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The Importance of Good Design, Maintenance and on-time Repair Work for Long Service Life of Structures

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ABSTRACT

Deterioration of concrete structures all around the world requires huge funds to keep structures operable at acceptable safety level. There are several factors which influence the maintaining a long service life of the structures at available funds. Such factors are: a good design and an execution of the structure, an appropriate inspection plan and inspections carried out by qualified inspectors, an adequate maintenance strategy and an on-time execution of the repair work. In the paper a case of the viaduct structure it is presented. In a short period of time this structure had quite extensive repair works due to inadequate inspections and assessment of the real causes for the deterioration problems. If a thorough assessment of the causes for deterioration problems had been performed on time, quite substantial funds would have been spared.

Keywords. Deterioration, Maintenance, Design, Service life, Strengthening

INTRODUCTION

Ageing concrete structures demonstrate every day how important is a good design, detailing of structural parts and execution of the structures. A few last decades revealed that adequate maintenance and on-time execution of remedial work of observed deterioration processes is equally or even more important for the long service life of the structures. All concrete structures are exposed to detrimental effects of the environment and other possible chemical and physical attack of the concrete. Among many structures of public interest infrastructure structures are mostly exposed to the public and political scrutiny due to their impact on the environment, economic growth and smooth traffic flow. Neglecting deterioration processes and delayed repair work in the past have created huge backlogs of deteriorated structures in the countries throughout the world, which need urgent repair work. Economic crisis and lack of funds for regular and additional extended maintenance of the structures even increase the existent backlogs. This also deepens worries of the owners and maintenance staff about the safety of the users and structures they are responsible for. Some recent examples from around the world, like Gardiner expressway in Toronto, Turcot interchange in Montreal, partial collapse of concrete slabs in the Sasago tunnel in Japan, etc., which are part of the important traffic infrastructure arteries, show concern of the operators and politicians as well, while looking for the optimal and adequate solutions for deteriorated structures within limited financial and time constraints. By delaying the necessary beginning of the repair work, unpopular actions - such as load restrictions, reduced speed, closing lanes or even closing of the whole structure - become inevitable and unpopular actions, until final solution for the structure is found and carried out. Such actions provoke unpopular public perception of the civil engineering and of the way the structures are built, managed and maintained.

KEY FACTORS FOR LONG SERVICE LIFE OF STRUCTURES

There are several stages from design to decommissioning ("from cradle to the grave") of the structures which contribute to long service life of the structures regarding the purpose of the structures, type of the structures and their environmental conditions. These stages are: good design and detailing of the structural components with respect to the loading and environmental conditions, quality of the execution of the structures, adequate through-life inspections and monitoring, effective maintenance with respect to the type of the structure and environmental conditions, and on-time performance of suitable, feasible and reliable preventative or repair works. The main goal is to preserve the structures at adequate safety and operability at low maintenance costs (direct and indirect costs). When designing structures for the anticipated period of service life a good designer should focus on what kind of environments can be anticipated in the interior and on the outer parts of the structures, what performances of the concrete are optimal for those environments and how to minimize the impact of possible deterioration processes with regard to the selected quality of the basic materials of the concrete and reinforcement. The same holds for the built-in equipments which are important for the functioning and safety of the working processes. Good detailing of concrete structural components is primarily focused on the selection of the cross section shape and dimensions of the components. Too thin elements and reinforcement congestion can be avoided by the appropriate selection of the cross sections. Structural elements should be designed in such a way that they are adequately accessed for the inspection. Premature deterioration processes of the structural elements which are adequately inspectable can be detected on-time. In this case the appropriate maintenance procedure may be selected in due time for the repair work or may slow down deterioration processes.

Quality of the execution of the structures has great influence on the length of the service life of the structures as well. Mistakes made during execution of the concrete work, such as poor concreting, too low concrete cover, placement of concrete of inappropriate quality, poor texture and structure of the finished concrete surface and concrete cover, inadequate treatment of the concrete surface after concreting, grouting, etc., contribute very much to premature start of deterioration processes. One of the key factors for good quality of the execution is a carefully prepared tender for construction. It should be prepared adequately with respect to the exacting of the construction work and avoiding lowest bid as the only condition for the selection of the contractor. The contractor should have certified personnel for specialized and demanding work with good QA, QS and internal control. For very demanding and complex structures it is good to introduce external quality control, independent of the contractor and the supervising consulting companies. It is essential that construction processes are supervised with consulting companies with competent supervising engineers.

