Long-term structural health monitoring on concrete structures

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ABSTRACT: Sustainability of the infrastructure structural performance can be assessed by performing continuous Structural Health Monitoring System (SHMS) on the structural deformational properties. The essence of SHMS can be considered to involve measurement, inspection, and assessment of in-service structures on a continuous basis with minimum labor requirement. However, human memory limitation, job position transformation, imperfection and inability to provide a reliable monitoring system can lead to overly optimistic reports on structural health. Therefore, a sustainable SHMS which fulfill AtoE characteristics i.e. Accuracy, Benefit, Compendiousness, Durability and Ease in operation, is necessary to be consider in designing a reliable long-term SHMS, especially for concrete structures which has been considered to be long-term maintenance-free structures. The concrete structural health condition can be assessed based on the field-retrieved actual stress data by utilizing EM Sensory technology. The concrete creep, and concrete shrinkage can be continuously monitored from the beginning of service life and the structural health can be assessed punctually during its life-span.

1 INTRODUCTION

Along the years of civilization, human beings have been creating numerous infrastructure systems for residence, industrial, defense and other various purposes. These heritages have been accumulating as a huge inventory of structures now. Most of those structures were made from harden soil, drying brick, stone and/or wood which have been utilized innovatively.

About one and a half centuries ago, such construction materials have been enriched by steel and concrete. The advantages of these two materials as ‘easy form’ and ‘high strength’ have grown up and speedup the construction of infrastructures significantly. Even now, most of the structures are built by steel and concrete. However, contradiction to the ‘initial wish’ as maintenance-free materials, significant deteriorations spread out everywhere. Especially in the last decades, fatigue and corrosion of steel structures and frost damage, alkaline silica response (ASR), carbonation of concrete structures, become serious issues. These phenomena occurred in the time when the ‘true life’ of steel and concrete have not been verified yet (Sumitro, 2001). If the deterioration propagates as the current speed, in a near future, preservation of the accumulated infrastructures’ inventory need a huge amount of reinvestment and it will shake the financial cores from the root.

Now, the only one choice of the possible solution which can be expressed as: identify the current degraded condition; stop the structural deterioration process; choose a suitable repair/retrofit strategy to a certain service level; perform health monitoring systematically; and reduce life cycle cost (LCC). In order to achieve the above objectives, this paper describes Structural Health Monitoring-Based Maintenance (SHMBM) focused in fundamental technique to identify reinforced concrete structural health condition.

2 BASIC CONCEPTS

2.1 *Service life*

The service life of a concrete structure or a concrete element is considered to be “the period of time, after being in use, during which all the performance properties are above accepted minimum levels, with a routine maintenance”. The service life of a certain structure is limited by its functional life and structural life. Nevertheless, this paper will focus in discussing concrete structural life.

The structural life of a concrete structure is associated with its safety and serviceability conditions, namely, it is related to situations such as collapse, deformation, cracking etc. These conditions depend mainly on the evolution of actions and materials during its lifespan (Branco and Brito, 2004).

Associated with probabilities of failure in a statistical analysis, design codes usually define the safety levels to be considered through the actions and material's resistance design values. In order to have safety (S), the material's resistance (R) must be higher than the action effects (A), or, considering probabilistic distributions as shown in Figure 1 by the following equation.

$$p(S) = p(R - A) > 0 \qquad (1)$$

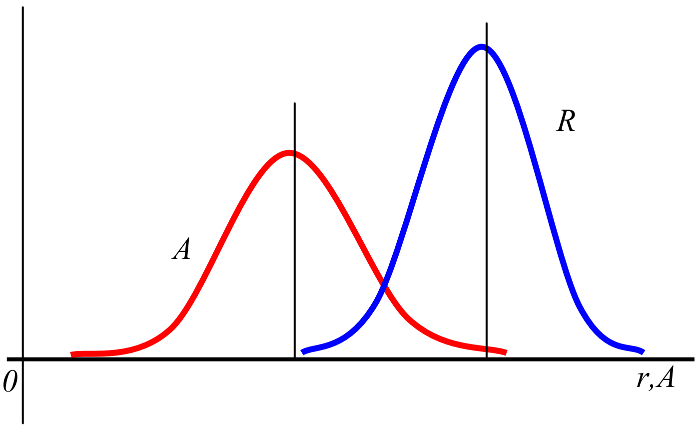


Figure 1. Statistical distributions for actions A and material strengths R.

