and more into focus over the past decades and it is apparent that the design rules could be refined if more testing was available.

This paper gives an overview over common design rules and present some of the experimental work which these rules are based on. It will be shown how the different rules consider various design factors and how the rules take the same factors into account in different ways. Further, the design impact from different design rules will be discussed. This leads to an overview over which factors would be relevant to experientially study further to develop more precise and more optimized design rules.

The presented evaluations are based on the work behind the development of the DNV GL standard DNVGL-ST-0126 "Support structures for wind turbines" issued in 2016 [1]. The goal with DNVGL-ST-0126 is to specify how design rules can be applied to wind turbine support structure designs in order to achieve an appropriate and consistent safety level, and this also included concrete fatigue design.

There is in general very little information available about full scale fatigue tests of concrete structures and similarly very little documentation for actual concrete structures which have been reported to fail due to fatigue. Further, the available experimental fatigue tests have been performed on a wide range of specimen shapes and sizes and no standardised test method for concrete fatigue performance has been established. Therefore, there is a need for further studies of connections between length scales in order to understand concrete fatigue failures in more depth and to maybe establish a standardised test method for fatigue performance tests. Another scale length connection which is relevant to study is the aggregate size, hence to investigate if there is a different fatigue behaviour of "concrete" and "grout". Examples of how this is handled in the current common design rules is given and the need for further testing of this is discussed.

This paper will also present a number of other relations which are implemented in the common design rules and present relations which are normally just assumed to be valid for the design rules.

3. Common design methods for concrete compression fatigue

Four detailed fatigue evaluation methods commonly used for wind turbine concrete structures have been compared and evaluated in connection with the development of the DNV GL standard DNVGL-ST-0126 [1]. One of the methods is the detailed design method according to DNVGL-ST-C502 [2] which has been applied for many years for wind turbine support structures as prescribed in the former DNV GL standard DNV-OS-J101 [3]. Even though DNVGL-ST-C502 and DNV-OS-J101 are aimed for offshore structures the fatigue design method is also applicable for onshore structures. This is for example supported by the fact that this method is similar to the method prescribed in the former Norwegian standard NS 3473 [4] for concrete structures in general.

Another method prescribed in other former DNV GL wind turbine guidelines (i.e. [5] and [6]) was based on the detailed design method prescribed in Model Code 1990 [7] and that method has therefore also been studied.

Since a new detailed design method has been included in the new Model Code 2010 [8] that method has also been included in the study, as the most recently developed design method of the four studied methods.

Another detailed fatigue design method which was found relevant to include in the study is the method prescribed in the Eurocode for concrete bridges EN 1992-2 [9]. The fact that this method is prescribed for bridge structures is not considered to exclude its use for other types of structures. It is merely seen to stem from bridge structures also being concrete structures which are subjected to large cyclic loading in contrary to most other concrete structures for example houses. For the detailed fatigue method prescribed in EN 1992-2 it has also been considered in the evaluation how some national annexes for this standard prescribes its use e.g. DIN EN 1992-2/NA [10]. Further, as EN 1992-2 is based on EN 1992-1-1 [11] this standard is also referenced in this paper when it is relevant for the detailed fatigue design method prescribed in EN 1992-2.

All the studied design rules describe the relation between stress range, mean stress level, and allowable number of load cycles. These relations are normally presented by so-called "SN-curves" where the relation between the normalized maximum stress (S_{max}) and the allowable number of load cycles (N) is presented for a fixed value of the normalized minimum stress (S_{min}). The stresses are normalized with respect to the compression strength of the concrete, and these relations are also most often the main focus of the available testing.

An example of the characteristic SN-curves[A)] for the four design methods is presented below. In the example S_{min} = 0.2 and dry conditions has been assumed (see later with respect to dry/wet environment).

