Prediction of Service Life and durability analysis of Pier Structure

By Fong Weng Khiong (fongwk@ascenfe.com)
Ascent Facilities Engineering Pte Ltd, Singapore

A durability investigation of a 30 year old barge pier structure located in a tropical marine environment was carried out. Preliminary as well as a detailed visual inspection of the structure was carried out in order to a) identify the different types of defects, b) estimate the extent and coverage of defects on the barge pier structure and c) decide the types of field and laboratory tests to be conducted and the extent of sampling. The important observations noted during the visual inspection were:

- Almost all the major defects were found to be located under the barge pier structure. The top surface of the concrete deck of the barge pier had no apparent defects except for abrasion wearing of the concrete surface.
- No other/excessive loading was noted on the barge pier except for pipes transferring waste oil to the island.
- Spalling of concrete was noted as the most common defect occurring at the beams and the slab. The spalling was noted at various stages from development of crack lines to spalled patches. This can be seen in Figures 1. Rusty reinforcement was exposed at some areas where the concrete cover had spalled off. At locations where previous repairs were found to have been carried out, the boundary of the patch repairs had started to crack and spall due to the expected phenomenon of macro-cell corrosion. Figure 2 shows the occurrence of cracking.

As part of investigation, determination of compressive strength, level of chloride concentration, depth of carbonation, concrete mix composition, petrographic examination, impact echo test and half cell potential measurements of the reinforced concrete has been performed and concrete cover and rebar diameter has been measured.

The half cell potential measurements were typically in the range of -355 mV to -599 mV in areas where no spalling had occurred. Based on ASTM C876-91:1999 [1], it can be said that there is "a 90% probability of corrosion occurring". This was also confirmed visually in the sample breakouts which revealed visibly corroded reinforcement. The pitting corrosion of the steel piles was found to result in a reduction in the cross sectional area, thereby affecting the load carrying capacity of the piles and consequently the stability of the entire structure.

The chloride concentration levels on the soffit of slab were found to have exceeded the threshold for initiation of corrosion (taken as 0.4% by weight of cement), hence implying that the deterioration of concrete was in the active corrosion or propagation stage. Even though chlorides level measurements were not carried out on the soffit of the beams due to difficulty in obtaining samples, the fairly visible and widespread spalling of the concrete indicated that chloride levels on the soffit would also have exceeded the threshold.

Carbonation of concrete was seen to be negligible from the recorded carbonation depths and hence not likely to have contributed to the corrosion process and spalling of the concrete.

The concrete compressive strength on the slab was found to be satisfactory. However the concrete compressive strengths on the some of the beams were seen to be comparatively lower. On the whole, the strength of the placed concrete was variable as evidenced by the compressive strength ranging from low to high values.

- The concrete cover of the placed concrete at the beams and slabs was found to be generally satisfactory.
- The concrete mix composition indicated a fairly consistent mix ratio of 1:3:4 (proportion of cement: sand: aggregate) from the laboratory test results.
- The impact echo test results indicated delamination on the underside of the slab which was found to be consistent with the physical condition on site.
- The petrographic examination of the in-placed concrete revealed variable

Evidence of defects of Pier Structure

mixing and compaction quality of the concrete. There were no deleterious aggregates detected, thereby ruling out any cracking from alkali silica reaction (ASR).

Prediction of Service Life

For the prediction of service life of the structure for initiation of corrosion, the ingress of chlorides was considered to be a diffusion process described by Fick's second law of diffusion [2]. This approach has been commonly used for the modeling of chloride ingress by Liam et al. [3], Engelund and Sorensen [4], Val and Stewart [5], Khatri and Sirivivatnanon [6] and several others. For cracking of the concrete cover, the semi-empirical model developed by Liu and Weyers [7] was used; this model is based on the determination of the time required to generate the critical amount of corrosion products that are needed to i) fill the interconnected void spaces around the reinforcing steel and ii) generate sufficient tensile stresses to crack concrete. Corresponding to two values of the ratio of molecular weight of steel to molecular weight of corrosion products suggested in Liu and Weyers [7], the lower bound and upper bound of the time to cracking are obtained.

Using the measured values of the various parameters, the time to initiation of corrosion was estimated to be between 8.3 to 11.5 years. The lower bound and upper bound of the time to cracking were estimated to be from 7.5 and 12.6 years respectively. Hence the service life of concrete in the structure for the limit state of initiation of corrosion and cracking of cover concrete was obtained as 15.8 to 24.1 years. With the age of the structure being 30 years, it could be said the structure is in the active corrosion or propagation stage; this also confirmed the findings of the durability investigation and hence provided a reasonable predictive basis for the stage of the deterioration of concrete and also for the planning of the rehabilitation options.

Remedial Recommendations

The rehabilitation solution for the pier structure was designed to suitably address the defects observed during the investigation. The necessary "immediate reactive" repair methods were proposed to address the defects that merited instant attention. This involved i) delaminated/spalled concrete repairs using the patch repair method, ii) repairs to cracks using epoxy resin injection, iii) strengthening of beams by increasing their sections size and reinforcement or by the use of fiber reinforced polymer laminates with moisture tolerant epoxy resins, iv) strengthening of the steel piles by welding additional plates and v) application of protective coating on the steel piles using a high build epoxy material.

