Durability of offshore structures – Engineer's judgement vs codal recommendation

Subash T.R., Dhanasekaran B. and Manoj Kumar S.A.

Offshore structures such as storage facilities, building, gravity based structure etc., are vulnerable regarding durability. BIS does not include any separate code for these structures. In current practice, IS 4651(Part 4):2014 and IS 456:2000 are referred to design these structures. IS 4651 mainly focuses on structures like jetty, quay wall etc., which has only a platform and substructure. But structures built above this platform/deck have higher loads on it. These loads with environmental loads play a vital role in service life of structure. An effort has been made to review, compare and discuss the various codal provisions pertaining to durability such as crack width limitation, nominal cover to reinforcement and serviceability load combination. Few researches related to durability are summarized to highlight the impact of these parameters in the durability/life of the structure.

1. INTRODUCTION

Structures which are built in the sea are commonly termed as offshore structures. Service life of these structures is generally reduced due to aggressive environmental condition. This leads to loss in terms of economy, materials, machineries, manpower etc. Since retrofitting/repair of offshore structure is challenging and expensive, due consideration need to be given for durability during design stage.

For prolonged service life of offshore structure, structural parameters pertaining to durability should be considered appropriately. Indian standards such as IS 456:2000[1] and IS 4651(Part 4):2014[2] have been referred for parameters which affects the durability of offshore structure. For durability consideration, engineers should prejudge the utility, vulnerability and importance of structure ahead of designing the structure. Codal provisions for structural parameters of IS 4651 and IS 456 are compared and recommended in this paper. A typical offshore structure has been designed as per IS 4651 and IS 456 to compare the influence of codal provisions on durability and material quantity.

2. COASTAL AND OFFSHORE STRUCTURE

Structures exposed to sea are often mentioned as (a) coastal structures, (b) maritime structures, (c) port & harbour structures, (d) offshore structures, (e) marine structures and (f) sea shore structures etc. In this paper, these structures are categorised as coastal structure and offshore structures based on its functionality in the sea.

2.1 Coastal structure

As per IS 7314:1974[3], port is described as truck line of communication; receive cargo, commercial part of harbour (quays, wharves, jetties, facilities for transfer of cargo, docks and repair shops). Harbour is described as any protected water area affording a place of safety for vessels. This paper has considered the port and harbour structures as coastal structure. Few types of coastal structures can be referred in Figure 1.

2.2 Offshore structure

The terminology offshore is defined in IS 7314 as zone exceeding from breaker zone to the seaward edge of continental shelf. Also, it is termed as direction of seaward from the shore. In this paper the offshore structure refers to structure other than coastal structure, which are located away from the shore line into the sea (includes foreshore and inshore zone) such as building or structure in platform referred in Figure 1.

3. ENVIRONMENTAL EXPOSURE CLASSIFICATIONS

Based on the severity of attack on surface of the structure, environmental exposure condition of offshore structures are