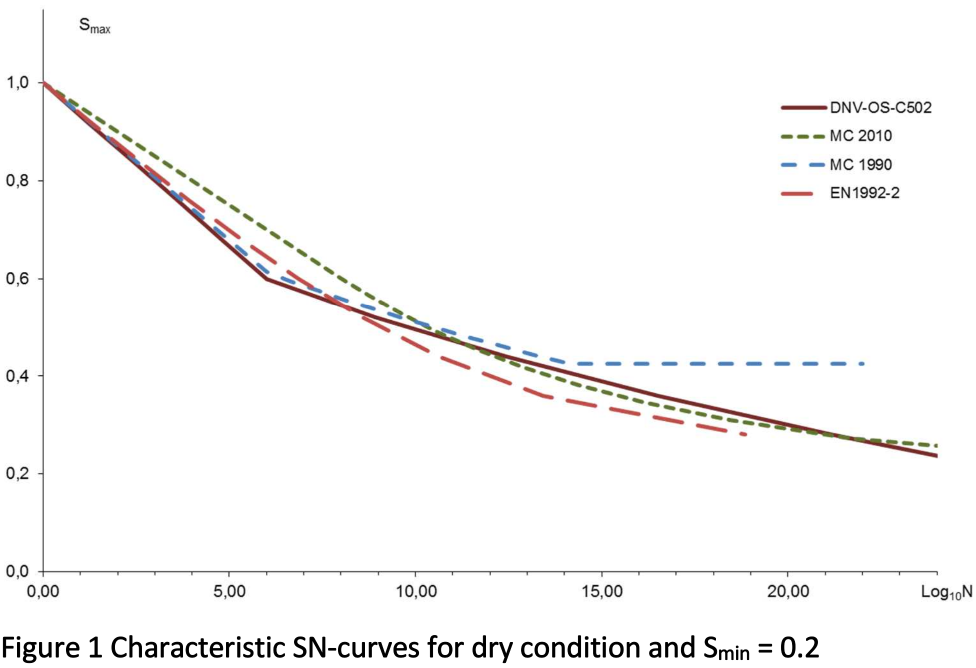

Figure 1 Characteristic SN-curves for dry condition and S_{min} = 0.2

It can be seen from the example in Figure 1 that the SN-curves crosses each other and for other S_{min} values the individual relations between the different curves are different, hence; no clear conclusion on one set of characteristic SN-curves being more conservative than others can be made. This will depend on the specific load spectrum in question as well as other structural parameters for example possible pre-stressing.

Other design factor which are considered in all or some of the evaluated design rules are:

- Partial safety factor
- Application of Palmgren Miner's summation
- Effect of high sustained loading
- Age of concrete when loading is initiated (in relation to strength increase over time)
- Environment (i.e. structures in water, saturated structures or dry structures)
- Impact from unloading during a load cycle (i.e. tensile stresses)
- Reduced partial safety factors based on inspection philosophy
- Stress gradient over compression zone
- Strength increase from confinement and/or effect from "partially loaded area"
- Change in fatigue sensitivity related to increasing concrete strength

For some of these factors very limited testing has been identified and others seem to be based on the behaviour of concrete in ultimate limit state, and yet other factors simply seem to have been assumed governing for concrete fatigue performance.

4. Overview over background literature for the common design methods

It has been found that the experimental test reports [12]-[16] include the test data which has formed the main basis for the four studied methods. The COSMAR report [12] is found to be one of the major background documents for the fatigue method in DNVGL-ST-C502 and NS 3473, and the SINTEF report [13] formed the basis for the fatigue method in Model Code 1990. The reports [14]-[16] are the documents which formed the background for the new fatigue design method in Model Code 2010 as describe in the FIB article [17]. It has not been possible to determine what the method in EN 1992-2 has been based on but it has some similarities with the method in Model Code 1990 and it is therefore assumed to be a further development of this method.

In general all reported experimental test series are found to be different in some way, and some of the differences are considered rather large. In addition, it is found that some key test parameters are difficult to determine from the test reports and it is therefore concluded that it would not be possible to do a detailed analyse of all data together without a deeper understanding of performed tests. Some of the main differences and uncertainties are listed below to indicate the complexity of a comparison.

The older test reports [12] and [13] include testing on concrete which is normally graded as "normal strength" and "high strength" whether the more recent test reports [14]-[16] mainly include testing on concrete which is normally graded as "high strength" and "ultrahigh strength".