As a sustainable long term remedial option, the use of a cathodic protection (CP) system was also proposed. As part of a proprietary system, sacrificial anodes would be installed on the concrete deck at i) the boundary of patch repairs to protect against macro cell corrosion, thereby mitigating corrosion of steel around patch repairs and ii) non-repaired areas which have highly negative potentials so to prevent further corrosion of the steel reinforcement. Further a galvanic cathodic protection system was proposed for the steel piles, wherein a zinc mesh anode would be placed directly against the inside face of a stay-in-place fiber glass form and corrosion would be prevented by providing an electrical current to the affected region.

The installation and use of a cathodic protection system was seen to be the most economical alternative from a life cycle perspective. SCI

REFERENCES

1. ASTM C876-91 (1999). Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete. ASTM International, West Conshohocken, PA, 6p.

2. Crank, J. (1956). The Mathematics of Diffusion. 1st edition. Clarendon Press, Oxford, 347p.

3. Liam, K. C., Roy, S.K. and Northwood, D.O. (1992). Chloride ingress measurements and corrosion potential mapping study of a 24-year-old reinforced concrete jetty structure in a tropical marine environment. "Magazine of Concrete Research", No 44(160), pp.205-215.

4. Engelund, S. and Sorensen J. D. (1998). A probabilistic model for chloride ingress and initiation of corrosion in reinforced concrete structures. "Structural Safety", No 20, pp.69-89.

5. Val, D.V. and Stewart, M.G. (2003). Life-cycle cost analysis of reinforced concrete structures in marine environments. "Structural Safety", No 25, pp.343-362.

6. Khatri, R.P. and Sirivivatnanon, V. (2004). Characteristic service life for concrete exposed to marine environments. "Cement and Concrete Research", No 34, pp.745-752.

7. Liu, Y. and Weyers, R.E. (1998). Modeling the time-to-corrosion cracking in chloride contaminated reinforced concrete structures. "ACI Materials Journal", No 95(6), pp.675-681.

Detecting Rebar with Proceq

The new, Swiss-made Profoscope by Proceq has made rebar detection easier, faster and more accurate all around the globe. The Profoscope allows construction and building industry professionals to avoid drilling into rebar, which is costly and dangerous. It has a scopebased detection interface that combines rebar proximity indicators with optical and acoustic locating aids.

Offering the best-in-class mix of features at a new lower price-point in the market, the Profoscope is small, light, cordless and ergonomically designed to fit in the palm of the hand. Made for one-handed operation, the language-independent interface provides both visual and acoustic indications of what lies directly beneath the concrete surface.

At first glance, the Profoscope user sees an apparently conventional instrument with a large graphic LCD display and selectable backlight that can locate rebar, measure cover depth and rebar diameter. However, because of the special positioning of the electromagnetic coils within the unit, the Profoscope allows a symmetrical triangulation of the rebar configuration that tells the user whether the Profoscope is actually located midpoint between two rebars or directly on top of one. This is a best-in-class feature that sets the Profoscope apart from any other similar instrument on the market and is especially useful when the user needs to drill into reinforced concrete and avoid damaging the expensive rotary drills and carbide drill bits.

Profoscope has unique real-time rebar-visualisation that allows users to "see" the rebar beneath the concrete. These unique features combined make the task of locating rebar a simple and efficient process; saving time and money for contractors and providing them with the information they need to do their job quickly and carefully.

Besides being fully integrated and coming in a compact design, the Profoscope also has user-friendly operation and a language-independent menu. The Profoscope's intuitive user interface means that no time is wasted trying to interpret signal values. The Profoscope also has a wide measurement range and regional settings. Supplied with a start-up test kit, a custom-made canvas bag, product documentation and accessories, it also comes with a 24-month equipment warranty and full service support. When purchasing the

Profoscope, the buyer is also offered the possibility of purchasing extended warranty coverage. SCI