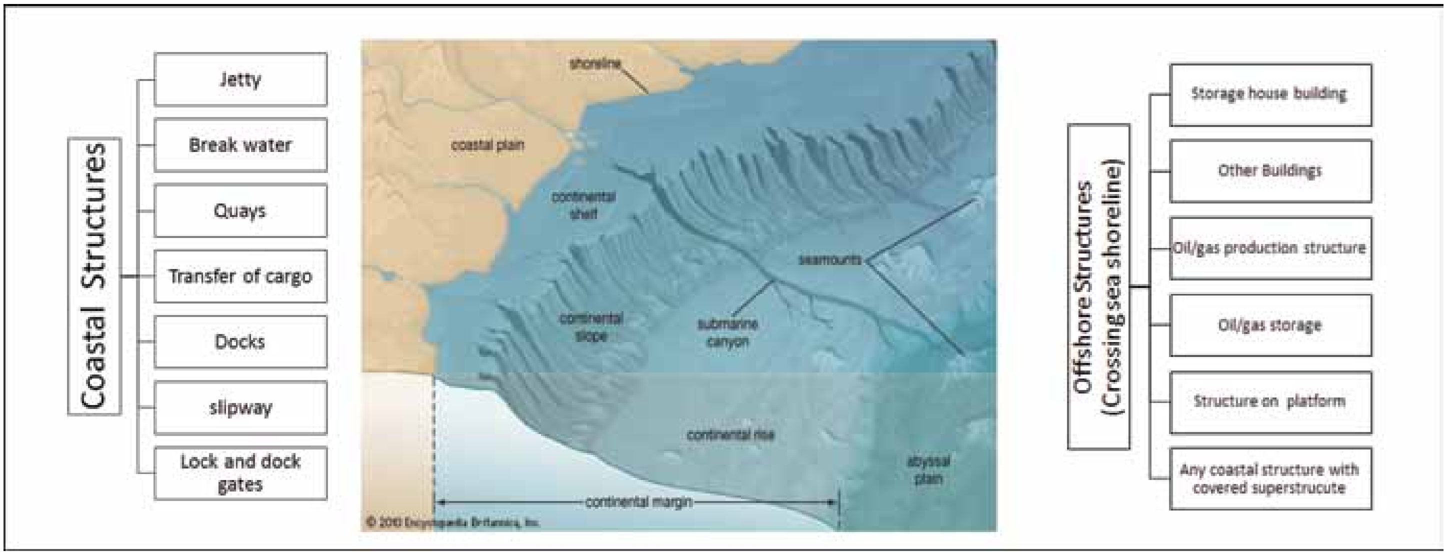

Figure 1. Coastal structures (left), Shoreline (center [5]) and Offshore structures (Right)

majorly classified as atmospheric zone, splash zone, tidal zone and submerged zone[6]. These classifications of the environmental zones as per IS codes are described in Table 1.

4. NOMINAL COVER AND CRACK WIDTH LIMITATIONS

The concrete cover and crack width is an important deciding factor for design engineers to achieve enhanced service life of the structure. Concrete cover for the reinforcement acts as a barrier for ingress of oxygen, moisture and chloride ions. Generally it is noted that adequate cover delays the propagation period of corrosion but increase in cover also increase the crack width [7].

Restricting the crack width to a limit based on the exposure condition is very significant. But the standards, IS 4651 and IS 456 mention different limiting values for crack width based on the exposure and loading conditions as described in Table 2.

Table 1. Environmental exposure classification based on IS codes

Code	Atmospheric zone	Splash zone	Submerged zone
IS 4651	Atmospheric zone – *"Above splash zone and where direct wave or spray impingement is infrequent"*	Splash zone – *"Zone between the chart datum and design wave height above the mean high water springs"*	Submerged zone – *"a).Continuous sea water immersion zone - Below Splash zone upto bed level b).below sea bed level"*
IS 456	Severe – *"Concrete exposed to coastal environment"*	Extreme - *"Surface of members in tidal zone"* Very severe – *"Concrete surfaces exposed to sea water spray"*	Severe – *"Concrete completely immersed in sea water"*

Table 2. Comparison of Nominal cover and crack width limit based on IS code

Parameter	Code	Atmospheric zone	Splash zone	Submerged zone
Nominal Cover (mm)	IS 4651	50	75	75 *(Immersed in water)* 50 *(Below seabed)*
	IS 456	45*	75 *(Tidal)* 50**(Spray)*	45*
Crack width limit (mm)	IS 4651	0.2# 0.3**	0.1# 0.2**	0.2# 0.3**
		Max of above values and 0.004 times the cover		
	IS 456	0.1	0.1	0.1

* 5 *mm can be reduced for concrete grade M35 and above.* # *sustained load- DL+ 50 % LL+ earth pressure.*
** *Transient load- DL+ berthing load and full crane load or LL+ earth pressure.*

5. SERVICEABILITY LOAD COMBINATION

Generally restricting crack width limit and reinforcement stress limit leads to reduced chloride ingress and increased water tightness of the concrete. Serviceability limit state (SLS) combination is considered to check the crack width. The SLS combination as per IS 4651 and IS 456 pertaining to crack width are depicted in Table 3.

6. STRUCTURAL PARAMETERS – ITS IMPACT ON DURABILITY

Current research mainly concentrates on the service life prediction of the structure rather than comparing only durability index. Researches confirm that increase in the nominal cover up to 75 mm enhances the service life drastically. Also restricting the crack width increases the service life. But both the factor increases the project cost and project schedule substantially. Few researches related to crack width and durability are discussed below. Although this is arrived based on a particular mix design, the behaviour can be observed and concluded for different mixes.

6.1 Cracked RC pipe piles exposed to marine environment [8]

Wei shao et al. observed that, for chloride concentration of 4.5 kg/m^3 with 75 mm cover depth, uncracked section have 70.6 years of life, 0.1 mm cracked section have 63.3 years of life and 0.3 mm cracked section have 52.5 years of life. For chloride concentration of 9 kg/m^3 with 75 mm cover depth uncracked section have 47.1 years of life, 0.1 mm cracked section have 42.3 years and 0.3 mm cracked section have 35.1 years of life[8]. Figure 2 shows that the cover depth and crack width limitation have significate effect on the service life.

