Conception for the repair of historic buildings with architectural concrete façades

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Summary
The repair of historical concrete structures must aim for the preservation of the original construction and the appearance of the concrete surface. This requires adequate methods which minimize the intervention on the building fabric while guaranteeing the durability and the structural safety. Particularly for repair of architectural concrete, local repair rather than treatment of the entire concrete surface should be carried out whenever feasible on the basis of technological considerations. Such an approach requires a detailed investigation of the structure as well as an estimation of the remaining life time of still undamaged sections of the structure. Suitable repair concretes have to be developed which, in addition to visual similarity with the original concrete, have to satisfy certain requirements with regard to their mechanical properties. In this paper the basis of the methods and procedures for an adequate repair work on historical buildings is presented.

1 INTRODUCTION

Soon after concrete was increasingly used as a construction material for buildings from the end of the 19th century, architects began to take profit of the design possibilities offered by this still new material. This also holds true for the design and treatment of the surface of concrete components, without terming this as "fair-faced concrete" or “architectural concrete” as it is commonly done today.

There are numerous historical buildings around the world that are impressive testimonials of this early applied architectural concrete. Famous examples are the Pantheon in Rome, the Sydney Opera House, Le Corbusier’s Unité D’Habitation in Marseille/France, the Cathedral of Brasilia/Brazil, and the Goetheanum in Dornach/Switzerland, see also Fig. 1.

The appearance of the concrete surface, which has developed over the years, is a characteristic and defining element of a building. This appearance is therefore also subject to the protection of monument preservation. Its aim is to preserve buildings as far as possible in their original state as historical testimonies of architecture. Any necessary interventions in the fabric of the building that serve to rehabilitate the building must be minimised and made as reversible as possible.

The methods commonly used today for the repair of concrete damages do not fulfil this requirement being valid for historical buildings. The reason is that in general the original appearance of the concrete surface and, connected to that, the impression of the entire building is often endangered if concrete repair methods strictly follow the conventional basic principles of current guidelines and regulations.

Moreover, the composition and properties of modern repair materials deviate considerably from those of the historical concrete. The combination of both materials would cause mechanical und physical problems.

Therefore, adapted repair concretes have to be developed and particular sustainable and gentle methods for the repair of architectural concrete of historical concrete structures have to be implemented. However, these methods must also meet the conventional durability requirements.

This gentle concrete repair method, which is technically in line with the state-of-the-art for conventional concrete repair, is normally applied just locally on the concrete surface. Hence, its application has to be especially proved for the considered situation at a historical building.

This paper gives an overview, deals with some particular aspects and indicates important conclusions.

Fig. (a):
Anatomische Anstalt Munich (1907),
architect Max Littmann

Fig. (b):
Detail from Fig. (a)

Fig. (c):
Stonemasoned concrete surface,
detail from Fig. (b)

Fig. (d):
Goetheanum, Dornach, Switzerland (1928),
architect Rudolf Steiner

Fig. (e):
Cathedral of Brasilia, Brazil (1970),
architect Oskar Niemeyer

Fig. 1 Three different historical concrete buildings, see (a), (d) and (e), and an example of a concrete surface, which was treated by stonemason technics, see (c)

2 DAMAGES AND CAUSES

At the façade of historical buildings several kinds of damage and defects can be found. By simplifying, damages on aged concrete surfaces can be classified as scaled and chalked surfaces, coverings of either mineral or organic origin, hollow regions with non-existent mortar matrix, cavities, insufficient compaction, honeycombs, cracks due to bending, restraint or surface effects, and cracking and spalling of concrete due to corrosion of the reinforcement.

The causes for damages on concrete surfaces are manifold. Deterioration of concrete surfaces is mainly caused by climatically induced strains such as frequent changes of temperature and moisture content, freeze/thaw cycles or dilution and leaching processes. Hollow regions and cavities are induced by the manufacturing process. Cracks at the surface are often the result of residual stress or restraint due to impeded shrinkage or temperature deformations. Severe damages on historical structures are caused by corrosion of the reinforcement which leads to spalling of the concrete cover. Thereby, not only the durability but also the load-carrying capacity and the structural stability often are reduced.