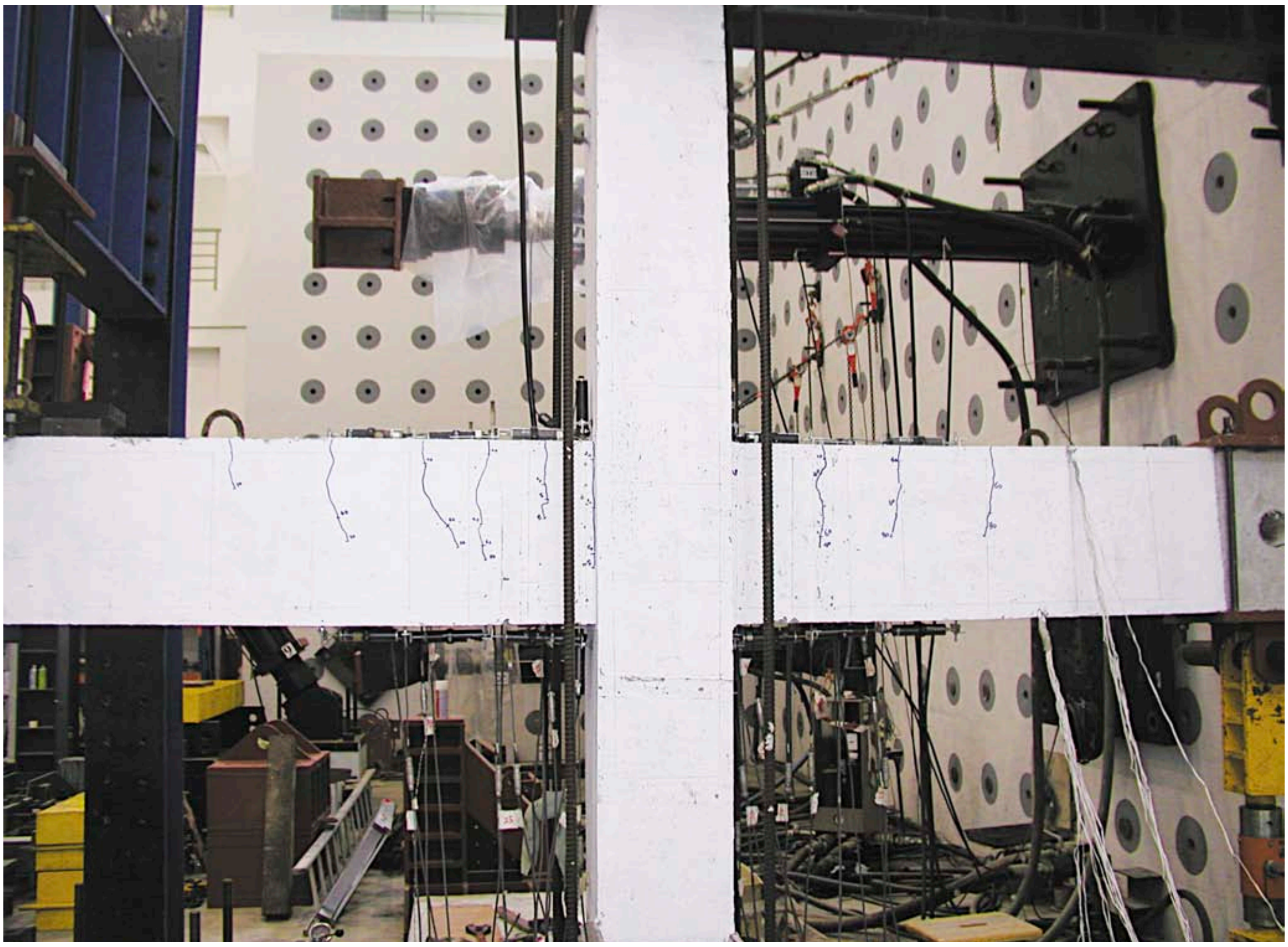
Enquiry: info-asia@proceq.com

The Profoscope allows construction and building industry professionals to avoid drilling into rebar.

Application of Piezoelectric Materials for Health Monitoring of Concrete Structures

By Bahador Sabet Divsholi[1] , Yaowen YANG[2]
Nanyang Technological University, [1]Sabe0002@ntu.edu.sg, [2]CYWYang@ntu.edu.sg

Health monitoring of concrete structures for determination of early age or long term properties is a very important topic. Piezoelectric materials have been widely used for health monitoring of structures over the last two decades. Piezoelectric Lead Zirconate Titanate (PZT) materials are robust, cost effective, sensitive to damage and ideal for already built structures. There are two common methods introduced to assess the condition of structure through PZT materials, i.e., the electro mechanical impedance (EMI) method and the Lamb wave propagation (LWP) method. In the EMI method, one piece of PZT is used as both actuator and sensor. A range of high frequency signals (typically over 30 kHz) with constant voltage will be sent to the PZT patch to actuate the structure, and the resulting vibration of structure is acquired through the same piece of PZT. The acquired vibration signal is called the "EMI signature". The peaks in the EMI signature represent the natural frequencies of the structure. Any change in structural properties such as hardening of concrete or development of crack will result in change in position and magnitude of the peaks or appearance of new peaks in the EMI signature. High frequency excitation enables good sensitivity of PZT sensors to small cracks for local health monitoring. In the LWP technique, one



Experimental setup

piece of PZT is used as actuator and another piece of PZT as sensor. The PZT sensors can be attached on the surface of structure (already built structures) or embed inside of the section (new structures). Figure 1 and 2 show the experimental setup and PZT sensors attached to surface of structure. Figure 3 illustrates the EMI signatures before (in healthy condition), during loading and after failure of the column beam joint. Root mean square deviation (RMSD) can be used to quantify the amount of changes in the EMI signature. Figure 4 shows the comparison between the load-displacement curve and the RMSD result. It is demonstrated that PZT sensors are able to identify the critical condition of the concrete beam-column joints and their behavior. Extensive research in the area of modeling and application of piezoelectric materials (PZT and macro fiber composites) for structural health monitoring is undergoing in School of Civil and Environmental Engineering, Nanyang Technological University under supervision of Prof Yang Yaowen. SCI