Most of the concrete structures should have established adequate through-life system of inspections and/or monitoring since the beginning of the exploitation. The system should depend on the importance of the structure, on the achieved actual quality of the construction with respect to the design quality and on the aggressiveness of the environment. Inspections and monitoring should be carried out by institutions which have qualified and trained inspectors, who are familiar with the concerned structures and important built-in equipments (e.g. expansion joints and bearings in bridges, etc.). Inspectors should be familiar with defects and degradation processes which may evolve in the cause of time with respect to the loading and all possible environmental loadings in and around the inspected structures.

Effective and on-time maintenance activities are key factors for the optimal length of the service life of the structures. Effectiveness of the maintenance activities strongly depend on the quality of the inspections, on due identification of the intensity and extent of defects with degradation processes, as well as on the choosing of suitable, feasible and reliable preventative or repair techniques, carried out by experienced and qualified contractors. It is recommended that personnel are trained and certified for the execution of specialized work.

AN EXAMPLE OF INADEQUATELY MANAGED BRIDGE STRUCTURE

Description of the structure. The viaduct was built in 1972. It has two parallel structures. The right structure is consisted of 15 spans of simply supported girders of the total length 591 m; the left structure is consisted of 15 spans of simply supported girders of the total length 553 m. The cross section of the superstructure is consisted of 4 longitudinal precast post-tensioned girders. The height of the I-shaped girders is 2,25 m and distance between the girders is 3,15 m. The length of the precast girders is 32,60 and 36,60 m. The outer girders are post-tensioned with 9 tendons 16ϕ7 mm and the inner girders are post-tensioned with 8 tendons. The quality of the prestressing wires is $f_y/f_{0,2}$ = 1700/1500 MPa. Design cube strength of the concrete was 50 MPa. The girders are linked together with deck plate and crossbeams over the supports and three crossbeams within each span. Crossbeams are precast elements and prestressed with 2 post-tensioned tendons. Deck plate is built of precast reinforced concrete elements of the height 0,20 m and of width 2 m. The length of the precast elements is half of the deck width. Precast elements were joined together by cast-in-place joints of the width 0,20 m. Sidewalks with integrated edge beams and curbs were also made of precast elements of the length 2 m. The transverse joints between the sidewalk elements were sealed by flexible seal. The whole superstructure is divided into 4 units. Over the abutments single gap expansion joints were built-in in the deck, intermediate expansion joints were lamella type expansion joints with 2 gaps each. The longitudinal girders are resting on elastomeric bearings, of which the bearings under the expansion joints are sliding elastomeric bearings.

The superstructure is supported by single column bents with hammerhead crossbeam at the top of the column. The height of the columns varies from 6 to 35 m. The shape of the column cross section is octagonal 3,50×2,50 m with 0,60 m length of the corner cuts. The width of the column wall is 0,30 m. Design quality of the reinforcement is $f_y/f_{0,2}$ = 360/240 MPa. Design cube strength of the concrete was 30 MPa. Shear-keys are made on the column crossbeam for transferring horizontal seismic loads. They are located under each crossbeam between the girders. The massive spread footing of each column is cast in rock foundation ground.

History of the development of deterioration and actions undertaken. A few years after the structure was built, maintenance personnel detected a few wetted spots on outer surface of the main girders. In the course of time small wetted spots evolved in larger narrow ones over the whole height of the girders. Most of them were located approximately every 2 m under the location of cast-in-place joints of the deck plate. At times superficial inspections from the ground were carried out by the operator’s staff. After 13 years in service, a consulting firm made a report for the issuing of the permit for the exceptional transport over the viaduct. In that report corrosion damages on some bottom flanges of the outer I-girders were already mentioned. A serious deterioration of concrete and reinforcement corrosion was observed also on the columns. In the meantime defects also developed in asphalt paving to such extent that extensive repair work of the asphalt paving was needed. Some investigations of the damages of the asphalt pavement revealed that at some locations also the waterproofing membrane was damaged as well as the upper surface of the concrete deck plate. At these locations concrete deck was damaged up to 5 cm deep and reinforcement corrosion was also detected. At some locations concrete cores were drilled for determining the presence of chlorides and depth of the carbonation. Based on these results it was decided that repair work of the deck was carried out in 16th and 17th year since the construction of the viaduct. The planned scope of the repair work was the replacement of complete pavement with waterproofing membrane and local repair of damaged concrete deck. Along both sides of the carriage-way one third of the sidewalk's damaged concrete was removed and replaced. It was decided that rehabilitation of the girders would be postponed for a few years. In the 17th year the repair of the damaged columns of both concrete structures was carried out. After the concrete repair the whole surface of the concrete columns was painted with protective coating.