Table 3. Comparison of SLS combination based on IS code

Load		IS 4651	IS 456				
Dead Load	Dead Load	1	1	1	1	1	1
	Earth pressure	1	1	1	1	1	1
	Hydrostatic Force	1	1	1	1	1	1
Live Load	Dynamic live load	1.1	1	-	0.8	-	0.8
	Static live load	1/0.5$^€$	1	-	0.8	-	0.8
	Wave & current load	1	1	-	0.8	-	0.8
	Berthing Force	1*	1*	-	0.8*	-	0.8*
	Mooring force	1*	1*	-	0.8*	-	0.8*
Wind Load	Working wind force	1	-				
	Extreme wind force	-	-	1	0.8	-	-
Seismic	Seismic force	-	-	-	-	1	0.8
	Tsunami force	-	-				
Others	Secondary stress	1	-				

* Berthing or Mooring Force shall be considered one at a time

$^€$ *50 % uniform distributed load for the sustained load combination checks*

6.2 Corrosion initiation in cracked fibre reinforced concrete [9]

Carlos G Gerrocal et al. observed that for corrosion, initiation period will be dramatically reduced for cracked concrete elements compared to uncracked elements regardless of the addition of fibres to concrete as shown in Figure 3. Also

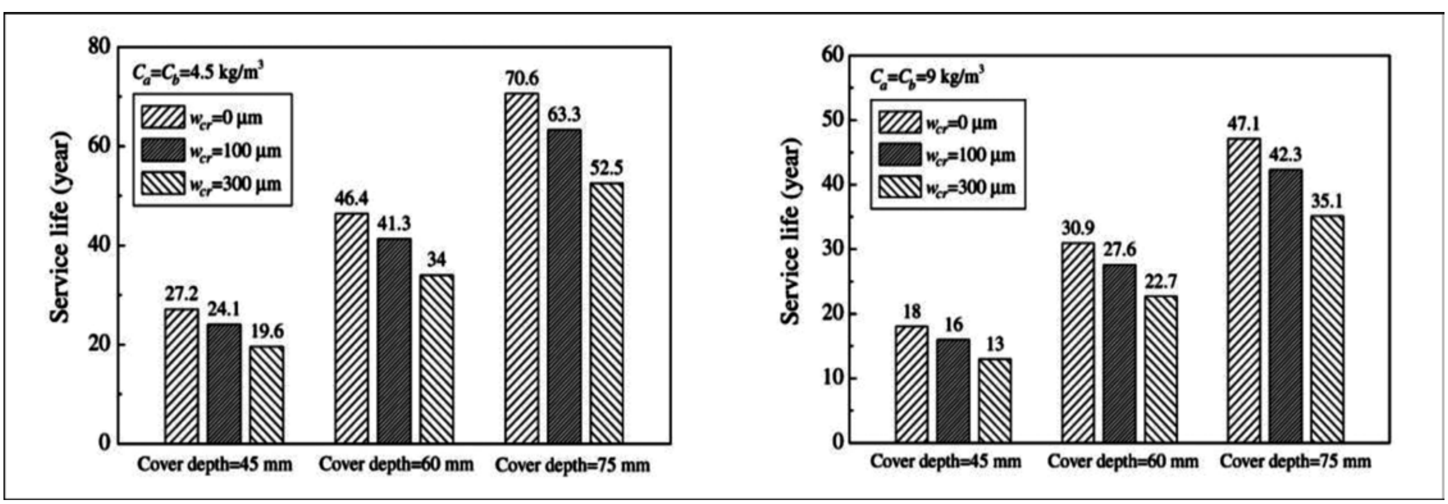

Figure 2. Effect of crack width in service life [8]