Position of PZT sensors and cracks in specimen

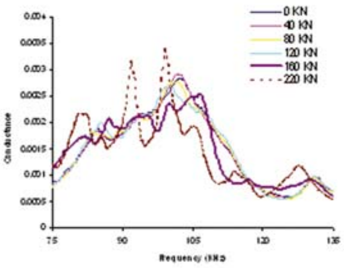


Fig 3. Signatures collected during test

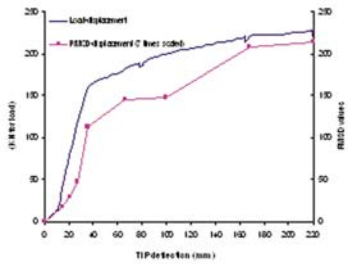


Fig 4. Load-displacement and RMSD results

ADVERTORIAL

MC - Rehabilitation System for Manholes and Non-Accessible Sewers

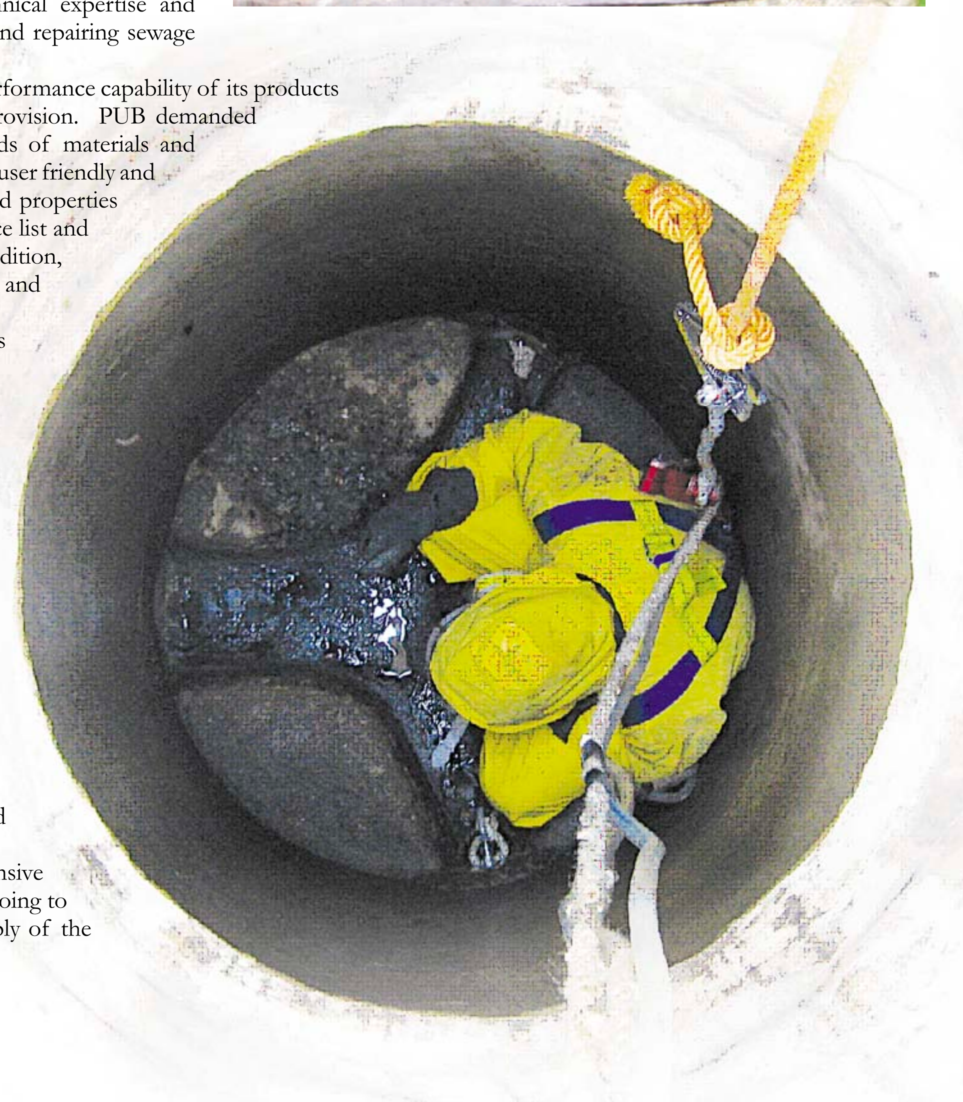
MC WAK

In conjunction with PUB MC aims to provide clean and beautiful streams and waterways that will enhance the quality of life for all Singaporeans and in order to ensure that we have clean waterways, it is important that sewers are functioning properly without leakages. Therefore, MC was involved in the infrastructure project to include sewer rehabilitation and redevelopment works.

Against this background, Singapore's state-owned water agency PUB (Public Utilities Board) has started extensive infrastructure projects in order to restore the pipeline network. Both public and private sewage networks in Singapore are in dilapidated state due to ageing. This harbours considerable dangers for groundwater and waterways.

