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Visual analysis and Schmidt rebound hammer test of Taj-ul-Masajid

Análisis visual y ensayos de índice de rebote con el martillo Schmidt en el Taj-ul-Masajid

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ABSTRACT

Taj-ul-Masajid, literally, the crown among mosques is an embodiment of genius structural engineering located in the heart of Madhya Pradesh, Bhopal. A unique combination of the Mughal Architecture in complete stone masonry and modern day RCC work, it is a liaison between the past and the present of structural engineering. A wonder in its own right, the structure is often neglected by technicians and conservationalists alike, a satire on their ingenuity. Now, in a severely dilapidated condition, the structure is in pressing need of structural rehabilitation. The authors intend to perform in-situ Non-Destructive Testing & Evaluation (NDT&E) of this structure and thereby suggest steps to better its present condition. As a first step, they've performed the visual analysis and Schmidt Rebound Hammer Test on the concrete portion of the structure which has been presented herein. The authors have also suggested a new approach for the verification of results obtained.

Keywords: structural engineering; in situ; non destructive testing & evaluation; visual analysis; Schmidt rebound hammer.

RESUMEN

Taj-ul-Masajid, literalmente, la corona entre las mezquitas, es un conjunto de destacada ingeniería estructural situada en el corazón de Madhya Pradesh, Bhopal. Se trata de una combinación única entre mamposterías de piedra y modernas estructuras de hormigón armado, constituyendo un punto de unión entre el presente y el pasado de la ingeniería estructural. Siendo una maravilla en sí misma, su estructura se ve a menudo despreciada por técnicos y restauradores a partes iguales, en una muestra de ingenuidad. Encontrándose en la actualidad en un estado bastante ruinoso, la estructura necesita urgentes trabajos de rehabilitación. Los autores de este trabajo han tratado de llevar a cabo una evaluación in-situ de la estructura mediante ensayos no destructivos (NDT), sugiriendo una serie de pasos para mejorar su condición actual. Como primer paso llevaron a cabo una inspección visual y una campaña de determinación del índice de rebote mediante el martillo Schmidt que presentan en este artículo. También sugieren una nueva aproximación para la verificación de los resultados obtenidos.

Palabras clave: *ingeniería estructural; in situ; evaluación y ensayos no destructivos; análisis visual; martillo Schmidt.*

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1. INTRODUCTION

If it is said that the quality of concrete is generally measured in terms of its compressive strength alone, it wouldn't be an understatement. Concrete structures are generally made to resist compressive stresses. In those cases where strength in tension or in shear is of primary importance, the compressive strength is frequently used as a measure of these properties. Compressive strength is also used as a qualitative measure for other properties of hardened concrete (1).

The composite material called concrete is composed of cement, sand, water, aggregate, mineral admixtures, and chemical admixtures. To develop methods, especially non-destructive methods, which provide a reproducible measure of concrete quality in a structure, a number of notable studies have been conducted in the past. However, the results produced by these NDT methods are influenced by various parameters such as size and type of aggregate, water-cement ratio, presence of reinforcement, mix proportions, environmental conditions, etc.

Though the strength of building based on its surface hardness dates back to more than a hundred years, a simple and low cost procedure was proposed only at the beginning of the 1950s gaining immediate attention from the scientific and professional world (2) (3) (4) (5) (6).

The Rebound Hammer Test was developed in 1930 in Germany. In 1948, a Swiss scientist, Schmidt developed the Schmidt Hammer for measuring the hardness of concrete by the rebound principle. Results of his work were presented to the Swiss Federal Materials Testing and Experimental Institute of Zurich, where the hammer was constructed and extensively tested. About 50,000 Schmidt rebound hammers had been sold by 1986 on a worldwide basis (7) (8). Its working is, today, governed by IS 13311 (Part 2): 1992 in India and is globally governed by different standards such as ASTM C805 – 1997, ASTM D5873, BS 1881: Part 202: 1986, EDIN EN 12398 (1996), SS 13 72 37, SS 13 72 50, SS 13 72 52, etc. In this particular research work, though, we'll be adhering to the Indian Standard [IS 13311 (Part 2): 1992]. As stated in the code previously mentioned, when the plunger of the rebound hammer is pressed against the surface of the concrete, the spring controlled mass rebounds and the extent of such rebound depends upon the hardness of the surface. The surface hardness and therefore the rebound are taken to be related to the compressive strength of concrete. The rebound is read off along a graduated scale and is designated as the rebound number or rebound index. Locations having very low rebound numbers indicate weak surface concrete and may be affected by corrosion (9).

