CONDITIONAL ASSESSMENT SYSTEM FOR REINFORCED CONCRETE MARINE STRUCTURES – A CASE STUDY

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SUMMARY

Current study mainly focusses on the development of a conditional assessment system for reinforced concrete structures present in marine environment demonstrating with a case study of cargo berths (CB) at Deendayal Port Trust, Kandla, Gujarat, India. The maximum tidal range at the study area is nearly 8m, making the field non-destructive tests (NDT) challenging. The proposed assessment system is based on the damage level classification (DLC) of structure, evaluated by a set of widely used NDTs. The study further investigates the usage of DLC system in comparison with the Condition Rating (CR) method developed by Verma *et al.* NDTs were conducted at 182 locations between CB 7-10 and observed that the condition of the marine structure, indicated by CR system and DLC system is similar irrespective of their different test approaches. The proposed DLC assessment system is reliable, quick, efficient and requires relatively lesser efforts compared to the CR system.

1. INTRODUCTION

Chloride induced corrosion is the prime reason behind the degradation of embedded rebar in reinforced concrete (RC) marine structures. Along with the chloride attack, RC members present in the intertidal zone and splash zone are imperilling to alternate wetting and drying cycles because of continuous waves and tides. This process escalates the corrosion of embedded rebar causing corrosion cracks, spalling of concrete, degradation of mechanical properties of rebar (Almusallam, 2001; Vanama and Ramakrishnan, 2020) and bond with concrete (Almusallam *et al.*, 1996; Coccia, Imperatore and Rinaldi, 2016; Lin *et al.*, 2017), thereby reducing the overall strength and service life of the structure. Such an aggressive environment and heavy operating load conditions make most of the marine structures deteriorate faster, resulting in lesser service life than they have been designed for.

Estimating the service life of RC structure demands ample of field and laboratory testing. Many researchers in the past have proposed models and methods for determining service life. However, there are very few models that apply to the structures in the marine environment. Verma *et al.* (Verma, Bhadauria & Akhtar, 2013) have proposed a model based on Tuutti (Tuutti, 1982), for estimating the service life of RC structures based on corrosion rating (CR) indices. However, calculating these indices requires a lot of field and laboratory tests, viz., estimation of chloride content at rebar depth, core testing, rapid chloride migration test (RCMT), depth of concrete cover, carbonation test etc., which entails sophisticated laboratory equipment. The present study proposes a damage index model that gives an idea of the condition of structure based on the widely used NDT methods, viz., half-cell potential test, UPV test, Rebound hammer test and so on, which are relatively quick and easy to perform. The proposed model also considers the mass loss of rebar due to corrosion and extent of physical damage caused to the structural members in terms of cracking and spalling of concrete etc. The present study discusses the typical challenges encountered during the field NDTs of a marine structure for the berthing of cargo ships and the possible solutions to overcome. The study demonstrates the effectiveness of damage index model (DLC) in comparison with the CR system for assessing the condition of marine structure with a case study of berthing structure at Deendayal port trust, Kandla.

2. STUDY AREA

Deendayal Port Trust (DPT) is one of the major and busiest ports in India, located on the Gulf of Kutch in Gujarat on the west coast. DPT facilitates a different type of cargo handling with the help of sixteen berthing structures. The present study focusses on the conditional assessment of cargo berth (CB)-7 to CB-10, located at Kandla creek (22°59'32.8"N 70°13'27.2"E). In the Gulf of Kutch region, the maximum tidal range is about 8m, and the tidal currents reach up to 3 m/s (Satheeshkumar & Balaji, 2015; Kumar & Balaji, 2015). The tidal range in this region is the second-largest among the other part of the Indian coastline because of its complex shape and sudden seabed variations on the head (Kumar & Balaji, 2015). The depth varies from 60 m near the mouth to 20 m at the eastern end of the Gulf (Satheeshkumar & Balaji, 2016).