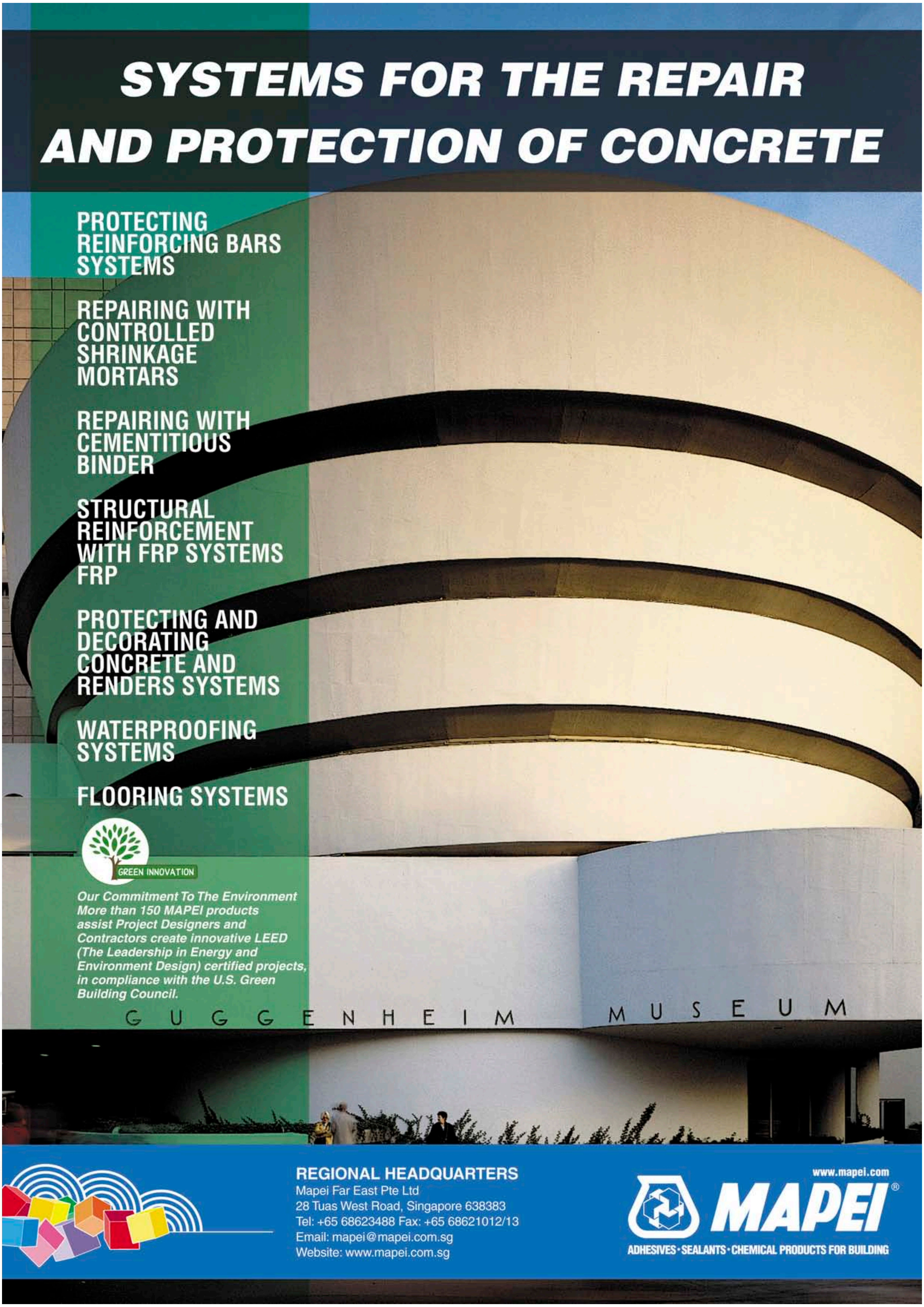
To carry out the extensive repair measures PUB was searching the international market for a company with proven competence in this specialist area. As one of the leading global suppliers of repair systems, MC's specialist department ombran possesses many years of technical expertise and experience in the area of modernising and repairing sewage pipelines and manholes.

MC impressed both in terms of the performance capability of its products and systems and in terms of service provision. PUB demanded high quality and environmental standards of materials and application, while products also had to be user friendly and yield high coverage. The aforementioned properties had to be evidenced by way of a reference list and certifications from official bodies. In addition, MC provided intensive technical support and training of applicators.



The project started in 2006 and is planned to be completed in 2014. The repair works are carried out in four phases. For the cladding of the over 4,000 pipe shafts, the newly developed ombran MHP from the range of the tried and tested specialist ombran mortars was used in this rather demanding project. This one-component, polymer-modified repair system is reprofiling and coating in one – an economic and time-saving advantage of great value in such a large-scale project. Where the wastewater pipelines were not walkable or accessible, the Konudur CIPP method was used over a stretch of 60 km lengths to repair the pipes and achieve a longer service life.