The above-mentioned characteristics of damages on concrete surfaces appear not only at historical buildings but also at ordinary concrete structures. Therefore, it is important for an evaluation of the affected concrete surfaces to categorise the building. For instance, fouling or scaling of the concrete surface of a historical building in many cases can be considered as part of its memorised appearance that should be preserved. This means that restoration is only reasonable if the deterioration of the concrete surfaces results in a decrease of durability, serviceability or stability. This has to be clarified by a thorough investigation of the building combined with a detailed damage analysis.

3 GENTLE CONCRETE REPAIRS

3.1 Repair concept and boundary conditions

When concrete repair is required at historical concrete buildings or monuments, there is the demanding task of reconciling technical requirements with the principles of preservation of monuments. This needs a careful sourcing of existing technical and descriptive documents related to the building and a comprehensive structural investigation in view of the extent and causes of the observed damages. Upon this basis a special repair concept has to be developed which preserves the building and its appearance while restoring the durability and structural safety.

The elimination of damage and the rehabilitation of durability of the concrete structure have to comply with the following conditions: minimisation of intervention, preservation of the original construction, preservation of the architectural and optical appearance of the structure with its original surfaces, sustainability and repeatability of repairs.

It is obvious that methods in which surface coatings or overlays made of polymer or mineral materials are applied to the entire surface of the structure are not suitable. Accordingly, only a restoration method can be used, that is based on local repair with concrete or mortar, which restores the passivity of the reinforcement. These methods are regulated in European and national guidelines, see e.g. [1], and are specified as replacement of carbonated concrete or concrete contaminated with pollutants or chloride. If possible and technically justifiable, imperfections of the concrete surface such as cavities, honeycombs or fouling should remain at the structure.

This kind of procedure is reasonable only if the extent of damage does not exceed a certain limit and if a forecast of the future progression of damage indicates a sufficiently high durability of both the repaired and especially the non-repaired surface areas. This evaluation requires a detailed and accurate investigation of the building. Its complexity exceeds significantly the usual extent of preliminary investigations that go along with a conventional concrete repair.

The performance of a gentle concrete repair shows some specialities. Among other things, the development of suitable repair concretes that are adjusted to the mechanical and visual properties of the old concrete as well as the surface finishing, in some cases using stonemason methods, are required.

A sporadic appearance of further damage during the estimated residual service life of the structure normally can – as is the case with every other repair method – not be excluded. Therefore, a methodical inspection and maintenance of the building is part of the repair concept.

3.2 Investigations prior to the repair work

The objective of such investigations is to create a solid basis for predicting the progress of deterioration and corrosion of the old structure so that a repair concept can be developed. The aim of this repair concept is to preserve the original concrete surface wherever possible. Furthermore, such investigations are necessary to derive measures for a suitable restoration of the deteriorated parts of the concrete surface, as well as to develop and specify repair mortars or concretes which are compatible with the old concrete surface in technological as well as in architectural respects.

The information that should result from the investigations can be classified into four major groups: history of the building, state of actions, ambient climate, exposure and service conditions of the building, structural design and construction, and building materials.

The technological investigations regarding the concrete should provide above all the compressive strength, tensile strength, modulus of elasticity, binding agent, mix ratio, colour of the mortar matrix and type, colour and grading curve of the aggregates, further physical properties like capillary absorption and diffusion characteristics.

The following particular information about the appearance of the original concrete surface is needed to allow for adjusting the visual properties of the repair concretes: surface texture of the concrete and its extent at the building, type and extent of scaled and chalked surfaces and fouling, and colour and brightness of the concrete surface.

Colour and brightness of the concrete surface can be analysed using methods and laws of the colour metrics. Practical methods of colour analysis have been developed at the Institute of Concrete Structures and Building Materials of the University of Karlsruhe (today Karlsruhe Institute of Technology, KIT). These methods combine colour metrics (e. g. CIELAB system) and digital image scanning, representing a qualified and quick tool for practical use [2].

Finally, on the basis of the investigations, strategies for maintenance and inspection of a particular member or the entire building have to be derived.