2.2 *Evolution of loads*

The characteristic value of the actions are defined in codes based on a statistical analysis usually considering the values associated with a certain reference period, associated with the structure target life.

During the concrete structure life, the characteristic value of the actions or of the action effects may vary, leading to a decrease of the structure safety, such as, successive repavement or insulation operations that lead to an increase in permanent loads, axle load increase due to changes in vehicles characteristics, and foundation settlement caused by a change in geological conditions.

Besides these changes, if, during the structure life, a rehabilitation design is performed, the quantification of the characteristic actions varies and this must be considered when structure safety is reanalyzed.

As time goes by, the remaining structure life is shorter, and for the same probability of occurrence, the characteristic values of the actions decrease, specifically for time-variable actions. This is important for rehabilitation design where the definition of a shorter life for the rehabilitated structure leads to a reduction of the characteristic values of the loads. Corrective values are referred in codes for actions such as wind and seismic loads. Correction factors for changes in characteristic values versus return period for wind is shown in Table 1.

Table 1. Characteristic values changes.

Reference period (years)	Correction factor
100	1.04
50	1
20	0.95
10	0.9

2.3 *Evolution of materials*

The evolution of the material properties in concrete structure during the structure life has two types of components; the first is associated with the evolution of the strength of the materials, and the second is related to the changes in the geometry of the structural elements or materials deterioration.

Considering the evolution of the strength of the basic materials, the steel strength is practically uniform throughout the structure life unless an accident such as a fire occurs. Nevertheless, problems may also arise with the fatigue strength of steel, specifically with prestressed steel, leading to a design with a conservative safety analysis and quality control during construction.

The strength of concrete increases with time from the design reference value (at 28 days after casting) until obtaining higher values of more than 35% after 1 year and 45% at the end of the service life. This evolution increases the design safety considered at design level. These evolutionary aspects can be considered in structure rehabilitation, through the use of a more realistic safety factor to quantify the strength design values. In fact, a more rational reduced safety factor can be obtained by performing detailed inspection and accurate in situ measurements.

Considering the durability problems associated with environmental actions, concrete deterioration and reinforcement corrosion may occur, with cross section reduction, leading to decrease in the geometric dimensions and material properties, and thereby to a decrease in the structure safety throughout the structure service life.

Recent codes present design specifications for materials and construction procedures theoretically leading to a structural life of around 50 years in case of bridge structure, considering the concrete degradation effects.

Nevertheless, those recommendations are still a bit far from the structural design procedures. In fact, in trying to make a parallel analysis for durability analysis, the "actions" are a set of typical environments and the "material resistance" is a set of construction procedures and material properties (cover, concrete components and characteristics). These are defined to ensure that the main properties of the materials are kept along the structure life so structural safety is not reduced by durability.

In the present situation, a safety analysis for durability, based on the environmental conditions and material properties, can hardly be implemented, and the current design procedures consist solely of performing a structural safety analysis and adopting the code specifications for durability.

2.4 *Testing and monitoring*

At the design stage, structure engineers estimate the behavior of a structure base don theoretical models that analyze its structural safety and durability.

During the construction stage, the design specifications are implemented, namely in terms of geometry and material properties. During this phase, several tests must be performed to check the compliance between the design and the effective properties of the materials.

When the structure construction is finished, acceptance load tests may be performed, within the conformity control, to check agreement between the theoretical models at the design stage and the actual global structural response of the structure.

During a structure's service life, several structural parameters are monitored to check the real behavior of the structure and to allow a quick reliability analysis if an accident occurs. Durability parameters are also monitored in this phase to obtain their effective evolution, by comparing them with design theoretical models, to allow for the evaluation of the real degradation of the bridge.

Field experimental testing and monitoring is an increasingly popular activity, since structure engineers and authorities became aware of their importance for obtaining a good quality construction control and for extending the structure life, along with the concurrent cost saving associated with repairs necessitated by unexpected problems.

