Structural integrity of residential buildings subjected to coastal inundation

R.Preetha, Tapesh Kumar Derwal, Sugunadevi. M, Kalpana Kumari,
Sudipta Chattopadhyaya, N.Suresh

[1] Civil Engineering Group,Indira Gandhi Centre for Atomic Research

predinesh@igcar.gov.in[1]*,tderwal@igcar.gov.in*[1]*,sugunadevim@igcar.gov.in*[1]*,kalpana@igcar.gov.in*[1]*,*
schatto@igcar.gov.in[1]*,nsuresh@igcar.gov.in*[1]

ABSTRACT

Residential apartments in a township near to coast of Bay of Bengal,were investigated for cause of severe distress in the form of concrete spallation,cracking, and settlement.The houses were inundated during Tsunami in 2004.Condition assessment of the buildings was performed through visual inspection,non destructive tests and chemical analysis.The structural audit conducted revals that the electrochemical corrosion initiated due to tsunami water stagnation has further progressed under severe coastal exposure. The paper discusses the cause and extent of damage in structural elements of the apartments and also indicates that the housing units are in precarious condition.

Keywords: *Reinforcement,corrosion,spallation,chloride,Tsunami*

1. INTRODUCTION

The allotment of houses in a residential township situated very near the coast of the Bay of Bengal, was stalled due to severe distress observed in the buildings. These houses are approximately 200m from the sea coast and were inundated during the tsunami in 2004, wherein the water level rose to the first floor and stagnated for a few hours. But no major distress was found in the immediate aftermath; hence, the houses were re-allotted after minor repairs, like replacing broken windows and doors, until the recent past. Though in the last 20 years, conventional maintenance and repairs were carried out time to time, it was found to be ineffective and the structure slowly degraded. The township is more than 55 years old, and due to the proximity of the sea coast, corrosion of external RC structures was widespread beyond the age of 40 years. But the extensive degradation found in these buildings were of concern. Hence, it was pertinent to assess the condition of the structures.

Similar reports exist from various tsunami-affected zones across the world. Corrosion distress in RC buildings in Aceh, affected by the 2004 tsunami, is available in [1]-[3]. Stagnation of the tsunami water may have been the cause of chloride ingress into concrete elements, leading to de-passivation at the reinforcement interface and consequent corrosion. There are also reports on rising dampness on masonry walls at locations inundated by the tsunami.[4-5]. Higher salinity in groundwater in these areas, leading to extensive distress in RC(reinforced concrete) structures with time[6-8], is one of the effects of the tsunami, which has not been addressed well yet.

Another aftereffect was damage to masonry walls, ascertained to be due to two reasons: one being the location, which exposed the wall to the hydrodynamic action of tsunami waves/storm surge, and the second being the intensive erosion and scouring of soil beneath the wall footing with low embedment [9-11]. In general, a structural audit has been conducted on structures subjected to any natural/man-made hazard, such as fire, or any major distress is observed. [12,14] .

Severe spallation in slab, columns & beams, and masonry cracking was observed in most of the houses now in the preview of this paper. Hence, condition assessment of the residential building was performed through visual inspection, non-destructive tests, electrochemical tests, and chemical analysis. Non-destructive tests included rebound hammer and ultrasonic pulse velocity measurements, and electrochemical tests were carried out using a resistivity meter and a half-cell potential meter at selected test locations. Chemical tests like pH, chloride content, and carbonation depth were also evaluated from the samples collected from the structure. In situ compressive strength of concrete was assessed through core samples.

The paper reveals the cause and extent of distress in structural elements of the residential buildings and also indicates that housing units are in a precarious condition.

2. DESCRIPTION OF BUILDING SYSTEM

The residential buildings with RC frames were constructed in 1991. These apartments had a plinth area of 57 m^2, featuring two bedrooms, a living room, a kitchen, a bathroom, a toilet, and a balcony. These houses were constructed with a mirrored layout, where the staircase is shared between the two houses in a G+2 configuration (Fig. 1).