Typically the amount of kinetic energy lost during contact between the pole and concrete must be determined via the stress-strain relationship of the concrete; therefore, rebound energy is correlated with the concrete strength and rigidity. However, the accuracy of RHT needs to be improved in real applications when estimating concrete strength using the surface rebound value (7). As per the IS, the type of cement, type of aggregate, surface condition and moisture content of concrete, curing and age of concrete and carbonation of concrete surface affect the values of rebound number in any particular analysis. A good correlation between the strength of structure and its modulus of elasticity and age can be developed. Therefore, Schmidt's Rebound Hammer is apt for determining the mechanical properties of a structure (10).

Over the years, the dependability of Rebound Hammer tests for the damage assessment of a concrete structure has come under much scrutiny. While some say it gives only an idea of the soundness and quality of concrete (9), others say that it gives only an approximate value of the in-place strength and in-place deformability of the structure (11). Still there are others who claim that the test is a very rough tool for comparing the quality of concrete surface by comparison with data obtained by means of different and more reliable tools, but it is not a tool for estimating directly the concrete strength (6). Studies have shown that rebound readings are sensitive to near-surface properties, thereby casting doubts on the accuracy of the test in estimating compressive strength. Factors that are found to influence the surface hardness include surface smoothness, age of concrete, moisture content, carbonation, presence of aggregates, presence of air voids and steel reinforcement, temperature, and calibration of the rebound hammer (12) (13). Nevertheless, the rebound hammer can be a reliable device for assessing the general condition of a structure and the homogeneity of concrete, provided that it is calibrated and a rebound correlation curve is developed and used for the specific type of concrete to be tested. The accuracy of the correlation curve is increased by testing a large number of concrete specimens (13). In case of in-situ analysis, this can be achieved by taking multiple readings on a single surface and taking an average of the readings. However, it is very important to mark weak points which may have occurred due to cracking, spalling, flaking, corrosion or any other defects. It is to be noted that in case such a point occurs in the survey, the pressing of the plunger amounts to a formation of a deeper crack or impression or the peeling off of the flaky surface, or in extreme cases, complete deterioration.

In this particular survey, it was found that although the major portion of the surveyed structure gave rather high values of rebound number and therefore, showed good strength, a large number of such weak points existed in the structure implying requirement for urgent rehabilitation in case the structure deteriorates completely through these weak points. The socio-cultural and economic value of the structure, which would be discussed under the next heading of the article, means that any such damage would be dreadfully unfortunate.

From the results of the visual survey and Schmidt Rebound Hammer test which were used in the present survey, the authors could deduce a startling result. To verify the anomaly which makes the aforementioned result startling, the authors suggest the use of a new approach.

2. TAJ-UL-MASAJID: HISTORICAL REVIEW

Taj-ul Masjid is a unique civil engineering structure in Bhopal, its uniqueness exemplified by the fact that it combines the medieval stone masonry with modern day RCC structure. The two different masonries which symbolize the past and present of Civil Engineering itself have been combined so impeccably that it is impossible for a common viewer to differentiate between the two. One of the largest mosques in India, this unique feature makes it a monument worth mention among so many great historical monuments in the country.

Taj-ul-Masajid was built in the newly laid out walled suburb named Bhopal Shahjahanabad after Shahjahan Begum.

Shahjahanabad was planned and laid out beginning 1874 in the northwest of the city and contained institutions of public good like schools, rest houses (serais), library and mosques besides the patron's palaces, most notable being Taj Mahal. The building in its entirety was planned around three water bodies, Noor Mahal Talab, Munshi Hussain Talab, and Motia Talab. Figure 1 gives a Road Map to Taj-ul-Masajid.