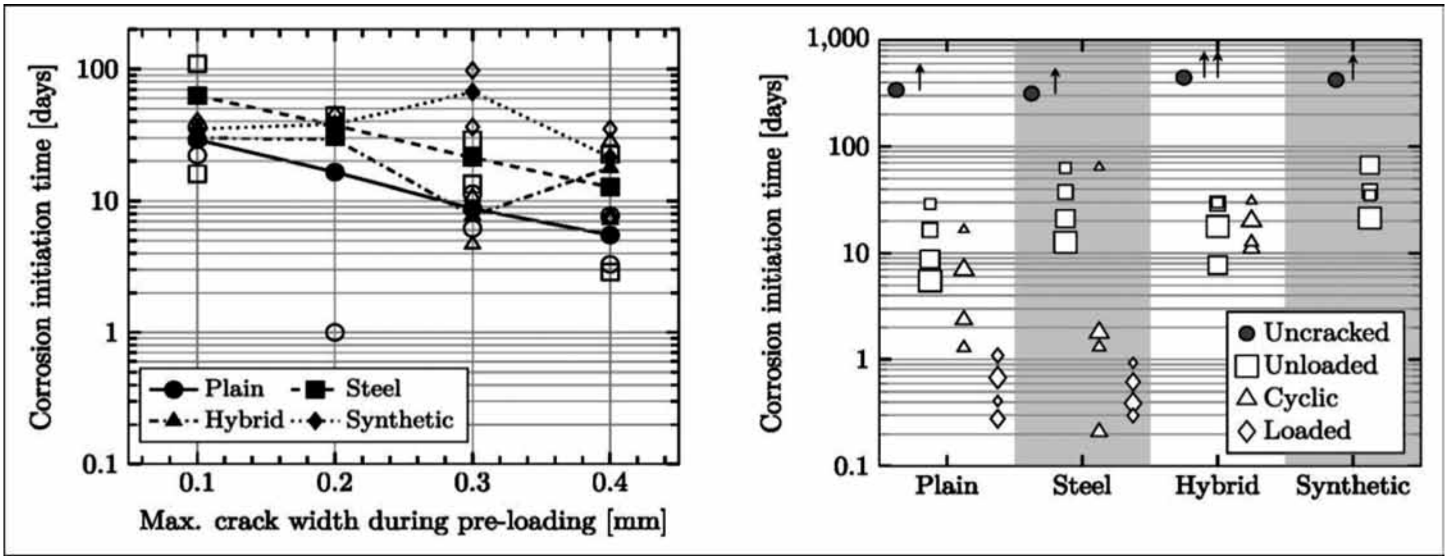

Figure 3. Corrosion initiation times for different crack width, different type loading for fibre reinforced concrete [9]