In 1989 a systematic periodical inspection of bridges on the whole network of national roads and highways began. In 19th year the general inspection of bridge structure from the ground level revealed extensive corrosion damages on many main outer girders of the superstructure and both cantilever parts of the deck plate. Heavy deterioration was visible also on the surface of both sidewalks. After 2 years a major inspection of the whole bridge was carried out for the first time since the structure was built. It revealed the seriousness of the corrosion damages of the main girders. A few edge girders had heavily corroded tendons up to half number of all tendons in the cross section and approximately one third of all outer girders had 1 to 3 corroded tendons. There were more intensive damages on the right structure than on the left one. Heavily corroded tendons are shown in figure 1.

Figure 1: Heavily corroded tendons with broken wires

The main sources for the leakage were inadequately grouted holes for the fixing rods of formwork under cast-in-place joints between prefabricated deck slab elements. Another source was heavy deterioration of the sidewalks and seals of the joints between the sidewalks' prefabricated elements. Therefore, the immediate action was the closure of the emergency lane of the right structure because the heaviest corroded girders were along that lane, and the speed over the viaduct was reduced to 80 km/hour. Next year a detailed inspection was carried out with mapping of all defects and extensive tests of concrete and reinforcement on site and in the laboratory. Because the structure was already rehabilitated 6 years ago, a detailed investigation was not performed on column bents, end abutments and asphalt pavement. A comprehensive report with results of the investigation was a basis for the design of the repair work. The main steps of the repair design were as follow:

- Contaminated and damaged concrete was removed with high water pressure technique.
- Locations with removed concrete of the girders were reinstated with hand applied or sprayed concrete depending on the depth of the removed deteriorated and contaminated concrete.
- Removed concrete in the area of the removed corroded tendons was replaced with cast-in-place concrete.
- Heavily corroded tendons were cut out and replaced with external flat tendons.
- Steel anchorage boxes for the anchorage of the external tendons were installed by prestressed high tensile rods at both ends of the girders.
- Saddles for the external tendons were fixed by bolts at the middle spans of the girders.
- Deteriorated concrete on cantilever part of the deck was removed and repaired by sprayed concrete.
- All sidewalks' precast elements were removed and replaced with massive cast-in-place concrete sidewalks.

Because the right structure would be closed during the execution of the repair work, weigh-in-motion measurements were carried out on the left structure to verify possible traffic management during the work on the right structure.

When the contractor began removing the precast elements of the sidewalks, local damages on the upper surface of the bridge deck were revealed along the curbs in the area which was not repaired during the last rehabilitation. After investigation of a few additional locations of the bridge deck, of which some of them experienced concrete deterioration, it was decided to extend the scope of the repair work on the whole upper surface of the deck slab, although the bride deck was rehabilitated just 6 years ago. This decision was adopted due to the requirement in the tender that the contractor must give a 10-year warranty for all executed repair work. Therefore the top concrete layer of the bridge deck was removed under the upper reinforcement by hydrodemolition over the whole area of bridge deck. After the new reinforcement was placed, the new upper concrete layer (which was 5 cm thicker than originally) was concreted. A new waterproofing membrane over the whole bridge deck was made and new asphalt pavement of the carriage way was built. On the left structure the cantilever parts of the deck were removed completely and rebuilt at the same time as the upper layer of the deck was concreted.

When a problem with deterioration of bridge deck along the curbs appeared, the inspectors who performed major and detailed inspection of the viaduct got a project of the last rehabilitation work. Among the drawings for the local repair work of the bridge deck there were also drawings of the repair work performed on columns. These drawings showed that positions of the stirrups of hollow octagonal columns are inadequate. They are placed inside of the main longitudinal reinforcement instead on the outside of the main reinforcement. The distance between the stirrups is 0,20 m over the whole height of the column. The inner and the outer layer of the longitudinal reinforcement are locally connected with cross links. During the repair work on the columns a reinforcement mesh was added locally only at those locations with significant reduction of the reinforcement cross section area. The mesh was tied to the concrete by bolts. Because the viaduct is located in the area with moderate seismicity, the concern about seismic vulnerability of the viaduct was raised. After a debate in the expert group about the necessity of the column strengthening with respect to the position of the stirrups, the owner temporarily postponed the decision about the adequate solution for the future.