The project was initiated after 1871 when Shahjahan Begum turned towards Islam influenced by her second husband's religious zeal. Taj-ul Masjid, designated as an Idgah, was built on a hillock at the highest elevation in the suburb and was planned to become one of the largest and best built mosques in the Indian Subcontinent. The mosque was different from its magnificent predecessors. It was grander in size; it dominated an urban landscape of imperial palaces, gardens, water bodies and public institutions. It was under construction in 1901 when its patron, Shahjahan Begum, died and the construction was later supervised by Sultan Jahan Begum. The project remained unfinished, in all likelihood owing to paucity of funds, for decades during the rule of successive Bhopal Nawabs and later following independence. In 1971, the work was recommenced, curtsy the ceaseless efforts of Allama Mohammad Imran Khan Sahadb Nadwi of Bhopal. The construction was completed by 1985. The design, while subscribing to the Mughal archetype both in form and material, was innovative in that it made provision for women worshippers via the 'Zanana gallery', 'commodious Zanana chapels' at either end and a 'mezzanine floor at each end of the mosque, near the minars'. The Zenana (women's) space was further subdivided to serve the differences in rank of their users ranging from the Begums to the noble ladies to the laity. Another first in the mosque construction in the India was the use of reinforced concrete in the 18-storey twin minarets (14). The structure has a pink façade, as can be made out from the photographs.

The area also comprises of a school for Arabic education with a library, research centre and rooms for lodging scholars and students. The Madarsa School (Islamic School), Darul Uloom Taj-ul-Masajid, Bhopal, was established in 1950 within the mosque's premises. Over 700 poor students are enlightened here, today. The students are not only exempted from paying tuition fees but are also offered free food and lodging.

For many years, Aalami Tablighi Ijtima, an annual three-day congregation that draws people from all over the world, was held at Taj-ul-Masajid. But, due to the lack of space, it has been shifted to Ghazipura Eintkhedi, a place outside the city.

Figure 1 gives the reader a glimpse of this magnificent epitome of structural genius.

3. MAJOR FEATURES

The ground floor Plan of the structure is shown in Figure 2.

Ground Floor

- Extension from East to West: 526 feet.
- Courtyard: 325 × 325 feet.
- Main Prayer Hall: 72 × 206 feet.
- 3 main gates along the boundary.
- Eastern Gate: 47 ft height, 40 ft width and 40 ft length.
- Northern Gate: 25 ft height, 25 ft width and 18 ft length.
- Southern Gate: 25 ft height, 25ft width and 18ft length.
- Women's Prayer Hall on both the sides.
- Inner courtyard has rooms.
- No of rooms: 120.
- Each measures: 8.5 × 13 feet.

Figure 1. Taj-ul-Masajid.