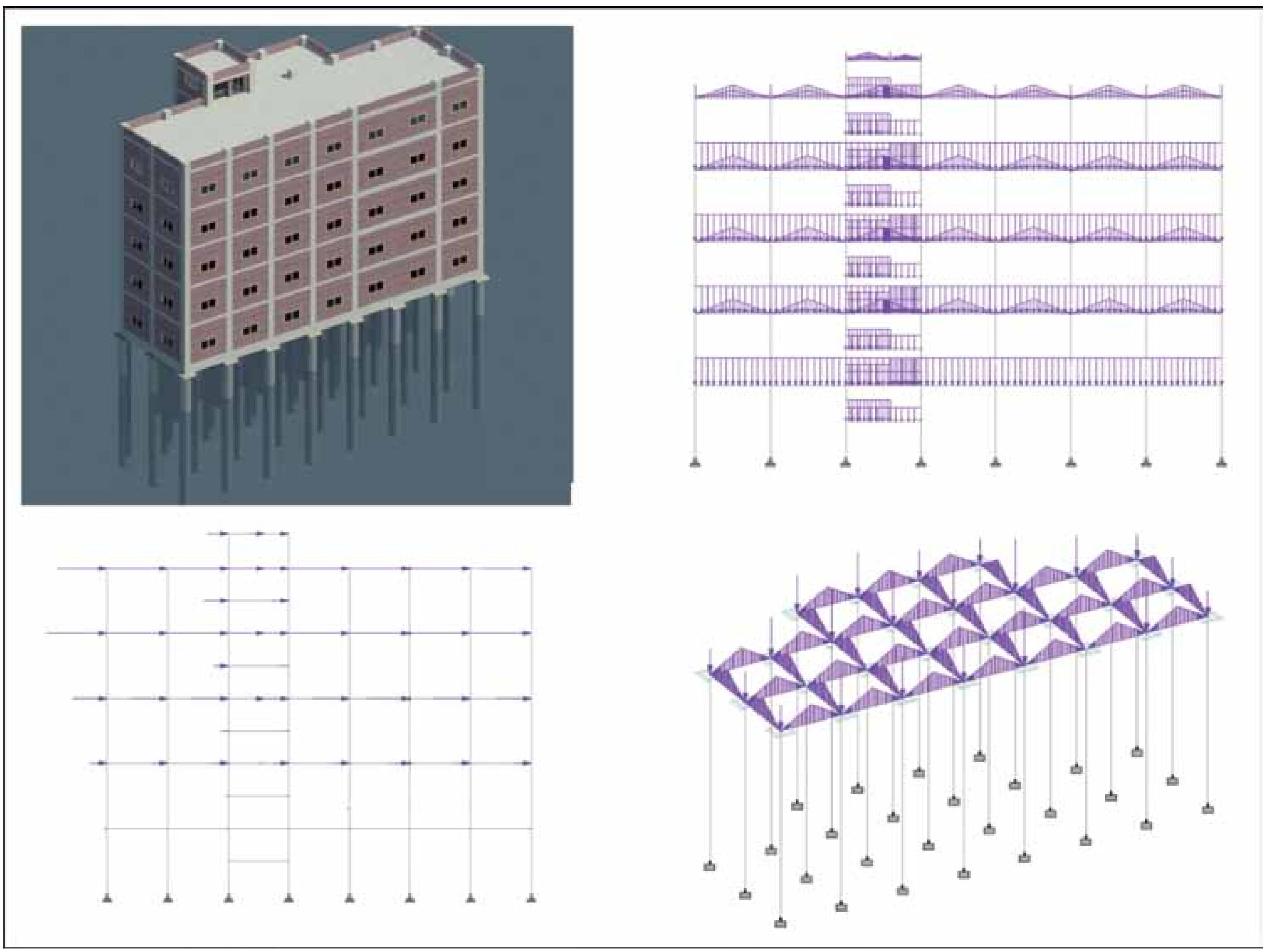

Figure 4. Isometric view and loading of the structure (clockwise from left top a. Isometric view building, b. Dead and live load of superstructure, c. Dead and live load of substructure, d. Seismic force of super structure)