Following completion of these extensive restoration works, the sewer network is going to play an important role in the water supply of the city-state. SCI


SYSTEMS FOR THE REPAIR AND PROTECTION OF CONCRETE
PROTECTING REINFORCING BARS SYSTEMS
REPAIRING WITH CONTROLLED SHRINKAGE MORTARS
REPAIRING WITH CEMENTITIOUS BINDER
STRUCTURAL REINFORCEMENT WITH FRP SYSTEMS FRP
PROTECTING AND DECORATING CONCRETE AND RENDERS SYSTEMS
WATERPROOFING SYSTEMS
FLOORING SYSTEMS
GREEN INNOVATION
Our Commitment To The Environment More than 150 MAPEI products assist Project Designers and Contractors create innovative LEED (The Leadership in Energy and Environment Design) certified projects, in compliance with the U.S. Green Building Council.
GUGGENHEIM MUSEUM
REGIONAL HEADQUARTERS
Mapei Far East Pte Ltd
28 Tuas West Road, Singapore 638383
Tel: +65 68623488 Fax: +65 68621012/13
Email: mapei@mapei.com.sg
Website: www.mapei.com.sg
www.mapei.com
MAPEI®
ADHESIVES · SEALANTS · CHEMICAL PRODUCTS FOR BUILDING

ADVERTORIAL

Restoration of the Guggenheim Museum

renovation works begins at the Guggenheim Museum.

The Solomon R. Guggenheim Museum, located along 5thAvenue in New York, is aimed at promoting an understanding and appreciation of contemporary art. It is one of the three museums (together with the Peggy Guggenheim Collection on the Canal Grande in Venice and the Guggenheim Hermitage Museum in Las Vegas) belonging to the Solomon R. Guggenheim Foundation, which was set up in 1937 for the purpose of collecting, conserving and studying modern-day art. In actual fact, the building holding the New York museum designed by the American architect Frank Lloyd Wright and completed in 1959 a year after his death, may be considered a work of art in its own right.

Wright was an architectural "visionary" who attempted to explore the unexplored, distancing himself from traditional design methods and pushing engineering to its limits. He created a circular structure for the Guggenheim Museum in New York, made entirely of concrete and designed as a spiralling ramp rising up over six levels to a two-storey glass skylight at the top. The spiralling form, inclined at an angle of 3%, allows visitors who have taken the lift up to the seventh floor to walk down the ramp while admiring the work set on the various levels until they find themselves back at the exit at the end of their visit.

An Unconventional Design

The building holding the Solomon R. Guggenheim Museum was constructed using unconventional methods, quite rusty surfaces) caused by problems which arose during the initial spraying operations and which are now part of the building's most distinctive features.

A Global Company Offering Local Solutions

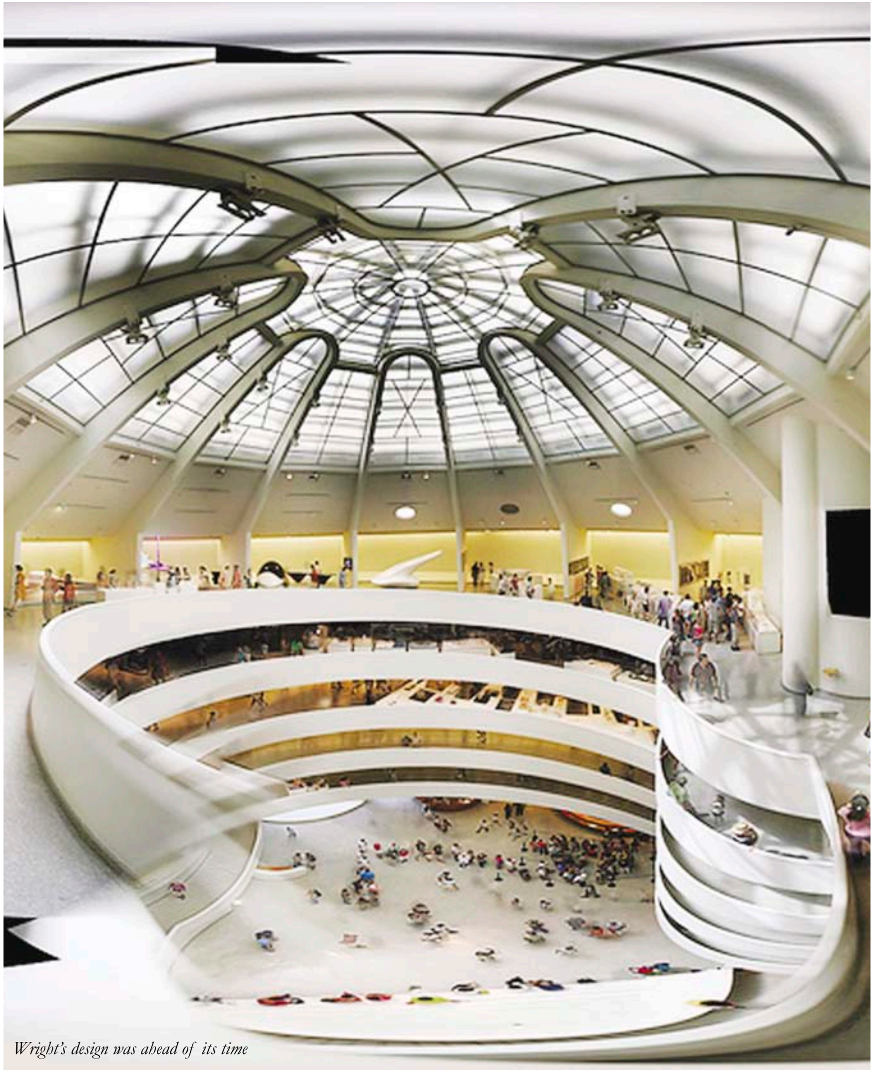
After the American research institute ICR (Integrated Conservation Resources) carried out a careful search for firms qualified to take on a restoration/renovation operation of this scale and after performing very careful laboratory tests on individual materials, Mapei was chosen to come up with a conservative restoration solution which would be ideal for this prestigious building.