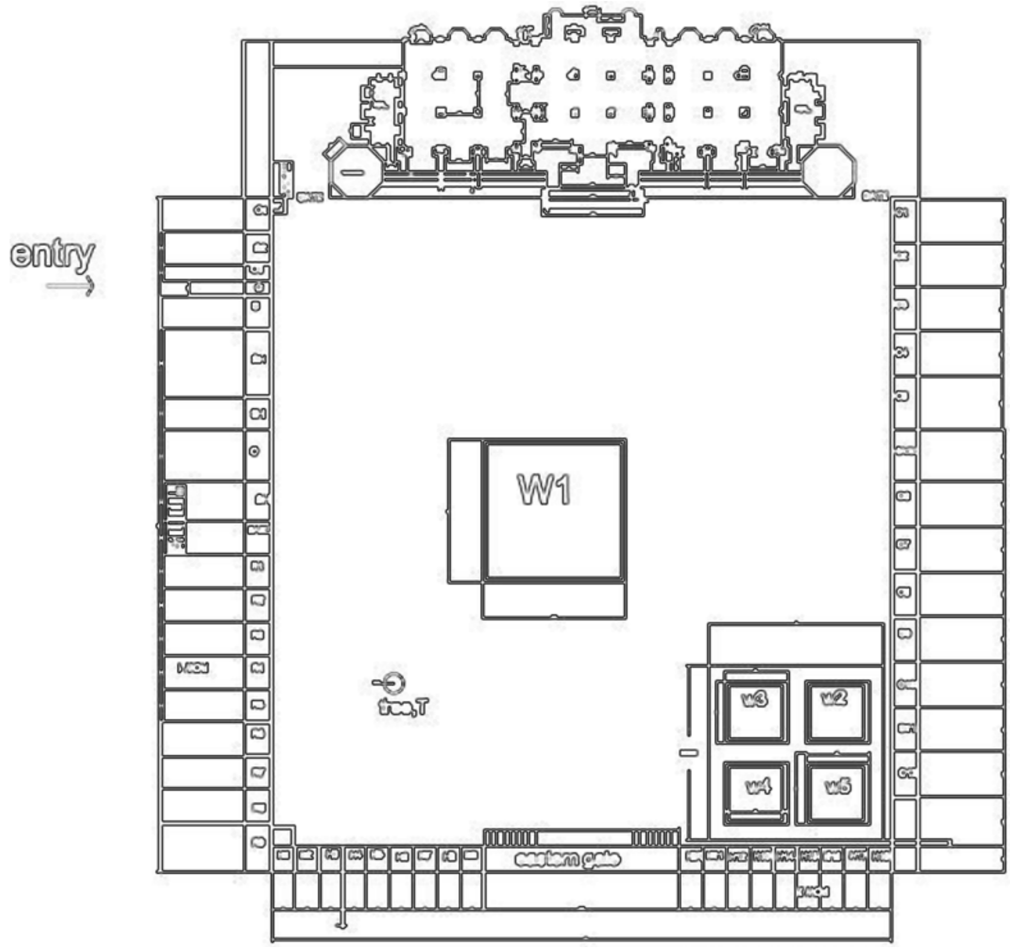

Figure 2. Ground Floor Plan.

Minarets

- No. of Minars: 2.
- Minar A Total Steps: 276.
- Minar B Total Steps: 252.
- Minar A Stone Steps: 114.
- Minar B Stone Steps: 85.
- Minar A RCC Steps: 162.
- Minar B RCC Steps: 167.

First Floor

- Separate prayer hall for women.
- Located on both the sides of the main prayer hall and at first floor too.
- Specially designed as per "PURDAH SYSTEM".
- Specifically built Parapet honeycombed to view only from inside.
- 10 arches each 2.60 m wide.
- Well defined architectural pillars and openings.

Supporting Basement

- Domes have 3 supporting basements as second floor.
- Each one is square in plan.
- Measuring 18.60 × 18.60 m, 21.94 × 21.94 m, 20.80 × 20.80 m respectively.
- Each basement has 9 extruding small domes.
- Ventilators are provided around each basement ceiling.
- Ventilators: 1 m × 0.30 m.
- Supported on large RCC and stone columns.

Domes

- Terrace Area: 82 × 258 feet.
- Domes.
- Middle dome is largest with height of 62.5 feet.
- Domes' pedestal: 65 × 65 feet.
- Domes' diameter - Dome A: 11.30 m, Dome B: 14.58 m and Dome C: 11.30 respectively.
- 2 staircases connect the domes.
- Each dome has a china mosaic tiling on it.
- Architectural doors and windows.
- Decorative Parapet of brickwork, RCC and stones.

4. A VISUAL SURVEY

Damage was observed in almost every single part of the structure. It was, however, noted during the survey that the most damaged of all five portions mentioned under the previous heading was the dome region, which the authors observed was in dire need of structural rehabilitation. Therefore the results of the subsequent test have been limited to this portion of the structure.

Ground Floor:

The major defects observed were blackening of stones, flaking, blistering, gap between joints, erosion, cracking, seepage, dampness, discoloration and efflorescence. Minor defects like vegetative growth, timber damage, breakage of joints, etc. were also observed.

Minarets:

The minarets were rather undamaged on the outside. Though stone discoloration was observed on the outside and flaking was observed on the inside.

First Floor:

Defects observed included improper bonding of dissimilar materials, efflorescence, dampness and flaking. Other defects were presence of broken glasses, chipping off of stones, etc. Cracks observed were mainly dormant cracks. This portion of the structure was quite undamaged when compared to the other portions.

Second Floor:

The portion had been subject to cracking, flaking, dampness, seepage, spalling, honeycombing. While some walls, including the ones marked first, second, sixth, eighth, were fully deteriorated, others like fourth and fifth were not damaged at all. The portion was also subject to chemical attack, especially sulphate attack, and carbonation.