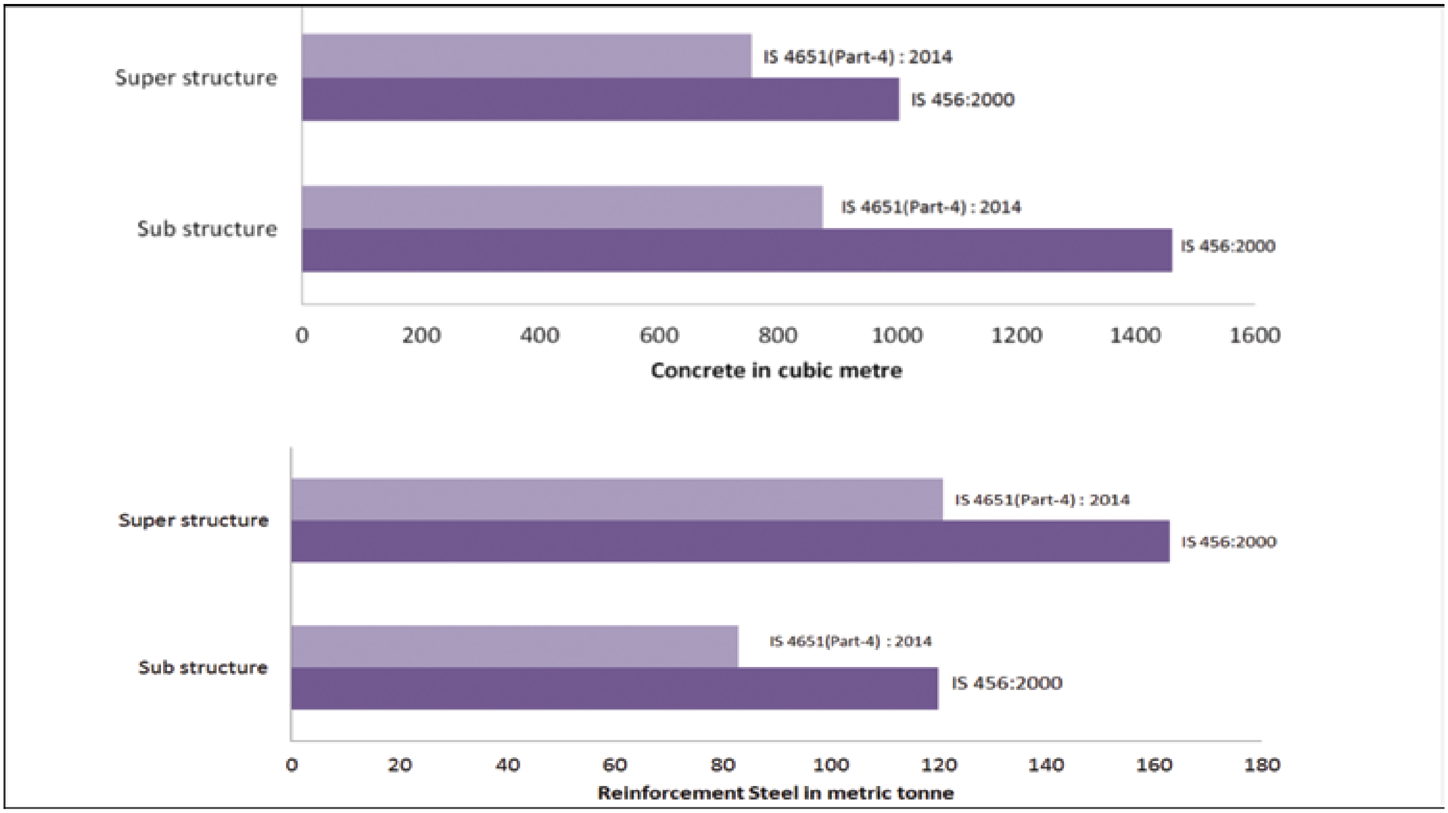

Figure 5. Quantity comparison between IS 4651and IS 456 (Top: Concrete, Bottom: Reinforcement steel)

for the concrete without fibre and unloaded section, the corrosion initiation time is observed to decrease with the increase in the crack width [9].

6.3 Assessment of corrosion in cracked reinforced concrete [10]

Brad Pease et al. conducted experiment for 0.3mm, 0.4mm, 0.6mm, 0.7mm, 0.9mm, and 1.2mm cracked specimen. Research concludes that pitting corrosion is exhibited for 0.3mm and 0.4mm cracked specimen and very larger area of pitting corrosion was observed in 0.6 mm to 1.2mm cracked specimen [10].

7. ANALYSIS & DESIGN OF TYPICAL OFFSHORE BUILDING

A typical offshore building with four stories as shown in Figure 4a is assumed to be located in seismic zone - III with 35m length and 15m breadth for the comparison of IS 4651 and IS 456. The structure rests on a piled platform with 75 kN/m^2 live load on deck level, 5 kN/m^2 for all remaining floor and roof is an accessible roof. Loading of the structure is shown in Figure 4b, 4c and 4d. The structure is designed by IS 4651 and IS 456.Tsunami force is not considered in this analysis.

From the analysis and design, concrete and reinforcement steel quantity variation between the codes is arrived and shown in Figure 5. It is observed that the concrete and steel quantity reduces in superstructure and substructure due to the structural parameter variation and accounting extreme environmental load in the serviceability load combinations.

The overall comparison of the IS 4651 and IS 456 with respect to durability parameter is represented in the Figure 6.

8. OBSERVATION AND RECOMMENDATIONS

From the referred codal provision and literature of offshore structures following observation and recommendation were drawn.

IS 456 specifies crack width limit as 0.1mm in all exposure conditions but IS 4651 mentions various crack width limit for different exposure and loading conditions.

Liberal crack width limit in IS 4651 is suitable for its structural type (Coastal structures/maritime structures/ Port and Harbour). However, the crack width specified in IS 4651 not adequate for offshore structure for its service life. Hence stringent crack width of 0.1mm is recommended for splash zone in all type of loading.