3.3 Evaluation of the structural stability

An evaluation of the structural stability of the load-bearing members has to be done considering the states of damage and repair on the basis of the results of the investigation and the valid regulations and guidelines. This is a typical task of the structural analysis, which may be complicated by the fact that sometimes the loadbearing capacity of historical buildings may not be proven by applying current guidelines. However, in the past there have been developed several particular guidelines for existing structure. Moreover, the fib Model Code 2020 also deals with existing concrete structures, including matters such as in-service assessment and intervention to extend the life and to improve the performance of these structures [3].

3.4 Prediction of durability and service life

A prediction of the corrosion risk has to be done both, in areas that should be locally repaired and in areas that remain original, respectively. The reason is that the gentle local repair of a historical concrete surface makes only sense if the future corrosion risk in the remaining original surface is sufficiently low. Hereby, the effect of the macro element corrosion has to be considered.

The frequent presence of moisture and oxygen and the destruction of the passivation layer of the reinforcement are prerequisites for corrosion. At historical buildings a loss of the passivation is caused only rarely by a local ingress of chlorides, but usually by the carbonation of the concrete. Thus, for the prediction of the future corrosion progress the prognoses of the carbonation development and the hygro-thermal behaviour of the concrete are necessary.

The decisive effects and correlations with respect to the probability of depassivation and the probability of corrosion, resulting in the carbonation induced corrosion of the reinforcement and related damages, are illustrated in Fig. 2. It shows the increase in the probability of depassivation (red area) with time, taking into account the relevant distribution functions for the carbonation depth and the concrete cover, respectively, see Fig. 2 (left, below).

The hygro-thermal behaviour of the concrete at the building façade is preferably evaluated by a numerical analysis due to the high operating expense and the long duration of in-situ measurements. For running the numerical analysis, the cross-section of the façade has to be modelled and realistic climatic conditions of an outdoor weathering have to be implemented (using e. g. official reference climatic data). Furthermore, the material properties need to be determined in detail. For this purpose, it is important to specify the material properties with the help of laboratory investigations, which are performed at samples taken out of the building's façade (e. g. concrete cores).

As a result of the simulations, the distribution of the moisture content is given in the course of an entire year in relation to the depth below the weathered concrete surface (see curved lines in the upper left part of Fig. 2). Significant changes and high moisture contents only appear close to the concrete surface. From a certain depth below the façade's surface on, there are no significant changes of the relative humidity within the wall's cross-section any more.

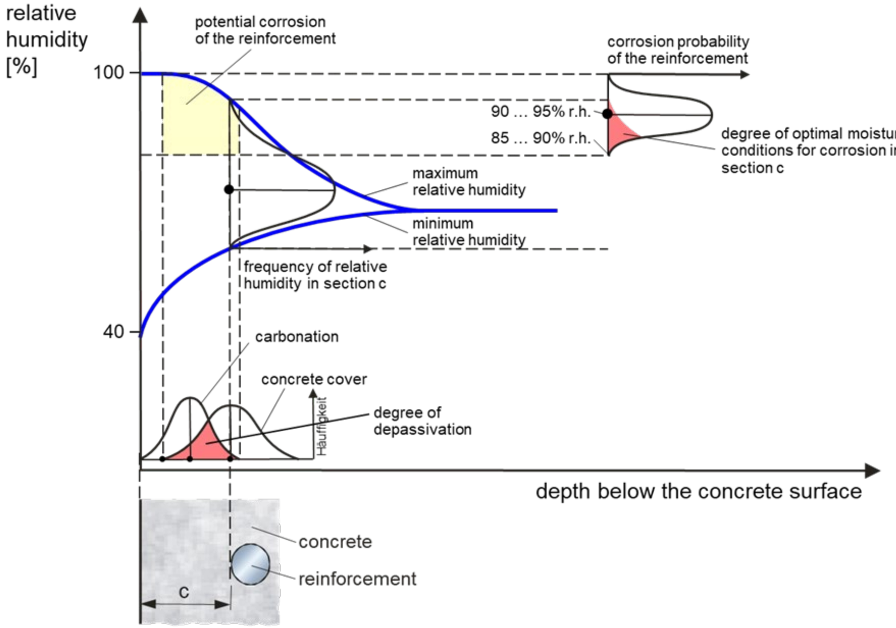


Fig. 2 Scheme for correlation of the parameters carbonation depth, concrete cover, ambient relative humidity, i.e. corresponding equilibrium moisture content of the concrete, and corrosion probability, which all are required for the prediction of the carbonation induced corrosion development of the reinforcement in concrete