The system proposed (and guaranteed by the Company for 10 years) then underwent further laboratory testing before it was approved. This system was developed thanks to constant and highly successful cooperation and exchange of information between Mapei SpA, the Group's mother company, and its American subsidiary, Mapei Corporation, and also between the Research & Development Laboratories in Milan and those in Deerfield Beach, Florida.

Solutions to Artistic and Technical Challenges

Due to the particularly innovative construction method which included a total lack of expansion joints in the building holding the Guggenheim Museum, right from the very beginning cracks began to appear. Down the years, oxygen, together with water and aggressive agents, penetrated into the cracks and brought about a gradual corroding of the reinforcement rods. This, in turn, led to rust forming on the ironwork and, consequently, the iron surface deteriorating and damaging the overall structure.

After the company commissioned to carry out the work removed the various layers of finishing that had been applied to the outside surfaces of the building over many years, ICR- technicians and structural engineers drew up a map of the cracks present, making a distinction between those subject to movements (and which subsequently developed into expansion joints) and those caused by shrinkage of the concrete. It was obvious that the different types of cracks had to be treated using different operating methods.



Wright's design was ahead of its time

Mapei Solutions

Mapei developed its own very concrete solutions for this project based on all the experiences it has gained over the last 20 years restoring prestigious works around the world.

1st Phase

Mechanical demolition and cleaning of the surfaces was done using a system designed to respect their original appearance. Pneumatic stone hammers were used for the mechanical removal, after locating the operating area and completely uncovering the reinforcement rods using diamond-edged discs.

The surfaces were then cleaned using the innovative "sponjet" system which does not cut deep down into the surfaces and leaves them looking as they originally did. The system uses an aluminium-oxide dust coating with polyurethane foam, which makes the material less abrasive, despite its hardness.

2nd Phase

Localised repair work was done on the demolished sections of reinforcement rods using a system which ensures effective protection against further decay. MAPEFER 1K, a one-component corrosion-inhibiting cementitious mortar was applied to the reinforcement rods after they had been cleaned, to ensure a re-alkalising protection and prevent dust formation.

MAPEFER 1K has proven to be an extremely beneficial product for installers, because it is extremely easy to work and apply by brush.

This highly innovative product, which is resistant to chlorides and aggressive agents found in the air, conforms to the DIN 50021 regulation (relative to the resistance to saline-fog test) and also passed the B117 test (for the same property) set by the ASTM (American Society for Testing and Materials).

After the MAPEFER 1K had dried, numerous sections of damaged concrete were repaired using PLANITOP XS, a special normal-setting, one-component, thixotropic mortar manufactured in Mapei Corporation's plants and marketed in the Americas by the Mapei Group's North-America subsidiary.