M20 grade of concrete was used for construction with clear cover provisions of 50mm for footings, 40mm for columns, 25mm for beams, and 15mm for slabs, lintels & sunshades. The safe bearing capacity of soil was 15 N/mm^2 as per the drawings. A 230mm brick masonry wall was provided in these houses. RC columns on isolated footings were founded at a depth of 3.6m, whereas the brick infill walls were resting on a wall footing hardly 1m deep.

Fig.1: View of the residential building

3. METHODOLOGY OF ASSESSMENT

Relevant structural drawings and design details were collected from records and 7 residential units were inspected.

3.1 Non-destructive tests

3.1.1 Rebound Hammer Test:

This is a simple and handy tool that provides a convenient and rapid indication of the compressive strength of concrete. The extent of rebound, which is a measure of surface hardness, is designated as Rebound Number, which is further correlated to the compressive strength of concrete [15].

3.1.2 Ultrasonic pulse velocity (UPV) test UPV test

It is basically a wave propagation test and consists of transmitting ultrasonic pulses of 54 kHz frequency through a concrete medium and measuring the transit time. The velocity of the pulse, which is usually expressed in Km/sec is correlated to concrete quality. The general criterion for concrete quality grading is given in Table 1.

Table 1: Criterion For Concrete Quality Grading[16]

Sl. No.	Velocity (Km/sec.)	Concrete quality grading
1	Above 4.5	Excellent
2	3.5 to 4.5	Good
3	Below 3.5	Doubtful

3.2 Chemical analysis

The chloride content in concrete was analysed by crushing the spalled concrete and also drilling samples from different members. Furthermore, the samples were subjected to the chloride test [17], and the same samples were subsequently tested for their concrete pH.

To determine the effect of carbonation, a 1.0% phenolphthalein solution was sprayed [18] on the drilled surfaces. The pink colour indicates that the concrete was not affected by carbonation, whereas the colourless one indicates carbonation.

3.3 Electrochemical tests

3.3.1 Resistivity testing of concrete:

The electrical resistivity is defined as the ratio between the applied potential and the current circulating between two electrodes, provded in the resistivity meter. The electrical resistivity is an indirect measurement of the porosity and the connectivity of the concrete pores. Interpretations of resistivity with regard to corrosion risk for concrete are given in Table 2.

Table 2: Interpretation of Resistivity results as per RILEM TC 154[19]

Resistivity in kΩcm	Risk of Corrosion interpretation
< 10	high
10 to 50	moderate
50 to 100	low
> 100	negligible

3.3.2 Half cell potential Test:

In this investigation, half-cell potentials with reference to the copper-copper sulphate electrode were measured for selected members where the rebars were exposed in the vicinity of regions where distress features were observed. IS 516 provides general guidelines for evaluating corrosion in concrete structures as outlined in Table 3.

Table 3: Corrosion Interpretation Based on Potential Values [20]

Potential Level	Corrosion Interpretation
Greater than - 0.2 V	Low probability of corrosion
- 0.2 to -0.35V	Corrosion activity in reinforcing steel in that area is uncertain
Less than - 0.35 V	High probability of corrosion
Less than -0.5 V	Severe corrosion

4. DISCUSSIONS

Based on the investigation & study carried out on various members, the following inferences were drawn.

4.1 Visual Inspection

During the visual survey of the buildings, several significant issues were identified.

4.1.1 Concrete

The inspection revealed extensive spallation of concrete and severe cracking in both internal and external RC columns, beams, and slab areas, accompanied by severe reinforcement corrosion in GF/FF of multiple apartments (fig.2-5). Key observations indicate that the primary causes of damage include exposure to tsunami inundation and the coastal environment, subsequent reinforcement corrosion, and ineffective or superficial repair attempts, as recently repaired RC structures have once again developed cracks. The damage is not limited to visible areas but extends to concealed sections, as evidenced by delamination of plaster revealing cracks and corrosion beneath the surface.