Corrosion of the reinforcement will not necessarily start if the carbonation depth has reached the reinforcement. It is a prerequisite that there is also a sufficient supply of oxygen and moisture at the location of the reinforcement inside the concrete. Maximum corrosion rates are observed, when the ambient relative humidity is at least 85 %, but still below 100 %, i.e. if the equilibrium moisture content of the concrete corresponds to these ambient humidities [4]. Therefore, noteworthy corrosion will not take place if the moisture content stays below a critical value which can already be the case in a relatively low depth below the surface.

For predicting the durability of the concrete structure, the above-mentioned parameters need to be correlated. Fig. 2 illustrates the procedure for correlating the parameters concrete cover, carbonation depth and relative humidity dependent on the depth below the concrete surface. In the lower left corner of Fig. 2, the overlapping area formed by the concrete cover and carbonation distributions symbolises the degree of depassivation. Similarly, the degree of optimal moisture conditions for corrosion is exemplarily determined in section c (c = concrete cover) below the concrete surface by the distribution functions of the relative humidity frequency in section c and the corrosion probability of the reinforcement. The yellow area in Fig. 2 marks the limited boundary conditions, for which corrosion is at all possible. Finally, it is obvious that a corrosion of the reinforcement is possible if there is simultaneously a probability of depassivation and a probability of a sufficient high moisture content. This is indicated by the red area in Fig. 2, upper part, right.

Additional important factors for damage resulting from corrosion are the concrete quality and geometrical conditions like the ratio between the concrete cover and the diameter of the reinforcement. For further information see as well [2].

The prediction of the durability and the remaining service life of the entire structure depends on several failure mechanisms and the combination of their occurrence. Furthermore, the complexity of the prediction increases if the structure underlies different geometries, climates etc. Therefore, special probabilistic methods are needed to predict the remaining life time of a structure. For further information regarding the prediction of service life see [7].

3.5 Development of repair concretes

Since the repaired concrete surfaces will not be coated, the repair concrete has to fulfil technological specifications as well as further requirements regarding the visual appearance of the reprofiled repair area.

Important demands refer to the fresh (workability, modellability) and the hardened (mechanical properties, durability, appearance) repair concrete. The properties of the repair concrete have to be especially adjusted and optimised to match with the properties of the old concrete. In general, the properties of the repair concrete should correspond approximately to the properties of the old concrete.

Shrinkage and temperature drops cause tensile stresses inside the repair concrete parallel to the surface and delamination stresses vertical to the bonding zone. The stresses reach a maximum at the transition zone between the old concrete and the repair concrete, and increase with increasing shrinkage or temperature drop as well as with increasing tensile strength of the concrete. Hence, to avoid delamination, the upper limit of tensile strength of the repair concrete has to be restricted. The maximum tolerable delamination stress is limited to the tensile strength of the old concrete surface.

Thus, the tensile strength as well as other properties of the repair concrete have to be accurately designed. The properties of the repair concrete can be adjusted by variation of the water/cement-ratio, variation of the binder/aggregate-ratio, insertion of air pores or hollow micro spheres, insertion of water repellents, and insertion of dispersing agents/polymers.

Further, other important properties of the repair concrete, as e.g. modulus of elasticity, capillary absorption, and diffusion resistance of water vapour and carbon dioxide have to be designed.

Once the technical data of the repair concrete recipe has been determined, the recipe must be fine-tuned with regard to the colour. The regulation of the colour and the brightness of the repair concrete is a demanding task which requires a lot of experience. If available, knowledge about the adjustment of different concrete ingredients, e. g. cement type and content, fine aggregates and colour pigments and the control of the surface texture are sufficient to reach a good result.