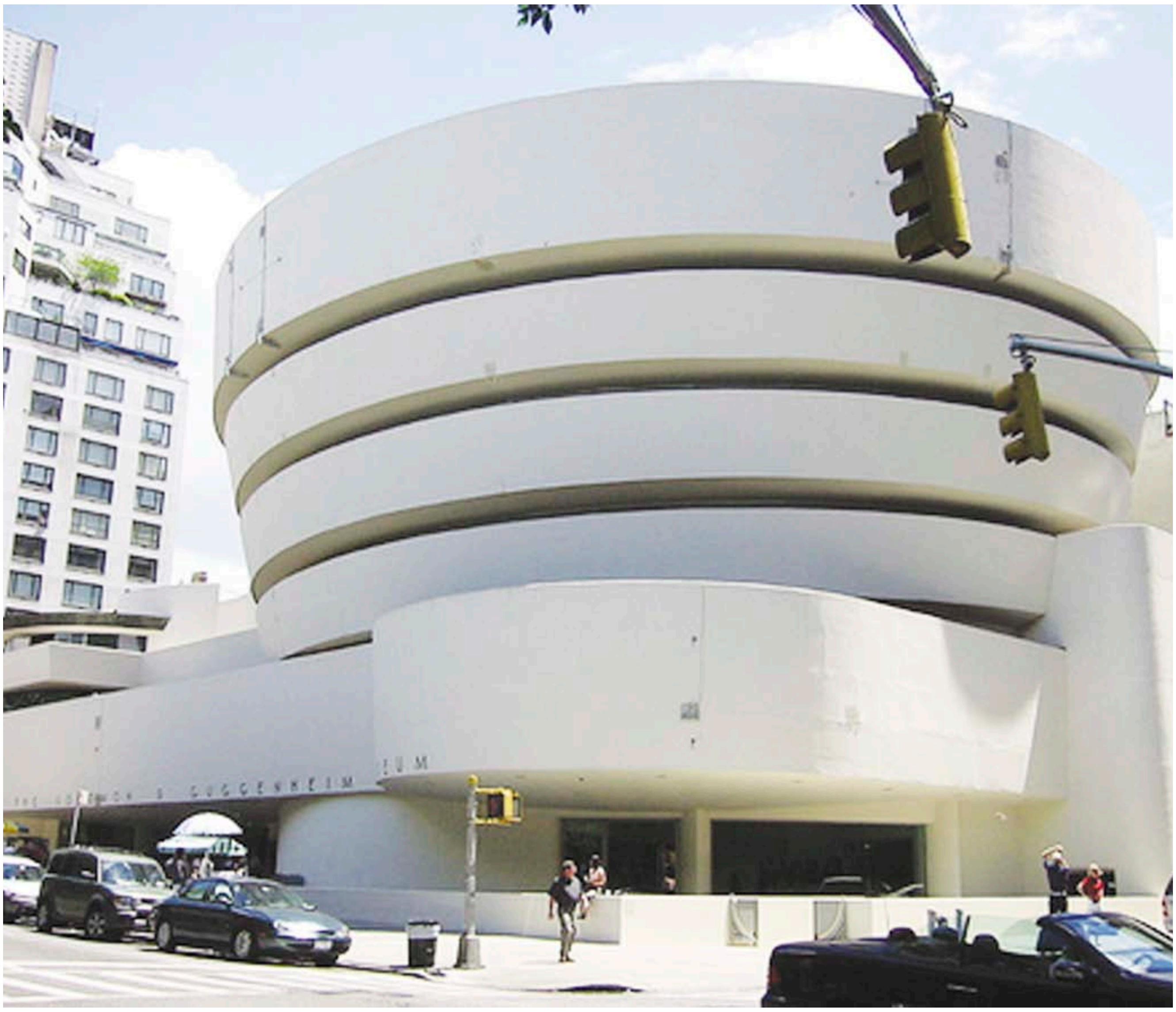
3rd Phase

Work is done on cracks subject to movements using an elastic sealant, which may be painted over. Cracks caused by a lack of joints could not be sealed using rigid systems without then reappearing in neighbouring areas.

The MAPEFLEX AC4 was applied to the cracks after first widening them and inserting a MAPEFOAM polyethylene foam cord in the bottom of the joint. In some cases cracks subject to smaller movements were sealed using ELASTOCOLOR RASANTE SF, a fibre-reinforced elastomeric under-coat with high filling properties and admixed with fine sand.

4th Phase

Protection was provided for the building's outside surfaces using a flexible mortar. The work was carried out using MAPELASTIC, one of



2007-2008: repairing of certain sections of the Museum's circular outside facade using PLANITOPXS mortar.

Mapei's biggest-selling product worldwide and used successfully for about 20 years. This two-component cementitious mortar is impermeable to water and carbon dioxide, flexible and capable of bridging cracks subject to movements of up to 0.6 mm in width. Developed to be as flexible as possible, MAPELASTIC is ideal for concrete structures which, like the Guggenhaim Museum, are subject to movements due to severe heat fluctuations or vibrations.

The product was sprayed-on using a special lance designed for smoothing agents so that any imperfections caused by the formworks were deliberately left visible. In certain parts of the building subject to notable wear-and-tear, MAPELASTIC was reinforced using MAPETEX SEL—a macro-holed polypropylene fabric used for increasing the product's tensile strength.

5th Phase

Application of an elastomeric coating in the original colour. Considering all the movements under which the Guggenheim Museum is subject, as previously determined in the case of protection, the finish coating also had to be flexible. For this reason, it was decided to use ELASTOCOLOR RASANTE, a fibre-reinforced filling undercoat which is applied using an airless spray. After drying, ELASTOCOLOR RASANTE forms a smooth coating which—thanks partly to the fibre content—follows any expansion substrate without cracking.

6th Phase

Protecting surfaces at street level was done using an elastic paint and anti-graffiti system. ELASTOCOLOR WATERPROOF was applied to the surfaces of the walls surrounding the rotunda at street level. This is an acrylic resin-based paint in water dispersion ideal for permanent, direct contact with water and guaranteeing long-lasting protection. The product is particularly suitable for painting all kinds of waterproof surfaces using MAPELASTIC or MAPELASTIC SMART as was the case here.

There are already plans to provide further protection using WALLGARD GRAFFITI BARRIER—a barrier-protecting surfaces against graffiti from spray paint, work crayons, markers, etc.

After completion of the renovation work, the scaffolding was finally removed on 22 September 2008—just in time to celebrate the 50th anniversary of its construction. Fifty years after the Guggenheim Museum was built, Frank Lloyd Wright's genius is still widely recognised worldwide thanks to this building. **SCI**