2.1 CHALLENGES ENCOUNTERED DURING FIELD TESTS

Structural auditing involves a few field non-destructive tests to assess the condition of the berthing structures. In a port like Deendayal Port Trust, most of the cargo berths are occupied with vessels, leaving a minimum gap for entering underneath the cargo berth. Large tidal variations within a day restrict the available time for reaching the test location. Moreover, the movement of high-speed navy craft, tug boats and passing vessels make the field tests more challenging. In such a scenario, accessing the structural members like deck beams (only possible during high tide) and piers (only possible during low tide) is a puzzling task that requires thorough planning. Some of the field tests require electricity and potable water that are difficult to possess under the berthing structure, where small boats are often hired for accessing the required test location for easy passage in confined spaces.

In the present study, overcoming all these challenges required rigorous planning before proceeding for the testing activities on the field. Primarily, high and low tide levels and timings on a given day were understood from the available tide tables. Accordingly, the sequence of testing was decided (from deck beams to piles or vice versa). Secondly, a boat that is just sufficient to accommodate test and boat operating team, the electric generator and potable water required for operating the testing instruments were hired. An adequate number of lifejackets, torch lights, helmets and other safety measures were taken during the testing underneath the cargo berths. Ropes were used to tie the boat to nearby structural piles to minimise the rolling caused due to the movement of high-speed navy/tug boats and passing vessels during the testing.

3. ASSESSMENT METHODOLOGY

The present study investigates the practical usage of the CR system and damage index model for the structures present in the marine environment through a case study at Deendayal Port Trust, Kandla, Gujarat, India. Conditional assessment methodology adopted, and the required tests need to be carried out to utilise the models are presented schematically in Figure 1.

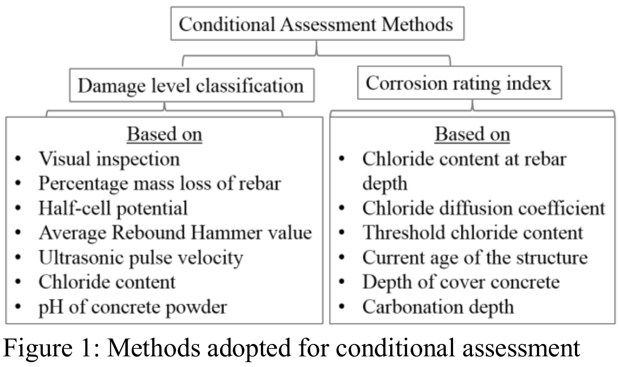

Figure 1: Methods adopted for conditional assessment

3.1 CORROSION RATING INDEX MODEL

This model was proposed by Verma *et al.* (Verma, Bhadauria & Akhtar, 2013) based on the corrosion model demonstrated by Tuutti (Tuutti, 1982). This method involves the estimation of corrosion initiation period and the present age condition of the structure. Arriving at the corrosion initiation period involves the estimation of chloride diffusion coefficient, chloride content at the rebar location and requires an idea of the chloride threshold value. It is to be noted that chloride threshold value is influenced by several parameters such as surface characteristics and metallurgical composition of steel, binder materials, type of reinforcement etc. (Mahima *et al.*, 2018). The chloride diffusion coefficient can be derived from Rapid Chloride Migration Test (RCMT), which however takes 24 h time for preconditioning and 24 h to 96 h of test time for each specimen depend on the electrical resistivity offered by the concrete core (NT BUILD 492, 1999). Core samples from the marine structure are usually chloride contaminated, thereby requires further pre-processing before the RCMT test to be carried out. Thus, estimating the parameters necessary for adopting the conditional rating index model is time taking process.

3.2 DAMAGE LEVEL CLASSIFICATION MODEL

Damage Level Classification model is based on the test results obtained from the most commonly used NDT testing, viz., half-cell potential test, UPV test, rebound hammer test, chloride and pH levels of concrete, cracks and spalling observed during the visual inspection and extent of mass loss due to corrosion. Unlike the CR model, this method is flexible with no compulsion on carrying out all the tests mentioned above. Such flexibility is essential since the site conditions may not always enable all the NDTs to be undertaken. In the DLC model, health score on the scale of 10 is adopted based on the performance of material/structure for each of the given NDTs, as provided in Table 1. Level of structural damage is assessed based on the average score obtained from the NDTs carried out, and then the structural condition is evaluated, as mentioned in Table 2. Thereby, this method is simple and requires minimal time for assessing the safety of the structure and gives an overall summary of several diversified NDT tests in terms of damage level.