In this paper, an overall structural health monitoring system which enables to monitor actual stress changes from construction stage and during structure's service life by applying elasto-magnetic sensory technology is discussed and an example field application for prestressed concrete structure is introduced.

3 SHMBM ENGINEERING

3.1 *Philosophy*

Structural Health Monitoring Based Maintenance (SHMBM) engineering is a civil infrastructure maintenance concept based on input from field monitoring data (Tominaga, et.al., 2002). The conceptual framework of reliability-based approach for concrete structures is modified to accommodate various structural degradation conditions as follows (Frangopol, et.al., 1997).

$$LCC = C_T + \sum_{i=1}^{m} C_{SHMBM}{}^{i} + \sum_{j=1}^{n} C_{REP}{}^{j} + C_F \qquad (2)$$

where C_T is the initial construction cost, $C_{SHMBM}{}^{i}$ is the SHMBM cost at i^{th} interval and $C_{REP}{}^{j}$ is the repair cost at j^{th} interval and C_F is the demolition cost. This approach was used to evaluate the reliability of an existing reinforced concrete structure with a non-uniform interval inspection strategy with the following assumptions: (1) service life is 100 years; (2) routine maintenance is scheduled once every two years; (3) all inspection costs are converted to the initial cost. As the result, the relationship of the expected inspection cost and LCC in various $\eta_{0.5}$ is shown in Figure 2, where $\eta_{0.5}$ is the damage intensity in which the SHM method has a 50% detection probability. By investigating the simulation result, it is confirmed that optimum LCC can be achieved with a certain quality of inspection technique.

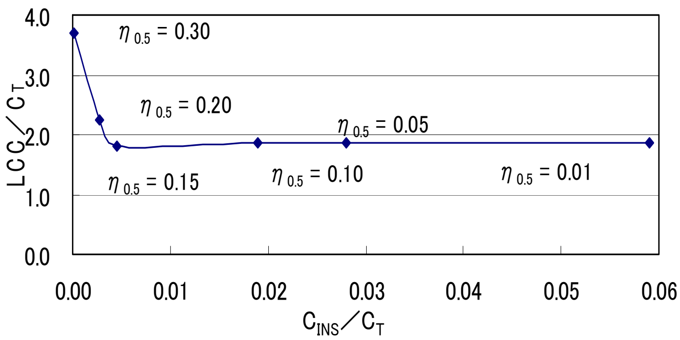


Figure 2. LCC optimization by an appropriate SHMBM.

3.2 *Proposed structure health monitoring paradigm*

Concrete structures can be evaluated by: (i) Post-deteriorated diagnostic and (ii) Pre-deteriorated diagnostic. Post-deteriorated diagnostic aims to assess structural rigidity after some anomalousness found mainly by visual inspection. It has disadvantages such as uncertain items and inevitable human erroneousness, and consequently, it results to unsuitable countermeasure occurrence and less of reliability.

On the other hand, pre-deteriorated diagnostic in which aims to assess structural rigidity regularly, has the following advantages such as deterioration is predicted by skilled and experienced engineers, utilizing NDE and the structural health assessment (SHA) is analyzed by involving LCC concept, so reliable maintenance management can be achieved. As one of the rational and planned inspection paradigm, here, actual-stress-based SHA for prestressed concrete structures is proposed as shown in Figure 3. Pre-stress loss directly influences load carrying capacity and effects to safety level reduction of prestressed concrete structures. Besides assuring current structural health condition, actual stress monitoring enables to provide a planned feasible repair and re-strengthen strategy based on the monitored pre-stress loss.