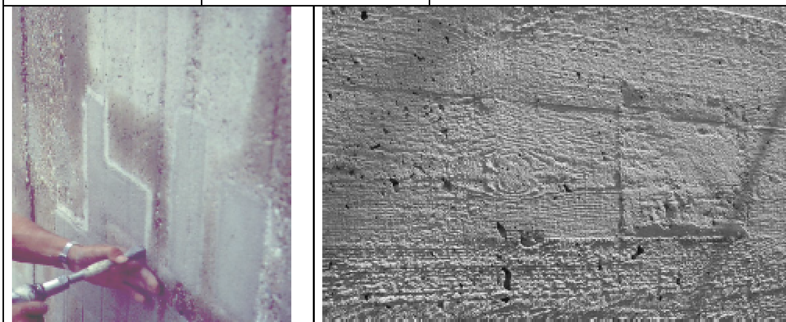
Apart from the development of the repair concrete, a bonding cement paste which serves as connection between the repair concrete and the original concrete has to be developed. Its properties have to be adjusted to the repair concrete. Before cement paste and concrete are used, the suitability of these materials has to be tested according to the valid regulations and guidelines.

3.6 Repair work

The required work steps for a gentle concrete repair are in general similar to those needed for a conventional concrete repair. However, there are a few modifications and additional procedures, which are essential for achieving a sustained success in the repair of a historical building [5]:

- The cleaning of the damaged areas shall take place very sparing. Thereby, the removal of surface layers has to be avoided. If it is technologically acceptable, a residual patina may be kept and should not be removed.
- The repair sections have to be accurately selected. Due to architectural and technological reasons, the boundaries of the repair sections are separated from the undamaged concrete by a cutter (depths approx. 5 mm) as done in natural stone repair. The cuts shall be straight and preferably follow visible casts from e. g. form boards or joints (see Fig. 3).
- After the removal of the damaged concrete and the corrosion products from the reinforcement, the repair area has to be thoroughly cleaned.
- The reinforcement has to be coated with a cementitious material if needed.
- A bonding cement paste has to be applied.
- The repair concrete has to be applied as long as the bonding cement paste is still fresh. The surface of the repair concrete has to be modelled if necessary.
- In some cases, the hardened repair concrete surface has to be adjusted to the old concrete surface. For this purpose, stone mason methods are used.

(a)	(b)	(c)
Defined limitation of the repair area by appr. 5 mm cuts	Chiselling out the damaged concrete. Exposing the reinforcement	Coating of the reinforcement with a cement-bound material and profiling the excavated area with a cement-bound repair concrete tailored to the structure (fresh in fresh with a bonding cement paste). Then adjustment of the texture of the fresh surface to the direct surrounding



(d)	(e)
Final adjustment of the surface texture to the direct surrounding using stonemasonry techniques (only if appropriate)	Completed repair work

Fig. 3 Details of a locally and gently repair work, including cutting (a), chiselling (b), coating (c), and surface adjustment (d); further, the completed repair work is shown (e)

4 FURTHER ASPECTS

Quality assurance should be followed as given e.g. in [3, 6]. Further, regulations are mostly provided by national guidelines.

After the gentle repair has been finished suitable maintenance should be carried out. In general, gently repaired surfaces need low-maintenance. One of the reasons for this is that the repair work was only concentrated on a very few small local areas, and was carried out with great care and was subjected to a high level of quality control.

The gentle concrete repair is resource-saving, economical and sustainable.

5 CONCLUSIONS

The gentle repair method described in this paper can be used very often for the restoration of historical buildings and monuments but also for other exposed concrete structures, old or new. The gained experiences show as well, that a gentle repair does not only result in an enhancement of the building's durability and appearance but also represents an economical resource-saving way of restoration. Normally, the gentle repair method is cheaper and more sustainable than a conventional repair, since repair takes place only locally and extensive surface coatings, which require regular maintenance or renewal, are avoided.

However, the application of the gentle repair method is not recommended if the prediction of the deterioration progress restricts the technological feasibility. In cases, where the extent of damage is so high, that the stability of a structure is endangered or where corrosion is caused by the action of chlorides, the gentle repair method is not applicable.

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