Domes:

The most severely damaged portion, the amount of damage witnessed in this portion can be made out from Figures 3 and 4. Dampness, Elastic Deformation, cracking, carbonation, chloride attack, sulphate attack, erosion, stone chipping, complete deterioration, and the structure was subject to every imaginable form of damage. The dome closest to the Motia Talab, Dome C, was the most severely damaged. The rebound number values for this dome were found to be the lowest, as is discussed in the following section. This dome, therefore, needs special consideration.

The results obtained for the three domes from the visual survey have been surmised in Table 1.

5. ANALYSING THE STRENGTH USING SCHMIDT HAMMER

Schmidt Rebound Hammer was used to assess the strength properties of different portions of the structure. Points showing significantly lower and significantly higher values were marked. They represented weak points and the presence of reinforcement respectively. Although the structure could be divided into many portions, the survey results have been limited to the domes. This is because the domes were the portions showing the most significant levels of damage in the visual survey and the strength evaluation results for other portions would have been redundant. Concrete surface around the

Table 1. Summary of the Results Obtained for the domes from the Visual Survey.

Structural Element	Defects Identified in Visual Investigation	Defect Area as a Percentage of Total Surface Area
Dome A	Dampness	20 %
	Cracking	Less than 5 %
Dome B	Dampness	Less than 10 %
	Cracking	Less than 1 %
Dome C	Dampness	50 %
	Cracking	10 %
	Spalling	25 %
	Flaking	35 %
	Blistering	35 %
	Honeycombing	15 %

Figure 3. Dome C.

Figure 4. Reinforcement Completely Exposed to External Environment in Dome C.

points to be tested were thoroughly cleaned before taking Rebound Hammer measurements. The upper surface of the plaster was removed so that the test could be performed on the hard concrete surface. Around each point of observation six readings of rebound indices were taken and the average of these values was taken [as per IS 13311 Part 2 (1992)].

Generally, in the Schmidt Rebound Hammer Test, the values of the compressive strengths in Pascal/Square Inch (psi) (C_{psi}) are established by using the Schmidt Hammer Curves, with reference to the rebound number (N). The values of compressive strengths in Newton/Square Millimetre (C_{mm}) could be calculated by the formula

$$C_{psi} = C_{mm} \times 145.037$$

However, in the present survey, no such numerical values have been mentioned as the values obtained were not correlated to the concrete core test results. However, the relative strengths obtained from the relation mentioned above could be used to deduce the following:

In case of dome A, the rebound number values indicated a fairly deteriorated condition. However, the values didn't show significant variations. This indicated that the loss in strength has been distributed throughout the structure rather uniformly. No weak or particularly vulnerable zones could be located. Therefore, despite the overall loss in strength, the structure is in no immediate danger of a collapse.

The rebound number values obtained for Dome B were significantly higher than those obtained for Dome A. The values showed great degree of uniformity throughout the structure. This indicated that the dome is in very sound condition.

The dome C showed lower values of rebound number as compared to dome A. The number of immediately vulnerable portions was high. The structure, it could be deduced, is in immediate need of retrofitting. The presence of weak zones indicates the possibility of failure of the structure through these points.

It can be deduced from the results of the visual survey as well as the Schmidt Rebound Hammer test that Dome C is the most vulnerable element in the entire structure. And yet the other two domes, which are built with the same material and around the same time and subjected to the same environment as dome C is, are not in any immediate danger of failure. In fact, dome B, as has already been discussed, looks in significantly good condition. This is an obtrusive fact. The authors therefore feel that further study into the microstructural features of the domes' material needs to be made. For this the authors of the manuscript suggest a new approach.

6. A NEW APPROACH FOR VERIFICATION OF RESULTS

The authors recommend the use of X-ray Diffraction test for the verification of results obtained through visual investigation and rebound hammer test. X-ray diffraction is one of the earliest and most widely applied techniques for studying the structure of solids. In the process of diffraction, electromagnetic waves of a given frequency but different phases interact to produce constructive interference (bright spots on the film exposed to the light) and destructive interference (dark spots) (15). In 1913, W.H. Bragg and his son W.L. Bragg formulated the following relation between the spacing of atomic planes in crystals and the angles of incidence at which these planes produce most intense reflections of electromagnetic radiations, such as X-rays and gamma rays:

$$2\lambda = 2d\sin\theta$$

Here, the variable d is the distance between the adjacent planes of atoms in a crystal (interplanar distance), and the variable lambda (λ) is the wavelength of the incident X-ray beam, n is an integer. In this relation, which is an example of

