Revaluation of Concrete Design in Marine Engineering

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The marine environment is notoriously harsh on man-made structures and the materials used for construction are severely tested by the elements. Reinforced concrete is one of the materials often used for nearshore, and offshore, structures. These structures, whether immersed in or suspended over the sea are subject to high levels of chlorides the potentially detrimental effects of which are well documented.

There is however also much anecdotal evidence of many older concrete structures which have apparently withstood the test of time in circumstances apparently similar to those which have caused heavy damage of more recently constructed structures.

By reference to recent and superseded Codes of Practice, case studies and theory this article investigates and compares current design practice with those used in the past. It focuses on two areas of reinforced concrete design; the influence of cover and allowable crack widths on chloride ingress and the impact of (allowable) steel strain on these and the dimensions of structural elements.

The article attempts to indicate whether a different approach to reinforced concrete design, within the limits of the codes, for marine structures might be more advantageous from the perspectives of engineering, construction, durability and economics and suggests avenues of future research on this subject matter.

1. Introduction

Deterioration and durability of concrete have been subject of considerable research effort over the years, the results of which have found their way in codes and standards and it is also a subject of particular concern in marine structures. This paper does not have the intention to give a detailed overview of such research, though some references are made, but to combine the results with case studies and experience and try and advice on a coherent approach and research for the design of marine structures from a practical perspective.

Several of the statements on design in this paper are based on the authors' experience/observations in port and harbour structures over the last decades.

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2. Case Experiences

There are several documented case histories of old reinforced concrete structures in various states of deterioration. What these cases make clear is the big difference in performance, with both severe and limited deterioration encountered.

Several such examples are listed by Costa and Appleton (2002) looking at a docks, wharves and a bridge respectively and found understrength concrete, reduced covers and honeycombs to have significantly contributed to the deterioration.

Two jetties in Singapore performed well after 50 years in terms of durability except in those places where the initial quality appeared to be less than in other parts as reported by Choong (2003).

One of the recurring findings here and in other cases appears to be that of bad workmanship or non-adherence to specifications or prevailing codes in those cases with problems. These findings correspond with what 'common sense' and guides such as the US Army Corps of Engineers manual[4] predict and conforms with both the experience of the authors and DMC in general which finds damage is often initiated at locations where quality of the concrete was lesser during the original construction.

Other areas where deterioration has been found to be more severe than on structures as a whole are those with higher occurrences of wetting and drying, particularly with seawater. These are often the undersides of structures over revetments where the slope causes increased wave run-up and/or breaking and splashing of waves leading to spray on the underside of concrete elements which is also not washed by rains. Similarly areas such as in front of mooring points can show higher incidences of delamination or spalling due to the drip of seawater from mooring lines which increases chloride levels.

These findings give relevant and important information for the design of reinforced concrete structures.

Fig. 1. Spalling at the base of a ramp over the tidal zone, the rest of the structure only shows mechanical damage.

Fig. 2. Spalling on top of a dolphin in front of mooring equipment.

3. Review of Deterioration Causes

3.1. *General*

One of the important factors determining the deterioration of reinforced concrete in the marine environment is off course chloride ingress. Codes and standards have long recognized this fact and categorized the marine environment as severe with associated requirements to reinforcement cover, crack width and concrete mix.

Though there are multiple other possible causes of deterioration of (reinforced) concrete chloride attack is a major and inescapable risk factor which will be further focused on.

3.2. *Chloride penetration models and tests*

Considerable efforts have been made in the past to produce models to predict chloride ingress speeds and profiles in concrete due to diffusion and capillary action in the concrete, the latter being a particularly important mechanism in the tidal, splash and atmospheric zones of marine constructions according to Meijers *et al.* (2003).

These theories have been tested and benchmarked against reality by means of tests as well as investigation of existing structures such as reported by Rincon *et al.* (2004). and Castro *et al.* (2001). which investigated the influence of environment and concrete properties on ingress profiles and speeds and compared these with models.

Some of these models appear to have reached a stage where reasonable predictions can be made with respect to the future behavior in new or existing structures from which risks with respect to (future) corrosion and service life can de deduced, though discrepancies are still found.

The chloride intrusion models do not appear to make allowances for local damages in the concrete such as cracks. If these are limited to common strict criteria this may not lead to excessive deterioration of the structure but may influence the interpretation of the models as they form conduits for the ingress of (salt) water into the concrete and build-up of salts in the splash zone, furthermore cracks also locally reduce the effective cover to the reinforcement. As shown earlier local damage is often the starting point of deterioration of concrete structures, and cracks may be no exception.