For the test specimen size the more recent tests are typically on smaller specimens than in the older tests with the smallest specimen size being cylinders with Ø60mm/180mm (ref.

[16]). The largest specimens are the ones presented in the COSMAR report [12] which are "bone shaped" specimens with; Length=800mm, Width=120mm, Depth=300/200mm (200mm being at the slim cross section at the centre of the bone shaped specimen). And regarding this it should be mentioned that recent unpublished studies regarding size effect seem to indicate that notable better test results are achieved for specimens in the lower end of this spectrum.

Regarding concrete composition, the more recent performed tests tend to have smaller maximum aggregate sizes (i.e. many test on grout) and test on fibre reinforced concrete/grout is only found in the more recent reports.

The test frequency range is found to be rather wide (from 0.1 Hz to 60 Hz), however; the influence of the test frequency is also one of the studied factors in many of the reports. Also regarding test frequency there is a difference between the older and the more recent tests with the highest frequencies used in the more recent tests.

Most tests are performed on dry or saturated specimens but also a few results are reported for specimens submerged in water. Unfortunately only few of the identified test series includes both tests in air and in water. Hence, it can be difficult to evaluate if different results stem from a water effect or stems from other of the variables which differs between the tests. The only test report where it has been found that specimens in water have been tested with unloading in the load cycles (compression/tension cycles) is in the COSMAR report [12].

Another challenge is that it, in many of the tests reports, is difficult to see whether the relative stress levels (i.e. S_{max} and S_{min}) are calculated based on the mean static strength or on the characteristic static strength (i.e. the definition of the "reference strength" is unclear). Naturally this is an important parameters to know when comparing the tests results to SN-curves as S_{max} and S_{min} are input to the SN-curves.

Common for all tests is that "run-out" is often considered at $2*10^6$ cycles, where the tests then are stopped. Thus, there is very little data for higher number of cycles. Another common trend in all test series is that the bulk of the tests are performed with S_{min} in the range of 0.05-0.1. In addition a reasonable amount of test at for example S_{min} = 0.2 and S_{min} = 0.4 are found but tests with higher values of S_{min} are rare, and comparison for higher S_{min} values is therefore also difficult.

5. Comparison of design results

Since the four common design methods in addition to different "characteristic SN-curves" also prescribe different ways to take the listed "other design factors" into account, and since not all methods prescribe all factors, a comparison of fatigue *design results* is depending on even more factors than the comparison of the "characteristic SN-curves" alone. The performed comparison of the four common fatigue design methods therefore involved a detailed comparison of how the prescribed design factors were described and it was sought to identify the backgrounds for these factors (e.g. performed testing).

As the focus of this paper is to outline areas for future testing the full performed comparison of design results, which the different methods will lead to for different design situations, will not be presented here. However, it shall be mentioned that in conclusion it was found; that a direct comparison of design factors was not enough to compare the actual design results. A number of comparison calculation were therefore also performed for typical wind turbine support structures of concrete, with application of various representative wind turbine loading spectrums. It was found that the method according to Model Code 1990 was in most design cases much more conservative that any of the other methods, where the other three methods gave somewhat similar results (especially when EN 1992-2 was applied together with DIN EN 1992-2/NA). And as the new Model Code 2010 is available it was decided not to refer to Model Code 1990 in DNVGL-ST-0126. But all other three methods were included with some adjustments and additions (e.g. effect form environment and strength increase at partially loaded areas).

An overview of the performed comparisons of the main design factors is given below and the background literature is referenced where it has been found relevant for the comparisons. The overview is made in order to identify areas where more testing could be beneficial.

5.1 Load safety factor

For the fatigue loads DNVGL-ST-C502 and EN 1992-2/EN 1992-1-1 specifies a load safety factor of 1.0 where Model Code 1990 and Model Code 2010 specifies a load factor of 1.0 or 1.1. The load factor of 1.0 in Model Code 1990 as well as Model Code 2010 can be used “if accurate stress analysis is possible”. The requirement in Model Code 1990 and Model Code 2010 for “accurate stress analysis” (in order to use a factor of 1.0) is assumed to be similar to the requirement in IEC 61400-1 Ed. 4 CDV (Annex K, Table K.3) [18]. Hence, for wind turbines the use of a load factor of 1.0 should be allowed for fatigue stress range when the coefficient of variation (CoV) of the fatigue load stress ranges is less than 20% (as specified in IEC 61400-1 Ed.4 CDV). Any further evaluation of the load safety factor is therefore not made in this paper.