Strengthening and repair of the columns. A few years after the finished rehabilitation of the superstructure deterioration processes were shown again on the concrete surface of some columns. Meshes of fine cracks appeared with local rust staining along the cracks and local delamination of the concrete cover. It is believed that deterioration is partly the consequence of the temperature variations and extensive watering of the column concrete surface during hydrodemolition work at the last rehabilitation work of the superstructure. Deterioration intensified particularly on the columns under the expansion joints which were not watertight in the sidewalk regions. The new rehabilitation of the columns was needed in the near future. Highway agency, which operates the structure, wanted to know about the resistance or safety of the structure during the earthquake event. The research project was initiated with the aim to analyze the viaduct as it is built with respect to the cycling loading during earthquake event and to give recommendations for the strengthening if needed. Because the behavior of the hollow octagonal columns with stirrups on the inner side of the reinforcement cage during cycling loading was not well understood, the scale models 1:4 of one short and one tall column were tested on the cycling loading in the laboratory. Both models after the finished laboratory tests are shown in figure 2.

Figure 2: Short and high column models after finished experiments

The models were cast in steel formwork. The tall column was made in several stages with the same formwork. The models were made of self consolidating concrete of the design concrete class C50/60. The models were tested in horizontal position and in the transverse direction. Axial load ratio for the short column was 0,061 and for the tall one 0,066. The short column failed in shear with delamination of the concrete and buckling of bars in compression zone. The tall column failed in flexure with delamination of concrete and buckling of the bars in compression zone. At the bottom part of the tall model wide cracks appeared at the level of the reinforcement overlapping. Through the hole in the column footing the propagation of cracks and other damages (delamination, buckling of reinforcement) on the inner side of the column were observed. The results of the laboratory experiments were used in nonlinear analysis of the real structure. The analysis showed that during an earthquake event only the behavior of the short columns may become problematic. One of the possible solutions of the strengthening of the short columns was to add a new layer of the concrete on the outer side of the column. This new layer would prevent premature buckling of the longitudinal bars at the bottom of the columns. The new concrete layer of the 10 cm thickness was reinforced with longitudinal reinforcement, which was not anchored in the footing. The distance between the longitudinal bars is 10 cm. The distance between the stirrups is 10 cm as well. To verify the behavior of the strengthened column, the scaled model 1:4 of the strengthened short column was built in the laboratory and tested on the cycling loading. Figure 3 shows the unstrengthened and the strengthened models after finished tests.

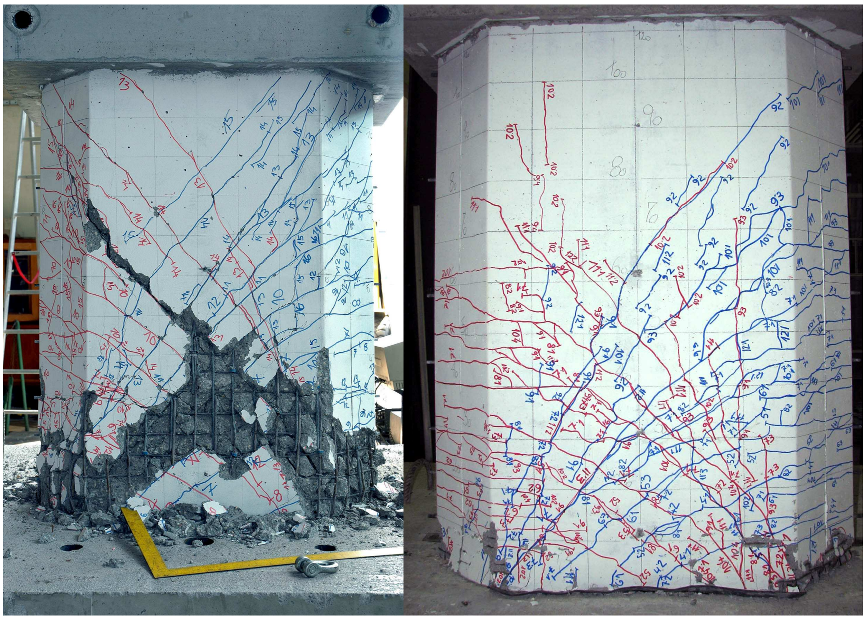

Figure 3: The original and the strengthened model of short column after finished test

Local delamination of the new layer and concrete surface on the inner side of the column began at 15 mm horizontal displacement. Local buckling of some vertical bars was also observed. A few longitudinal bars were ruptured at the bottom of the column at 28 mm of horizontal displacement. Additional longitudinal bars ruptured at displacement of 36 mm. At the same time a larger area of concrete delaminated on the inner side of the column and many inner longitudinal bars buckled. The results of the tested model of the strengthened short column showed satisfactory behavior during cycling loading. The hysteresis behaviors of both models obtained during the tests are presented in figure 4. Based on results of tested models and nonlinear analysis of the viaduct it was recommended to add a new reinforced concrete layer (10 cm thick) over the whole height of the short columns. The added new longitudinal reinforcement should not be anchored into the footings.