Table 1: Adopted scoring scheme based on test results

Criteria		**Score**					
		10	**8**	**6**	**4**	**2**	**0**
Visible inspection	**Cracks**	Nil	Minor	Minor	Medium	Large	Large
	Spalling	Nil	Nil	Minor	Minor	Medium	Heavy
Reinforcement corrosion		Nil	< 5%	5-10%	10-20%	20-30%	> 30%
No. of points having half-cell potential values <-300 mV		Nil	< 5%	5-15%	15-30%	30-50%	> 50%
No. of points having UPV values < 3 km/s		Nil	< 5%	5-10%	10-25%	25-40%	> 40%
Avg. rebound hammer value		> 45	40-45	30-40	20-30	10-20.0	< 10
Chloride content (kg/m³)		< 0.6	< 0.6	< 0.6	> 0.6	> 0.6	> 0.6
pH of concrete powder		> 12	11.5-12	10-11.5	10-11.5	9-10.0	< 9

Table 2: Damage level classification scheme of structure

Damage Index	Damage Level	Structure condition	Remarks
10.0 - 9.0	0	Good	No visible damage but more significant part in the initiation period
9.0 - 7.5	1	Minor Damage	Minor visible damage, if left unattended may lead to a loss in structural integrity
7.5 - 6.0	2	Moderate Damage	Moderate visible damage, loss in structural integrity initiated, need to be attended as soon as possible
6.0 - 4.0	3	Severe Damage	Severe damage visible, falling pats may be dangerous, but the loss of serviceability and safety of the structure is minimal, need to attend at the earliest
4.0 - 2.0	4	Heavy damage (Reduced safety)	Loss of serviceability and reduced safety of the structure, immediate action has to be taken
2.0 - 0.0	5	Heavy damage/ Collapse	Repair or rehabilitation may not be possible, visible. Demolition may be thought upon for the safety of nearby structures and public

4. NON-DESTRUCTIVE TESTING

For arriving the parameters required for assessing the condition of berthing structures by CR method and damage index model, a set of field and laboratory tests have been conducted.

4.1 FIELD TESTS

Overcoming the challenges encountered, firstly, visual inspection was conducted to understand the site conditions. Six field tests were carried out as per the respective standards. Tests include direct field measurements viz., half-cell potential (ASTM C876, 2015), Schmidt rebound hammer (IS 13311 (Part 2), 2018), ultrasonic pulse velocity (UPV) (IS 13311 (Part 1), 2018), carbonation depth (by phenolphthalein indicator) and sample collection for various laboratory tests viz., core cutting, collection of powder samples at the surface of the rebar for chloride content and pH tests (Figure 2). Mainly two criteria were followed in deciding the test locations. Firstly, test locations covered each type of structural member (namely, deck slab, facia wall, fender columns, deck beams, tie beams and the piers) of Cargo Berths (CB) 7 to 10. Secondly, more attention was given to the first 15 m seafront side of cargo berthing structure, as this region is more susceptible to damage and observed to be highly corroded during the reconnaissance survey. Any damage in this area widely affects the port activities such as loading, unloading and berthing. Both criteria were met to the maximum possible extent, as can be observed from Figure 3. However, at few panels, the criteria were partially fulfilled due to the limitations in accessing the test locations, as the cargo berths were already occupied by vessels on the day field tests were conducted.

In total, 1778 samples were collected at 182 locations, as itemised in Table 3. Knowing the fact that retrieving rebars from a reinforced concrete structure can potentially damage the structural members, in the present case study, to avoid the damage of the berthing structure to the maximum possible extent, the corroded reinforcement bars were collected only from two possible locations (CB 7 and CB 9), as mentioned in Figure 3. In total, 20 corroded rebars of nearly 500mm length were retrieved, as shown in Figure 2. Retrieved rebars were then cleaned in accordance with ASTM G1-03 (ASTM G1-03, 2017) and weighed. Comparing with their pristine condition (as mentioned in structural drawings provided by Deendayal Port Trust), the average mass loss due to corrosion is estimated to be around 45.97% and 31.53% for the rebars retrieved from CB 7 and CB 9 respectively.