5.2 Structural capacity factors

5.2.1 General

Based on the study of the four standards[B)] it is concluded that all standards define the characteristic concrete compressive strength as the 5% quantile of the 28 days strength of 150mm x 300mm cylinders. Also all four standards specify the partial safety factor for fatigue investigations to be $\gamma_{c,fat} = 1.5$ (under comparable assumption for construction tolerances). Further, Palmgren Miner’s summation is prescribed for all studied fatigue design methods, however; where Model Code 1990, Model Code 2010 and EN 1992-2 specifies that a damage sum up to 1.0 is allowed, DNVGL-ST-C502 prescribes a maximum allowable cumulative damage ratio of 0.33 (for structural parts which are not to be thoroughly inspected). Hence, there is an added safety related to the damage limit for the method according to DNVGL-ST-C502. In general, the background documentation [12]-[17] includes evaluations of applicable safety factors and damage limits, but no complete calibrations of safety factors have been identified for any of the methods. It has neither been possible to identify any thorough investigations on whether or not the Palmgren Miner's summation can be considered applicable for compression fatigue in concrete in general.

Other design factors to include in design according to DNVGL-ST-C502 are:

- A general reduction factor of "1-f_{cck}/600" to be multiplied to the characteristic concrete compressive strength f_{cck}[c)]
- A factor "C_1" related to dry/wet environment
- A factor "C_5" to be multiplied to the fatigue design strength for grout material (if not determined by testing a factor of C_5 = 0.8 applies)
- A strength increase factor "α" considering the stress gradient over compression zone for members in bending
- A strength increase factors for partially loaded areas

5.2.2 High sustained loading

The factor "1-fck/600" in DNVGL-ST-C502 is specified to "...consider transition of cylinder strength into in-situ strength, ageing effects due to high-sustained stresses etc." (and it is applied in both the fatigue limit state design and for ultimate limit state design). The last part of this definition is similar to the reduction factor $\beta_{c,sus}$ according to Model Code 2010 when determining the "fatigue reference compressive strength" ($f_{ck,fat}$). The $\beta_{c,sus}$ factor is also described as the effect from "high sustained loading" (or "high mean stress"), but it is also mentioned in guidance notes in Model Code 2010 that the effect in addition takes into account the effect from faster test loading than real life loading. Further, $\beta_{c,sus}$ for fatigue assessment is described in the same way as the factor α_{cc} for ultimate limit state in Model Code 2010 and α_{cc} is specified to be compensated by (i.e. "equal out") the effect of strength increase over time. A similar assumption is found in EN 1992-1-1 where α_{cc} is recommended to 1.0, but if the effect of strength increase over time (β_{cc}) is taken into account after 28 days then α_{cc} is recommended to be 0.85 (see also β_{cc} as described below).

The effect from "high sustained loading" is in literature typically described to result in a strength decrease of 15-20% (see for example [19]) and the $\beta_{c,sus}$ factor in Model Code 2010 is also fixed to 0.85 for fatigue evaluations. Both Model Code 1990 and EN 1992-2 also prescribe a similar reduction factor of 0.85, but according to DIN EN 1992-2/NA this factor (i.e. "k_1") can be taken as 1.0.

Some of the background reports (e.g. [13]) discuss the effect from "high sustained loading" in relation the SN-curves since it will elevate the SN-curves if they are related to the "long term strength" instead of the "short term strength" (where the latter is common practice when presenting and evaluating fatigue tests).

Another issue to consider regarding "high sustained loading" is that the mean stress already is included in design methods. Based on these observations regarding "high sustained loading" this is found to be an important factor to investigate further.