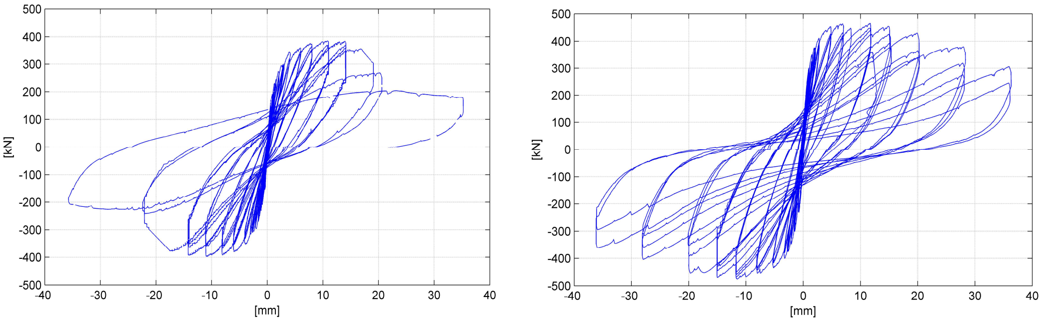

Figure 4: Hysteresis behavior of the original and the strengthened model of short column

Because other columns had deteriorated outer concrete surface as well, it was recommended to add a new concrete layer on the outer surface of these columns, too. With new concrete layer the future durability of the columns would be much better with respect to conventional repair work with sprayed concrete or locally hand applied repair mortar. At the end, the owner decided that on other taller columns a new layer of the height of 4 m would be added only at the bottom of the columns. During the laboratory test at the bottom of the tall column model wide cracks appeared at the level of the reinforcement overlapping. In the figure 5 are shown columns during repair work in 2008.

Figure 5: Tall columns and hammerhead crossbeams during the repair work

The major inspection, carried out two years after finished repair work on columns, revealed a few small delaminations at some edge parts of the hammerhead crossbeams. On some main girders thin longitudinal cracks appeared. Protective coating of the main girders is locally deteriorated. Deterioration of the anticorrosion protective coating and corrosion were observed on many short prestressed bars of the anchorage cages for external tendons. Cracking of the concrete of some girders was observed in the support region over the elastomeric bearings. Damages of the elastomeric bearings were found as well. They were more severe at the locations under the expansion joints. Corrosion damages were also observed on some parts of the expansion joints, although the inspection of the expansion joints from the underside is very restricted and difficult due to narrow space.

CONCLUSIONS

A decrease of the anticipated length of the service life of the structures due to premature deterioration processes, especially the infrastructure ones, has become an important issue of the infrastructure policy in many countries throughout the world. Neglecting of proper and on-time maintenance activities in the past decades of the last century during construction boom caused huge backlogs of deteriorated and obsolete structures. To counteract these raising problems, management systems have been developing for different types of the structures. The most notable are bridge management systems for the management of bridge structures or pavement management systems for the pavement structures. Various inspection techniques have also been developed for reliable identification of different defects and deterioration processes. Of course, inspections must be carried out by well-trained and qualified inspectors who are able to identify on-time durability or capacity problems of the structures. This recognition has also launched research into identifying of different possible deterioration mechanisms on one hand, and the influence of different environments on durability of the concrete structures on the other hand. At the same time the research of different materials and the development of the techniques for the repair or for slowing down of deterioration processes has been taking place.

An example presented in the paper shows that if the owner or his consultants had recognized the problems on time, they would have spared substantial funds. If they had recognized the cause of the leakage of the main girders and had made detailed inspection with adequate testing on site and in the laboratory earlier, when the problems were evident, then they would have been able to perform different sequences of repair actions and avoid the same type of the repair work in a very short period of time. It is also an enormous responsibility of the owner to have a good team to work on such problems. If he does not have enough competent staff, then he has to hire a competent consulting company with experts who can advise him about different possibilities to tackle the encountered problems within short and long term financial constraints. This holds true for new and old structures. Many problems could be avoided throughout the service life of structure with proper and on-time accepted decisions (fib, 2008). For the optimal solutions on the infrastructure networks within the time and funds constraints it is also important to implement a cross-asset management for all infrastructure structures.

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