Fig.2: Extensive Spallation in slab

Fig.3: Cracking in RC columns and shelve

4.1.2 Masonry

The presence of widespread cracks—horizontal, vertical, and diagonal —indicated structural movements and potential differential settlement in some areas (Fig. 6). Additionally, corrosion of embedded electrical conduits had resulted in secondary damage to masonry walls. Rising dampness was evident up to the roof at the ground floors (Fig.7).

Fig.4: Severe corrosion in lintels

Fig.5: Severe distress to the balcony

The structural integrity of the houses inspected is severely compromised due to widespread and advanced deterioration in various structural components.

Fig.6: Settlement cracks in masonry walls

Fig.7: Dampness upto roof in ground floor house

4.2 Non Destructive Tests

The overall compressive strength values obtained from the Schmidt Hammer test [15] indicate lower results (<30N/mm^2) in most areas. Additionally, there is significant variability in these values, highlighting inconsistencies in the concrete quality. This variation can be attributed to the presence of cracks or the presence of 10-15mm thick repair plaster. At some locations, rebound hammer tests were conducted on both cracked and uncracked areas to compare the compressive strength of the concrete. The results indicated good compressive strength in the unaffected area compared to the cracked area. Figure .8 highlights the NDT.

Fig.8: a) Rebound hammer test b) UPV test c) resistivity measurement

The Ultrasonic Pulse Velocity (UPV) values observed at the tested locations predominantly indicated that the concrete quality falls into the "doubtful" category. However, a few locations exhibited UPV values that classified the concrete quality as "good" according to the standards set forth in [16]. This variation in UPV readings highlights significant inconsistencies in the concrete quality across the different tested locations. Fig. 9 shows no discernible pattern between the two NDT methods, which suggests either that the quality is inconsistent or that there is significant damage. According to [19], 60% of the resistivity values indicated a high to medium risk of corrosion (Fig. 10).

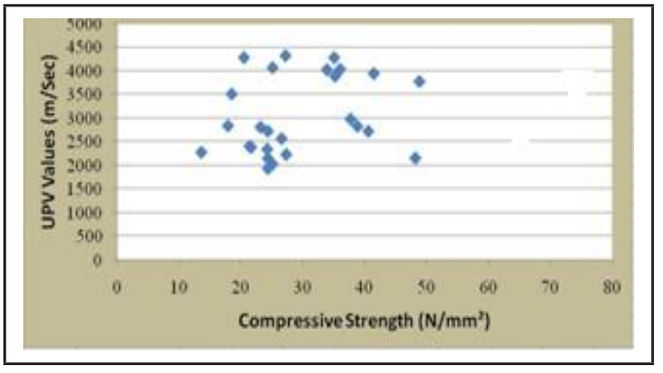

Fig.9: Strength from Rebound hammer vs UPV

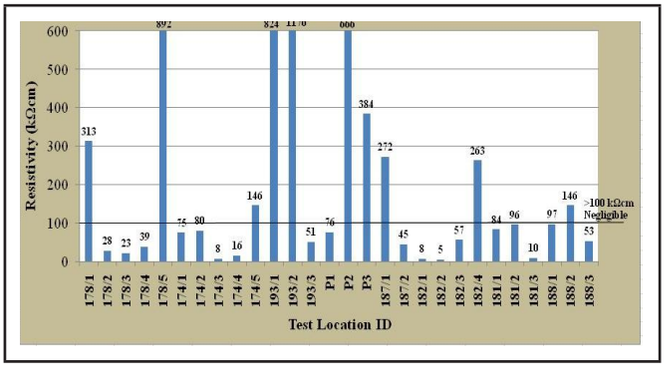

Fig.10: Resistivity

Based on the tests conducted on the reinforcement in the column and lintel areas, the Half-cell potential graphs indicate that the probability of corrosion varies from low probability of corrosion in second floor RC elements to severe corrosion in ground floor (Fig.11); therefore, it can be concluded that there is a risk of corrosion [20] in these areas.