3.3. *Cracking*

Despite the statement in the previous paragraph cracks, when maintained within the prescribed ranges, do not appear to have been a major cause of durability problems according to Schiessl (1980). This does however not equate to stating that cracking is not a concern and given the long-term nature of empirical evidence in this area there may however be some areas of concern with current design and construction practice.

4. Design of Marine Structures' Concrete Elements

4.1. *Brief historic perspective*

Mid last century mild plain reinforcement steel was supplemented with higher yield deformed bars. These bars have a better bond and combined with the higher strength allow for better utilization of the concrete leading to smaller concrete members compared to plain bar applications in many situations. This was followed by codes moving away from allowable stress designs as a guide to an Ultimate Limit State vs Serviceability Limit State approach.

This approach, combined with 'better' concrete and steel materials led to more optimized designs with higher stresses. These higher stresses however also lead to larger strains resulting in larger crack widths which, in most standards, are limited for aggressive environments.

This should not come as a surprise as the 1962 Dutch concrete code[5] already states that, referring to the higher grade reinforcement steel, the 'higher stresses are only then advisable if it is ascertained that the cracks do not develop to a width that makes corrosion of the steel possible' (translation by author). The code further states that plain bars with a steel stress of 140 N/mm^2 will generally adhere to standard with respect to cracks while deformed bars with a steel stress of 220 N/mm^2 will not in the case of aggressive environment.

4.2. *Design in practice*

Following theory and codes the width of cracks at the concrete surface, once the crack pattern is developed, has a direct relation to the strain in the reinforcing steel. As a result of this, following e.g. the formulae BS8110 part 2, the method to limit crack width with a given configuration, if required, is by lowering the strain in the reinforcement bars.

Lowering of the strain in the steel can be done by increasing the amount of reinforcement in the element or alternatively the structural elements can be deepened to increase lever arm and thus decrease stresses at similar reinforcement levels. The latter method however generally means increased concrete volumes.

In practice the desire to reduce over-water work and weights or thinner members to prevent hydration temperature problems often leads to reduced member sizes, which is possible from a strength perspective by the higher strength materials. With the higher covers required for the aggressive environment this can lead to passing the allowable crack widths with reinforcement quantities that are sufficient for ULS conditions. The crack criterion is then often met by increasing the reinforcement till the criterion is just met.

Similarly, the use of prefabricated elements, in itself a measure at least partially meant to increase quality of over-water work, has led to 'stacked' structures where early elements carry much of the selfweight of the structure before the full cross section is developed and mobilized. This leads to high strains in the construction stage which results in a high number of developed cracks initiated in the construction stage but present throughout its life. Similarly the use of thinner walls in e.g. pumphouses to reduce thermal stresses leads to higher service stresses.

Though utilising the above or similar approaches the design crack widths remain within code limits the higher incidence of cracks and bigger average cracks are a departure from the more robust structures of the past.

4.3. *Concluding*

Over the past decades there has been a focus on increased utilization of the capacity of materials and the preparation of 'economical' i.e. cheap designs with minimized use of materials and maximized construction speed. This appears in practice to be done by focusing on the Ultimate Limit State and then checking the design for the Serviceability Limit State ensuring that it, just, meets these criteria. As can be deduced from the previous this can lead to an increase in the reinforcement and basically an underutilization of the high yield steel.

Given further that cracks are determined under serviceability limits this leads to an increased likelihood of cracks being present. Combined with the fact that the calculated crack widths can only be considered to be expected values there appears to be considerable chance that a high number of cracks will be present, of which a number will be larger than the allowable width.

5. Proposal

Much of the foregoing concerns result from the authors' experience. It is suggested that research into the depth of chloride penetration in the vicinity of cracks may shed light on the risk associated with this. Similarly a metastudy comparing designs spanning several decades and their behavior may yield correlation between these factors.

Till such time a return to robust designs, and giving attention to SLS limits appears a reasonable course of action to reduce risks. Increased use of lower strength reinforcement could also be considered to reduce the discrepancy between ULS and SLS requirements.

It further remains of the utmost importance to ensure proper execution of works and adherence to specifications. To ensure this a yet to be published report of *fib* Commission 5: Structural Service Life Aspects also draws attention again to the importance of proper detailing to allow for good workmanship, as they often appear to be the root cause of durability problems. In that sense 'robustness of design' should also include the proper detailing of reinforcement and elements to ensure proper cover etc.

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