X-ray interference or X-ray diffraction (XRD), if the values of θ and λ are known, one can determine the d-spacings. An X-ray diffraction pattern, which is a graph between the intensity of X-rays scattered at different angles by a sample, is plotted. A phase is a specific chemistry and an atomic arrangement and each phase has a unique "fingerprint" diffraction pattern (16). Therefore, when properly interpreted, by comparison with standard reference patterns and measurements, this becomes a powerful tool for identification of a chemical phase. In case of a mixture sample, the diffractogram or the diffraction pattern is a simple addition of each individual phase. XRD tests can used to discover crystalline phases, phase distribution and also to provide quantitative analysis of identified phases.

The following methodology is proposed for the use of XRD test for the verification of results obtained in the Visual Investigation and Rebound Hammer test.

Samples for XRD test could be extracted from the three domes by mechanical means and finely grounded. The X-rays generated by the diffractometer would be collimated and directed onto the finely grounded sample. The X-ray signals would then be detected by a detector and processed either by a microprocessor or electronically, converting the signal to a count rate. During data collection, the sample would remain in a fixed position and the detector would scan over a range of 2θ values. The result would be in the form of a diffractogram, a graph between 2θ and intensity in Cycles per second. The intensities obtained and the d-values corresponding to them can be used to search for the respective chemical phases with the help of Hanawalt's Powder Diffraction File Search Manual (17) (18). Each crystalline substance has a unique 'fingerprint' diffraction pattern.

The identification of different crystalline phases in concrete samples may point towards different aspects of the performance of concrete.

The manner in which different chemical phases affect the performance of concrete differently could be illustrated by the presence of ettringite in concrete. While primary ettringite formation is considered positive given that it helps in regulating the setting of concrete, the formation of ettringite in the later stages is often attributed to be highly damaging to the concrete health. Similarly, copiapite, a product of pyrite oxidation which in turn results in crystal growth of various sulfates, may result in heaving because of the expansive nature of sulfide to sulfate conversion. It has been observed in the literature that the presence of many complex phases point towards the asymmetry of the specimen. The identification of such damage causing phases would not only help in verifying the results obtained in the present study, but also help in predicting the chemical reasons for the same.

7. DISCUSSION

The following major points could be deduced from the above analysis:

- The Dome C of the structure is in a severely dilapidated condition and may even fall off entirely in the near future, in case the proper retrofitting techniques are not applied.
- Among the three domes, Dome B seems to be the least affected. The minarets which were built before the domes seem unaffected. This indicates a severe case of external environment deteriorating the structure.
- The presence of weak zones in the structure is alarming as the structure may fail through these points.
- The non-uniformity of strong zones, which should've exhibited the presence of steel, shows that the RCC work was done rather arbitrarily than based on a process.

Schmidt Rebound Hammer Test is able to satisfactorily reinstate what has been observed in the visual survey.

8. CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

9. CONCLUSION

In all, it was observed that while a large portion of the structure is nearly undamaged, there are portions in the concrete half of the structure which are in urgent requirement of rehabilitation and may potentially fall off. As the structure is always considered to work as one complete system, damage to one part of the structure would mean complete damage and total loss. Therefore, it becomes imperative to put in efforts to quickly strengthen the structure.

Schmidt Rebound Hammer has been able to satisfactorily suggest the weakening of the structure, which was earlier suggested by the visual survey. The complete deterioration of Dome C has been clearly indicated in both the surveys. The need for its repairing has been emphasized umpteen times. Apart from the tests that have been performed in this particular analysis, the authors also suggest the use of a new approach, namely X-ray Diffraction test to evaluate the microstructural aspects of the material used in the three domes. The three domes which are built of the same material and around the same time are showing great variation in strength related properties. The authors believe that this anomaly could be attributed to the microstructural properties of the material in the domes. X-ray diffraction test is an apt tool to study such microstructural variations. After making this important analysis, the authors believe that it will be possible to suggest techniques for retrofitting of the structures.

But, before that is done, it is even more important to properly assess the other physical and corrosion-related aspects of the structure, if any, to draw out a complete picture of the structure's condition. Also a detailed map showing the rehabilitation works to be done with a complete economic analysis is a must. The authors are currently pursuing this objective.

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