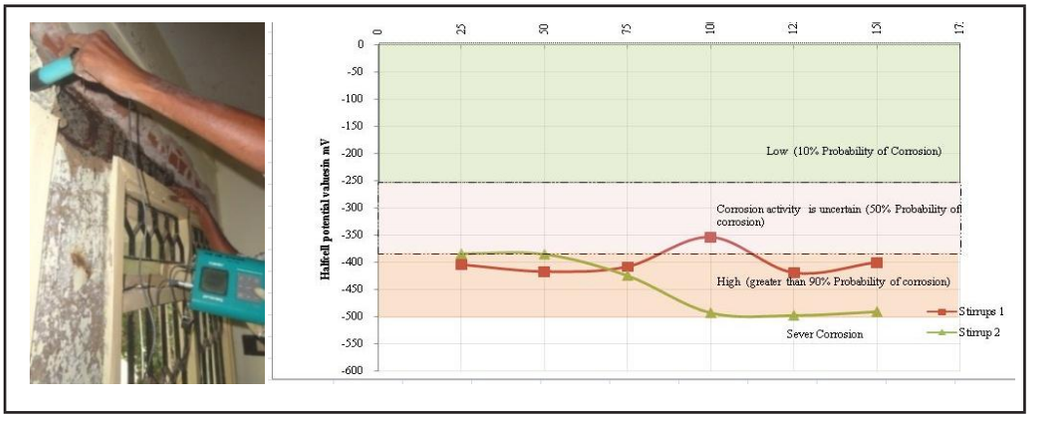

Fig.11: Half cell potential mapping

The analysis of cylindrical core samples (75mm diameter & 150mm length) reveals that the equivalent cube strengths[21], ranging from 35.52 N/mm² to 44.04 N/mm², exceed both the design strength of 20 N/mm² and the minimum grade requirement of 30 N/mm² as per the environmental exposure conditions specified in IS 456[22].

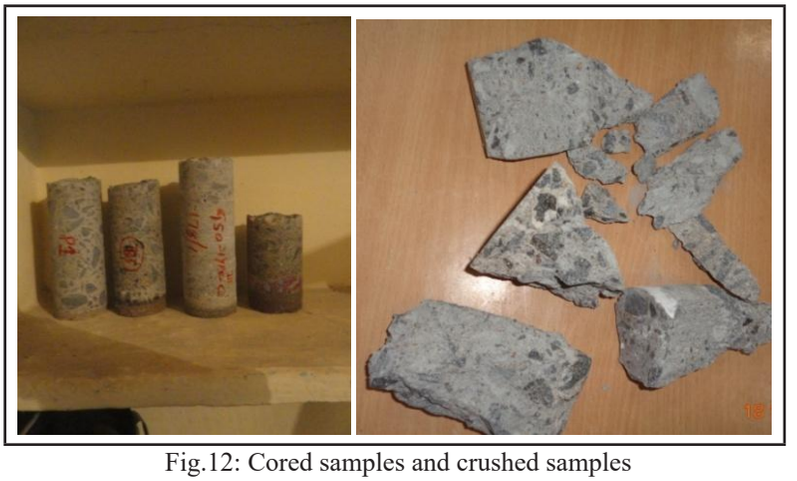

Fig.12: Cored samples and crushed samples

However, during compression testing, evidence of non-uniform aggregate distribution was observed (Fig. 12), with localised areas exhibiting excessive fine aggregates and a corresponding increase in cement paste. This indicates potential segregation of the concrete mix during placement or compaction. While the compressive strengths meet the required standards, the presence of segregation raises concerns about the overall homogeneity and quality of the concrete in certain areas, which may have impacted long-term durability.