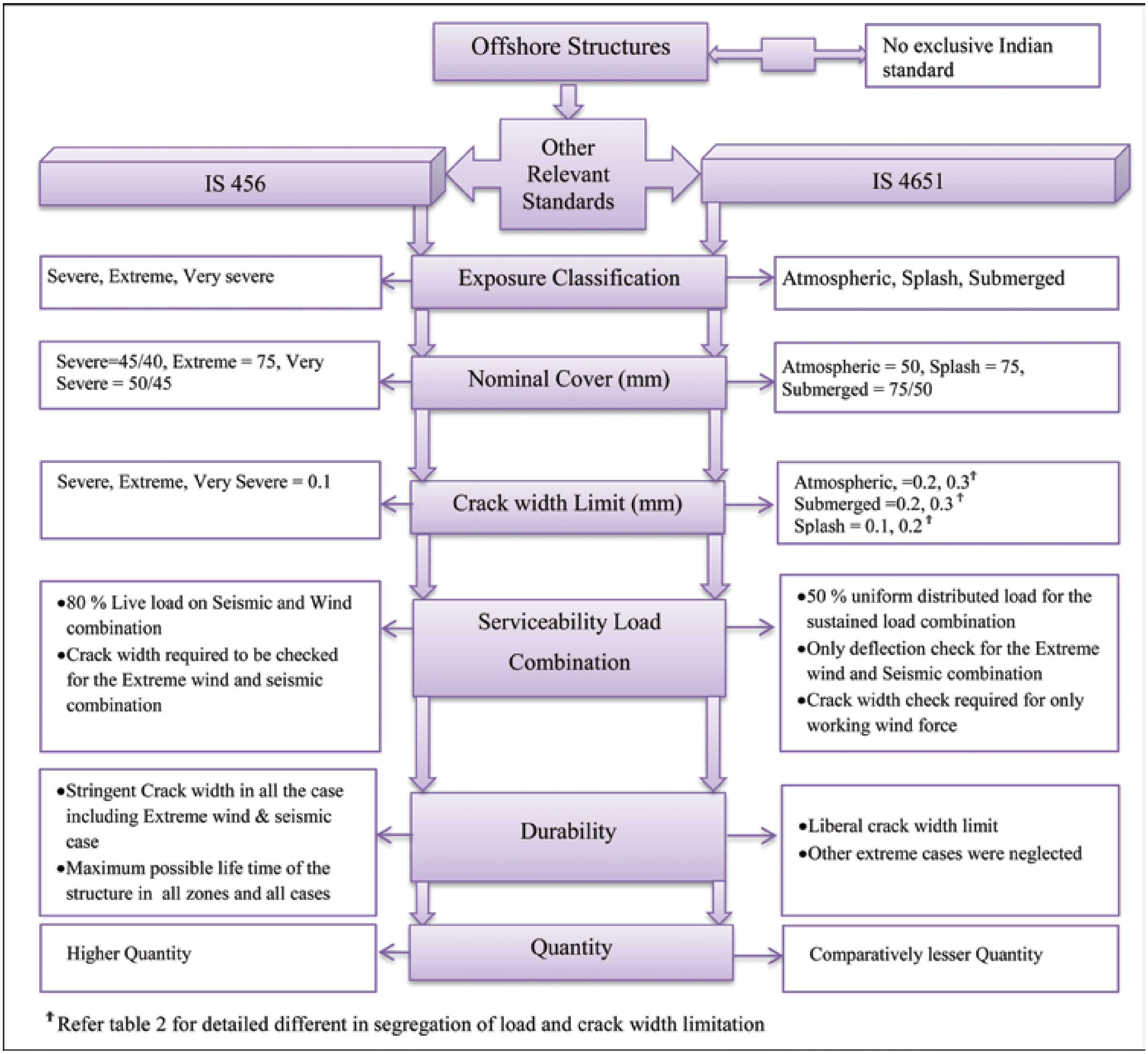

Figure 6. Codal provision and its impact on durability and Quantity

In splash zone: As per IS 456, nominal cover is 75mm for tidal zone and 50/45 mm for spray zone. But IS 4651 provides 75mm nominal cover for the entire splash zone. It is noted that provision of 50/45 mm nominal cover for spray zone in IS 456 is insufficient, as spray zone is almost equally vulnerable zone when compared with tidal zone.

In atmospheric zone: IS 4651 specifies 50mm nominal cover with 0.2mm crack width limit and IS 456 specifies 45/40mm nominal cover with 0.1mm crack width. For design of offshore structures, 0.2mm crack width is recommended for atmospheric zone based on its severity and accessibility to repair.

In submerged zone: IS 4651 specifies 75mm nominal cover and IS 456 specifies 45/40 mm nominal cover. It is recommended to adopt 75mm nominal cover for submerged zone, but the crack width should be restricted to 0.2mm in all loading cases (sustained and transient loads). Achieving different cover to splash and submerged in difficult in construction aspect, so it is recommend to provide 75 mm cover for submerged zone also

Table 4. Codal provision and recommendation for the cover and crack width

Description	Atmospheric zone		Splash zone		Submerged zone	
	Cover	Crack width	Cover	Crack width	Cover	Crack width
IS 4651	50 mm	0.2/0.3 mm	75 mm	0.1/0.2 mm	75 mm	0.2/0.3 mm
IS 456	45/40 mm	0.1 mm	50/45 mm and 75mm	0.1 mm	45/40 mm	0.1 mm
Recommended	50 mm	0.2 mm	75mm	0.1 mm	75 mm	0.2 mm

The recommend cover and crack width for the different zone for offshore with the codal provision in IS 4651 and IS 456 is tabulated in Table 4.

Wind force: IS 4651 does not include the extreme wind force in the serviceability combination but working wind force is considered. On the other hand IS 456 does not segregate working wind force and extreme wind force.

Seismic force: IS 4651 does not include the seismic load in the serviceability combination as included in the IS 456. IRS - Concrete Bridge Code [4] is similar as IS 456, which includes the seismic combination in serviceability as included in the IS 456:2000.