Table 3: Details of the number of tests undertaken for the study

Test Name	No. of test locations (No. of samples collected)				
	CB 7	CB 8	CB 9	CB 10	Total
Retrieving corroded rebars	1 (10)	-	1 (10)	-	2 (20)
UPV Test	9 (162)	9 (160)	9 (165)	9 (176)	36 (663)
Half-cell potential test	9 (90)	9 (90)	9 (90)	9 (90)	36 (360)
Chloride content test	9 (9)	9 (9)	9 (9)	9 (9)	36 (36)
Rebound Hammer test	9 (162)	9 (160)	9 (165)	9 (176)	36 (663)
pH of concrete powder	9 (9)	9 (9)	9 (9)	9 (9)	36 (36)
Total	46 (442)	45 (428)	46 (448)	45 (460)	182 (1778)

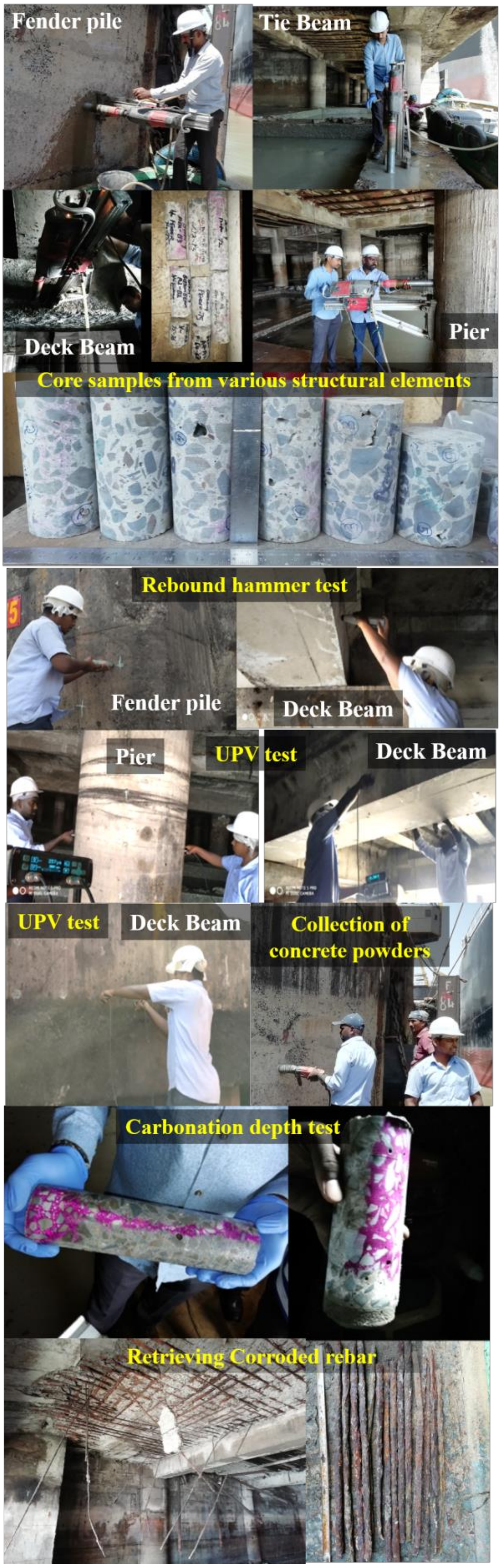

Figure 2: Different on-field NDT tests carried out between Cargo Berths 7-10

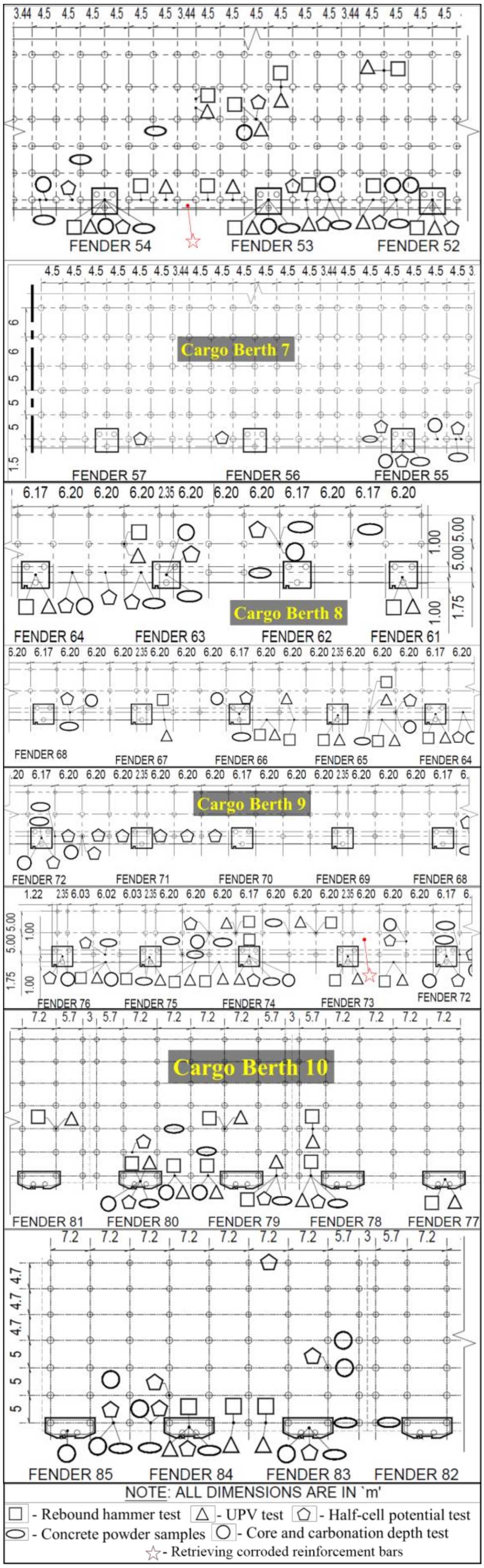

Figure 3: Location of NDTs carried out between CB 7-10

4.2 LABORATORY TESTS

Chloride content at rebar level and the chloride content of the concrete powder samples collected from the field are tested in accordance with Indian standard (IS 6925, 2013), as shown in Figure 4. Compressive strength of concrete was estimated in accordance with IS 516 (IS 516, 2018) based on the results obtained from compression test carried out on core samples collected from the field. L/d correction and cylinder to cube strength conversions were appropriately considered for getting the equivalent cube compressive strength of concrete. The pH of the concrete powder samples was obtained from the pH meter.

Rapid chloride migration tests have been performed for various core specimens obtained from CB 7 to 10 in accordance with NT BUILD 492 (NT BUILD, 1999), as shown in Figure 4. As the sample diameter (69 mm) is lesser than the prescribed dimension (100 mm), appropriate silicon rubber sleeves of 69 mm inner diameter were used. Specimens were preconditioned for more prolonged durations until the chlorides present in the samples were extracted. Specimens were supplied with appropriate voltage (NT BUILD, 1999) and monitored the resistivity offered by concrete specimen against the chloride ingression using a patented device (Vanama and Ramakrishnan, 2019).

Figure 4: Laboratory test set-up

5. RESULTS AND DISCUSSION

Field and laboratory test results required for estimating the corrosion initiation time are presented in Table 4, for CB 7 to 10. Condition rating of the cargo berth at present age is determined based on the chloride content and depth of carbonation as given in Table 5. Further, the residual life of the structure is estimated by the model based on Tuutti (Tuutti, 1982) and presented in Figure 5 for CB 7-10. However, arriving at the diffusion coefficient of concrete which was contaminated with chlorides was challenging and required longer preconditioning and extraction of chlorides from the specimen. It is observed that there are mainly two qualitative differences between the proposed Damage Level Classification (DLC) method and the existing Condition Rating (CR) system. Thus the first difference is the speed of obtaining the test results and corresponding time required for its implication in assessing the condition of the structure. As stated in section 3.2, the DLC method is based on the most commonly used NDT techniques whose results are relatively instant and quick compared to the experimental tests that CR system adopts, which typically take 48 hours for obtaining the test results. Secondly, the DLC method is based only on empirical tests. In contrast, the CR system requires, certain assumptions related to the chloride threshold limit which in turn depends on several parameters such as surface characteristics and metallurgical composition of steel, binder materials, and type of reinforcement used at the time of construction.