4.3 Chemical Analysis

The carbonation process has been initiated in the RCC members (fig.13), which has started in the plastered surface and subsequently penetrated into the concrete, evidenced by a depth of carbonation of 15-20mm and pH in the range of 9.5[18]

Fig.13: Carbonation depth measurement & test for chloride

The chloride ion analysis[17] of spalled concrete and core samples(10 samples) from the GF/FF of the building structure revealed on an average, an acid-soluble chloride ion content of as high as 1.803 kg/m³, significantly exceeding the permissible limit of 0.6 kg/m³ as per IS 456. This indicates severe chloride contamination in the concrete, which is likely to have accelerated reinforcement corrosion and compromised the structural integrity of the RCC structure.

The diameters of the corroded rebars were measured at various locations, including beams, soffit slabs, and lintels, using a digital vernier caliper. Upon inspection, it was observed that in some areas, the rebars had experienced significant corrosion, resulting in a reduction of more than 50% of their original diameter (Fig. 14). This severe loss in cross-sectional area was noted at multiple points.

Fig.14: Measurement of diameter using venier caliper

The service life of the RC structures exposed to different chloride exposure conditions can be estimated using the nomograms [23]. Mixes with chloride diffusion coefficients less than 10^-12 m^2/s cannot be considered due to limitations with the nomograms. For the mix used in the buildings with cement content of 310kg/m^3 and w/c ratio of 0.5, life is estimated using the lowest diffusion coefficient available. As the concentration of chloride at reinforcement level has exceeded the chloride threshold (Fig.15) (assumed to be 0.4% of cement content) ,the corrosion process is initiated in most of the RC elements.

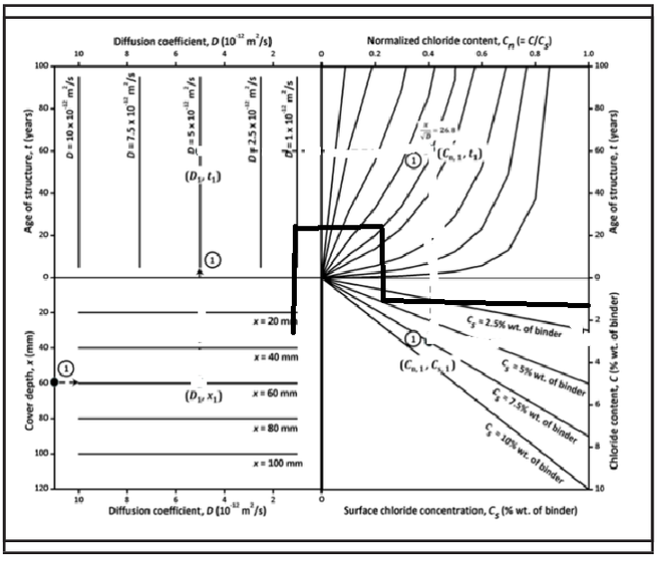

Fig.15: Nomogram based on Fick's second law of diffusion for predicting initiation of corrosion [23].

5. CONCLUSION

Based on laboratory and site assessment results, the structural integrity of the reinforced concrete building is evaluated to be compromised. The cracking and spallation of columns, lintels, beams, balcony canopies, and the initiation of corrosion, as measured by a reduction in the diameter of reinforcement and through potential mapping, could cause catastrophic failures. The electrochemical corrosion initiated due to tsunami water stagnation had further progressed due to the severe exposure condition. The variability observed in the homogeneity and durability of the RC structural elements indicates a lack of compaction in the concrete, which has further accelerated the rate of degradation.

After a precise evaluation of the structure using the aforementioned methods and careful corroboration of the results, it is inferred that these houses have significant concerns regarding the deterioration of the RCC beams, columns, soffit slab & lintels, which must be controlled. Implementing a combination of crack repair, corrosion control, structural retrofit, and surface restoration techniques is crucial for effective rehabilitation of the apartments..

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