Compromising the extreme wind force and seismic force in serviceability for offshore structure leads 25 to 35 % reduction in the material cost. Designing offshore structure as per IS 4651 appears economical. But every extreme wind and minor seismic, structure should be monitored for cracking and repaired properly. This is not practical, if the structure is having inaccessible location.

Unmonitored and unrepaired concrete after the environmental effect leads to corrosion to larger extent if the crack width is more than 0.3mm [10]. This leads to drastic reduction in expected life time of structure.

The structures which are inaccessible (or) difficult to repair shall be checked for stringent crack width limit. Also, check for all extreme environmental load (wind and seismic) is mandatory for offshore structures as followed in IS 456.

9. CONCLUSION

The recommended values and factors of the structural parameter of IS 4651 and IS 456 were referred for the design of offshore structures. Environmental exposure classification, Nominal cover to the reinforcement, crack width limitation and serviceability limit state combination and it's relation with the durability of the structure is presented. The impact of crack width limitation and service life is observed and summarized. A typical Offshore building is compared for quantity based on IS 4651and IS 456. Based on the studies, observation and critical recommendation has been made.

References

1. _______*Indian standard code for plain and reinforced concrete - code of practice*, IS 456: 2000. Bureau of Indian Standards, New Delhi.
2. _______*Indian standard code for Code of practice for planning and design of ports and harbour: General design consideration*, IS 4651 (Part 4): 2014.Bureau of Indian Standards, New Delhi.
3. _______*Indian standard code for Glossary of terms relating to port and harbour engineering*, IS 7314: 1974. Bureau of Indian Standards, New Delhi.
4. _______*Code of practice for plain, reinforced & prestressed concrete for general bridge construction*, IRS Concrete Bridge Code : 1997. Indian Railway Standard- Research Designs and Standards Organisation, Lucknow.
5. Encyclopedia Britannica, Inc. http://www.britannica.com/science/continental-shelf
6. Saravanan Ramalingam and Manu Santhanam., Environmental exposure classifications for concrete construction – A relook, The Indian Concrete Journal, May 2016, Vol. 86, No. 5, pp. 18 – 28.
7. M. Shafqat Ali, Chenhui Ji and M. Saeed Mirza., Durable design of reinforced concrete elements against corrosion, Construction and Building Materials, June 2015, Vol 93, pp. 317-325.
8. Wei shao and jingpei li., Service life prediction of cracked RC pipe piles exposed to marine environments, Construction and Building Materials, May 2014, Vol 64, pp. 301-307.
9. Carlos g.berrocal, Ingemar Lofgren, Karin Lundgren and Luping Tang. Corrosion initiation in cracked fibre reinforced concrete: Influence of crack width, fibre type and loading conditions, Corrosion Science, June 2015, Vol 98, pp. 128-139.
10. Brad Pease, Mette Geiker, Henrik Stang and Jason Weiss. The design of an instrumented rebar for assessment of corrosion in cracked reinforced concrete, Materials and Structures, August 2011, Vol 44, Issue 7, pp 1259-1271.

Subash T.R. holds ME in Geotechnical Engineering from College of Engineering, Guindy, Chennai. He is Chief Engineering Manager at Larsen & Toubro Construction. He has an experience of 23 years in design and construction of infrastructure projects. His domain of expertise encompasses Structural Engineering, Tunnel & Underground Engineering, Dam and Hydro power Engineering. His areas of research interest are dynamics behavior of the structures, complex infrastructure projects, service life evaluation and modern tunneling techniques. He is a chartered engineer at Institution of Civil Engineers (U.K) and active member of Indian Society of Hydraulics and Indian Geotechnical Society.

Dhanasekaran B. holds ME in Hydraulic and Water Resource Engineering from Indian Institute of Technology Madras, Chennai. He is Engineering Manager at Larsen & Toubro Construction. He has an experience of 17 years in design and construction of infrastructure projects. His area of interest is development of infrastructure projects with advanced techniques, durability studies, underground design and advanced dewatering techniques. He is a chartered engineer at Institution of Civil Engineers (U.K) and active member of Indian Society of Hydraulics and Indian Geotechnical Society.

Manoj Kumar S.A. holds ME in Structural Engineering from Government College of Engineering, Coimbatore. He is Asst. Engineering Manager at Larsen & Toubro Construction. He has an experience of seven years in design and construction of infrastructure projects. His area of interest is durability of steel and concrete structures, service life prediction and long term behavior of the structure.