5.2.3 Environment

A factor similar to "C_1" in DNVGL-ST-C502 (related to dry/wet condition) is not seen in any of the other three standards. However, Model Code 1990 and Model Code 2010 specify that they are not applicable for structures in water, and it has therefore been concluded that a similar restriction apply for design according to EN 1992-2 due to the similarities of the methods. In the selection of "C_1" a distinction is made between compression-compression load cycles and compression-tension load cycles for "in water" condition. The "in water" effect is considered to be related to for example build-up of pore pressure in cracks and therefore related more to whether the concrete is wet, rather than actually submerged in water.

It is not clear if the restriction in Model Code 1990 and Model Code 2010 for structures in water also is intended to apply for wet condition and it is therefore found relevant to investigate the effect from water further. And such evaluations should also consider whether unloading appear in the load cycle or not.

5.2.4 Grout and high strength concrete

A factor similar to "C_5" in DNVGL-ST-C502 (for grout material) is as for "C_1" not seen in any of the other standards, however; since this structural grouts are commonly high strength grouts the factor can be compared with the expression "($1-f_{ck}/400$)" in Model Code 2010 which is another reduction factor in Model Code 2010 when determining the "fatigue reference compressive strength" ($f_{ck,fat}$). The expression ($1-f_{ck}/400$) is in Model Code 2010 described as a factor which "take into account the increasing sensitivity of concrete with increasing compressive strength". The same factor is found in both Model Code 1990 and EN 1992-2 but with a denominator of 250 instead of 400, but it has not been possible to find out why this factor was introduced initially in Model Code 1990 (which was the first issued of the three standards). It was for example not mentioned in the background report [13], where the SN-curves for Model Code 1990 were developed. The change to ($1-f_{ck}/400$) in Model Code 2010 is described in the FIB article [17] but it is not found to be strictly related to test results, rather to an engineering evaluation.

The factor might be related to the concern for a more brittle fracture typically seen for high strength concrete in the ultimate limit state, however; this is not known for sure and no testing has been found related to whether a similar effect is relevant in the fatigue limit state. It is therefore found relevant to investigate further if and how the fatigue sensitivity increase with the concrete strength.

As the "C_5" factor in DNVGL-ST-C502 is related to grout materials it is also interesting to evaluated the length scale effect related to aggregate size to get a better understanding of any such effects.

5.2.5 Stress gradient over compression zone

Both DNVGL-ST-C502, Model Code 1990, and Model Code 2010 describes methods which allow for a reduction of the calculated edge stress in a concrete member in bending (related to stress gradient over compression zone). A similar reduction is not described in EN 1992-2 or its related standards. This effect could therefore also be relevant to study. It is however the authors experience that it is rarely the cross sections with high bending where fatigue is the design driver for typical wind turbine concrete support structures.

5.2.6 Confined concrete/Partially loaded area

Two special structural conditions are commonly described for concrete design to allow for strength increase in the ultimate limit state. These are “confined concrete” and “partially loaded areas”.

Regarding possible strength increase factors for “partially loaded areas” and/or “confined concrete” very little testing related to fatigue strength can be found, and in the available evaluations the effects for the two different conditions are often see as one. But since both effects require reinforcement through or enclosing the loaded area in order to take the strength effect into account the calculations are not that different for the two approaches when the methods are applied to a partially loaded area.

Based on initial testing which DNV GL has been involved in, a factor of 1.3 has been prescribed for design according to DNVGL-ST-C502 for the highly loaded area underneath a wind turbine steel tower bottom flange. However, the initial testing also show that additional testing was needed in order to get a better understanding of the mechanisms and to possibly generalize this to other partially loaded areas or confined concrete in general.

5.2.7 Strength increase over time

In Model Code 1990, Model Code 2010, and EN 1992-2 a "β_{cc}" factor is prescribed as the strength increase over time. This factor is not found in DNVGL-ST-C502 and no testing has been found related to fatigue strength development over time. It is therefore also found relevant to study this factor further and to evaluate in more details how strength development over time can be considered for concrete fatigue design.