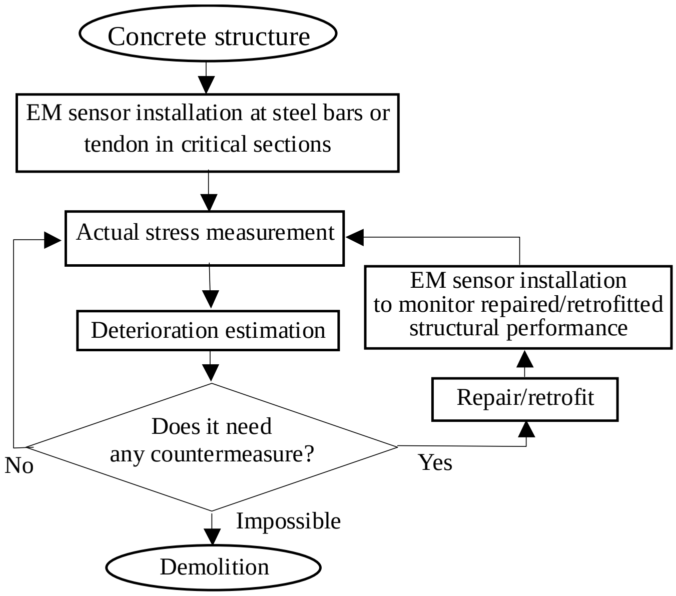


Figure 3. Actual stress based Structural Health Assessment.

4 STRUCTURAL HEALTH MONITORING

4.1 *EM sensory technology*

Elasto-magnetic (EM) stress measurement technology was developed by utilizing stress-dependent magnetic physical properties (Chen, et.al., 2000). One of the easiest ways to magnetize a material and study its magnetic characteristics can be carried out using the principle of magnetic induction and two solenoids a primary coil and a secondary coil with the material whose magnetic characteristics are to be investigated as the core as shown in Figure 4. DC current pulse is applied across the primary coil, it produces a magnetic field (H) and the magnetic flux density (B) within the specimen following the principle as shown in Figure 5. For practical purpose, a technical saturation of incremental permeability defined as the ratio $\Delta B / \Delta H$ is approached.

Pre-fabricated EM sensor takes the form of a hollow cylinder in the middle of which the measured object (wire, strand, cable, bar) passes through. It should be slipped onto the measured object beforehand. In case of existing structure, the sensor is wound on the tendon or reinforcement in-situ by fixing two halves cylindrical bobbins. This type of EM sensor enables to measure actual stress of external tendons in outer cable PC bridge, steel cables in cable stayed bridge and suspension bridge, and steel embedded in concrete without the necessity to install the sensor during the construction period (Sumitro, 2001).

This cylindrical EM sensor has no mechanical contact with the measured element so it will not be overloaded, it is resistant to water and mechanical in-jury, its characteristics does not change with time and its lifetime is predicted to be at least 50 years.

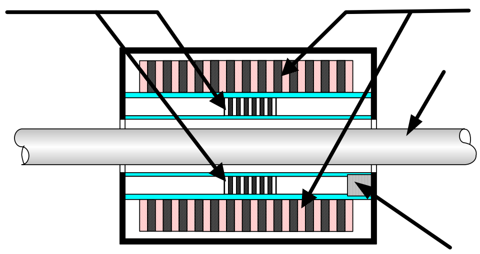


Figure 4. EM sensor structure.

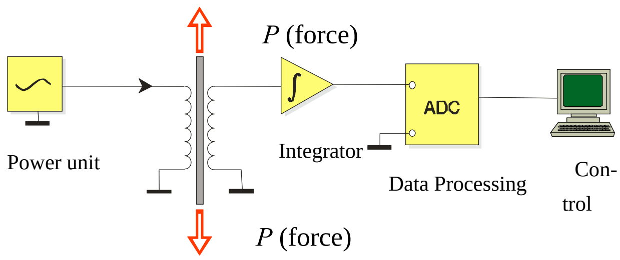


Figure 5. Magnetization principle.

4.2 *During construction monitoring*

In order to verity the applicability of EM sensory technology on controlling pre-stressing during construction, eight EM sensors were installed at the Kamikazue viaduct, as a part of Second Tokyo-Nagoya Expressway, i.e., four pre-fabricated sensors and four site-fabricated sensors. The sensor configuration was shown in Figure 6. The cylindrical pre-fabricated sensors were inserted before tendon installation, and by considering EM sensor application on the existing structure, the site-fabricated sensors were also placed after tendon installation.

Two pre-fabricated sensors (EM-A1 and EM-A2) were placed in tendon 2E1, and two site-fabricated sensors (EM-B1 and EM-B2) whose the same magnetic design specification, were placed neighboring to the pre-fabricated sensors (EM-A1 and EM-A2). Similarly, the others two pre-fabricated sensors (EM-A3 and EM-A4) were placed in tendon 2E6, and two site-fabricated sensors (EM-B3 and EM-B4) whose the same magnetic design specification, were placed neighboring to the pre-fabricated sensors (EM-A3 and EM-A4).