NDT results were incorporated in the proposed DLC model and presented in Table 6. The DLC method rates the structural condition on the scale of ‘0’ to ‘5’ based on the score arrived from the corresponding NDT test results. Where, level ‘0’ indicates the “no visible damage” to the structure and scale ‘5’ indicates the “Collapse condition of the structure”. That is, higher the average score, lesser the damage. On the other hand, Conditional Rating system categorises the damage level of the structure on the scale of ‘0’ to ‘9’, where ‘0’ indicates the “excellent condition”, and ‘9’ shows the “need for replacement of the structure”. For instance, consider the structural condition of the Cargo Berth 7 indicated by CR and DLC models (Table 5 and 6). CR system states that the condition of CB-7 is “Maintenance is a must for continuous use, likely to repair”, which implies the reduction in the service life of the structure. Whereas the DLC model indicates the “Loss of serviceability and reduced safety of the structure, immediate action has to be taken”. Thereby, it is observed that both the systems classify the structural condition similarly, irrespective of their different test approaches.

This exercise shows that, with limited field NDT results, the condition of the marine structure can be adequately assessed to represent their actual structural condition using the DLC method. Thereby, the proposed model helps in reducing the time and efforts required for effective conditional assessment of a port structure like cargo berths compared to the CR system. To effectively make use of the proposed DLC method in assessing the overall structural condition of a reinforced concrete marine structure, it is suggested that as many NDTs as possible are conducted. It is also recommended that certain criterion are adopted to allow the spatial distribution of the test locations over the test area and the number of tests deemed to be optimal for assessing the structure by the DLC method.

Table 4: Estimation of the corrosion initiation period

Parameter	CB 7	CB 8	CB 9	CB 10
Concrete cover (c) m	0.05	0.05	0.05	0.05
Diffusion coefficient (D) m^2/s (x 10^{-12})	3.04	2.23	2.23	2.12
Threshold chloride content (C_{th}) kg/m^3	0.60	0.60	0.60	0.60
Surface chloride content (C_s) kg/m^3	1.92	2.55	2.49	4.31
Corrosion Initiation time (T_{ini})Years	12.76	12.56	12.95	8.55

Table 5: Condition of berthing structures based on the 'CR' method

CR index	Years from construction				Action required
	CB 7	CB 8	CB 9	CB 10	
0	0.00	0.00	0.00	0.00	Excellent condition
2	12.76	12.56	12.95	8.55	Corrosion initiated, required regular inspection
5	26.50	**28.00**	**28.00**	**20.00**	Maintenance is required to increase the service life
6	**34.00**	33.15	33.02	23.82	Maintenance is a must for continuous use, likely to repair
7	39.31	38.29	38.04	27.63	Structure must be closed for maintenance
8	44.62	43.44	43.05	31.45	Poor condition not likely to be repaired
9	49.93	48.59	48.07	35.27	Replacement of structures