5.2.8 Load frequency

Regarding “the effect from faster test loading than real life loading” (which for example Model Code 2010 also notes the $\beta_{c,sus}$ factor to account for) there are various investigation regarding the impact of frequency of the loading but no clear conclusion has been found. However, in [12] it is concluded that there is no impact from changing the frequency from 0.2 Hz to 1.0 Hz, but that longer lifetimes are found for 3.0 Hz. And in [13] it is concluded that the test frequency shall be representative for the load which the structure will experience (typically around 0.3 Hz for a wind turbine structure).

As many of the more recent testing is done at higher frequencies that the earlier testing the impact from test frequency should be a subject for further research.

5.2.9 Additional design factors

In addition, to the above listed design factors there are other factors and relations which are not considered in any of the investigated methods, but which based on the test reports studied in connection with development of DNVGL-ST-0126 are found to potentially have an impact on fatigue resistance of concrete. These factors and relations are:

- Size of structural element (vs. test specimen size)
- Order of loading (high loading early or late in the lifetime, or random loading - also related to whether strength increase can be considered)
- Curing conditions for the concrete structure (e.g. heat treatment)
- Impact from mixed-in fibres

These factors and relations would therefore also be relevant to study further in order to more exactly determine their impact and to evaluate if and how to consider them in design.

6. Conclusion on focus areas for future testing

As presented above the commonly applied design methods for compression fatigue in concrete are not directly comparable and they include to some extend different design factors, and include similar factors in different ways. It is therefore found that both a more in-depth investigation of the "characteristic SN-curves" and of the related "other design factor" could be beneficial in order to optimize concrete compression fatigue design.

In order to evaluate the existing "characteristic SN-curves" the following factors should as a minimum be studied (in addition to the relations described by the SN-curves themselves):

- Length scale effects related to test specimens (e.g. should the test specimens be of a minimum size and is there a length scale to consider in actual designs?)
- Sensitivity to test frequency and its relation to the actual load frequency on the in-place structure

This could be performed by a combination of; collecting all available data, and perform new testing where the listed issues are compared. In connection with the work, or in addition to this, it should be considered to develop a standardized test method for compression fatigue in concrete. It would also be beneficial to have more test running until actual fatigue failure is registered (and not assuming "run-out"), even though this naturally will result in longer testing periods.

It should also be sought to create a better basis for evaluating which other design factors are important to consider in design and determine their effects. Based on the comparison studies the following factors have been identified as the most important to gain more experience on:

- Sensitivity to "high sustained loading" (e.g. is the mean dependence of the SN-curves sufficient to take this effect into account, or are additional design factors necessary?)
- Sensitivity to strength (i.e. is the *relative* performance of the concrete reduced with increased strength?)

- Sensitivity to aggregate size (i.e. is there a length scale effect to be considered related to aggregate size?)
- Sensitivity to environment: The physical phenomenon related to impact on wet structures should be studied to gain more knowledge about whether the effect is mainly related to submerged structure or related to wet structures.
- Sensitivity to confinement and strength increase at partially loaded areas (what are the mechanisms which governs this and what is for example the effect of reinforcement?)
- Applicability of Palmgren Miner's summation (is it applicable to all kind of concrete structures, or shall the order of loading for example be consider in certain cases?)

A better understanding of all these factors would ultimately enable a thorough calibrate of the partial safety factors for fatigue design.

In addition, the following topics would also be of high interest to have focus on:

- Fatigue in fiber reinforced concrete (can mixed-in fibers with certain characteristics, be used to improve the compression fatigue performance of concrete?)
- Shear fatigue (is compression fatigue design rules directly applicable for "strut calculations" in structures with shear reinforcement and/or can the methods for calculating shear fatigue in structures without shear reinforcement be optimized?)

7. References

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[A)] By “characteristic SN-curve” is here meant the SN-curves prescribed in the respective standards but illustrated without the prescribed safety factors and other factors which are prescribed to be included for design.

[B)] In this paper the term “standard” is used as the term for documents in which the evaluated design methods are prescribes regardless of whether the term used in the respective documents is “standard”, “code” or “guideline” etc.

[C)] The characteristic strength is in DNVGL-OS-C502 denoted f_{cck}. In the other studied standards it is denoted f_{ck}.