Note: Numbers in bold represents the present age/condition of CB

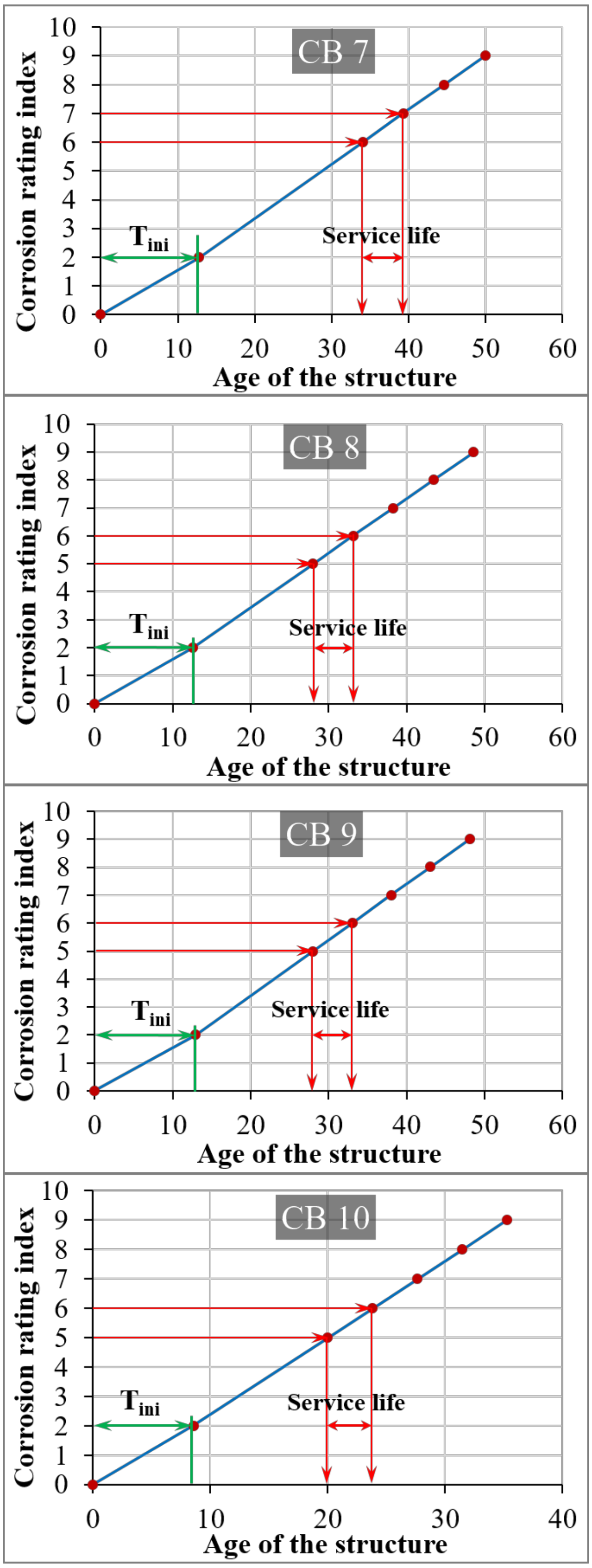

Figure 5: Residual life estimation of berthing structures

Table 6: Damage level classification of cargo berths

Criteria		Score			
		CB 7	CB 8	CB 9	CB 10
Visual Insp.	**Cracks**	2	2	2	0
	Spalling	2	2	2	0
Reinforcement corrosion		0	-	0	-
No. of points having half-cell potential values < -300mV		0	4	4	0
No. of points having UPV values < 3 km/sec		8	8	8	8
Avg. rebound hammer value		6	6	6	6
Chloride content (kg/m^3) (Cl)		4	4	4	4
pH of concrete powder		4	4	4	4
Damage Index (average score)		3.25	4.29	3.75	3.14
Damage Level		4	3	4	4
Structure Condition		Heavy Damage	Severe Damage	Heavy Damage	Heavy Damage

6. CONCLUSIONS

Carrying out the field non-destructive tests is always challenging for busy port structures. The procedure followed in the present study gives a possible solution to overcome these challenges and successfully conduct the field tests in the marine environment safely. The present study demonstrates the effectiveness of the CR system and proposed DLC model for assessing the condition of marine structure with a case study of cargo berthing structures at Deendayal port trust, Kandla. The major conclusions of the study are summarised as follows.

- Conditional assessment models for estimating the service life of the structure (like CR system) require the reliable data related to the chloride diffusion coefficient of concrete, which is time-consuming and challenging to obtain for chloride contaminated concrete.
- Estimating the corrosion initiation period (in CR system) required extensive data related to the type of materials used for the construction of the structure, which is difficult obtain for old ports due to lack of as-built drawings and information on mixture designs adopted at the time of construction. Thereby, numerous assumptions need to be made for obtaining the condition and residual life of the structure using the CR system
- The damage level classification model proposed in the present study is only based on the widely used NDT methods that are relatively easy to perform and avoids tedious and time-consuming laboratory tests.

It can be concluded from the present study that the condition of the berthing structures 7 to 10, Deendayal Port Trust, Kandla, indicated by a method based on CR system and DLC methods are giving the similar results irrespective of their different test methodologies. Thereby, the present comparative study demonstrates the effectiveness of the developed DLC model in the marine environment that helps reduce the time and efforts required for effective conditional assessment of marine structures like cargo berths.

7. ACKNOWLEDGEMENTS

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