The pre-stress measurement result on tendon 2E1 is shown in Figure 7. It is observed that both type of EM sensors (pre-fabricated and site-fabricated) measurement results have a good agreement with the tendon stresses calculated based on the pressure gage results. In the case of pre-fabricated and site-fabricated sensors comparison, it is obtained that for the design stress level of tendon 2E1, the fraction of EM-A2/EM-B2 at the anchorage

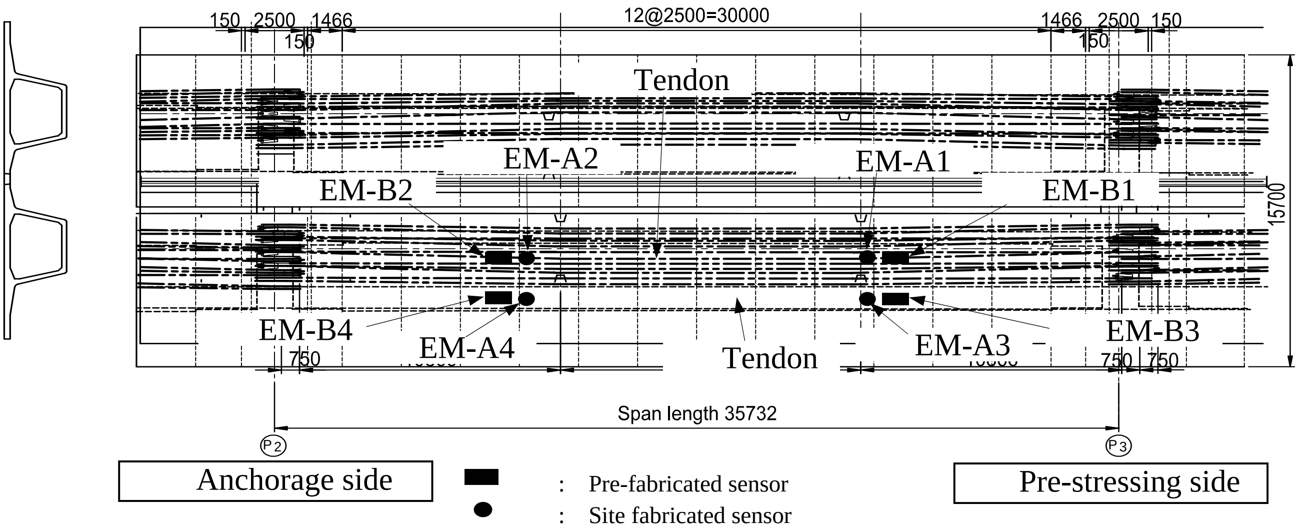
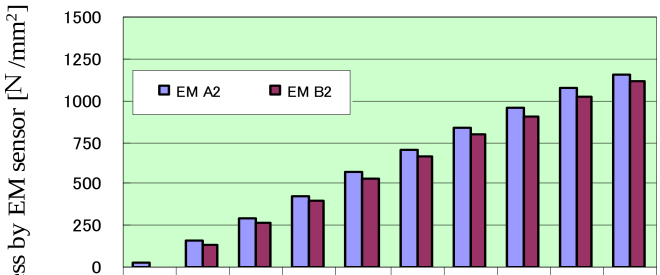


Figure 6. Sensor configuration.

side is 0.7%. Averagely, the measurement difference between pre-fabricated sensors and site-fabricated sensors is 2.7%. Therefore, it is confirmed that EM sensory technology is reliable for pre-stressing control during construction.



Jack [N/mm²]	0	144	289	433	578	722	866	1011	1155	1271
EM A2	30	155	290	430	570	706	836	952	1070	1156
EM B2	5	129	260	400	535	668	796	909	1024	1109

Figure 7. Actual stress measurement results on tendon 2E1.

4.3 *Life span monitoring*

Pre-stress-losses in a life-cycle time of external prestressed concrete bridge are significantly effected by concrete creep, concrete shrinkage and steel tendon relaxation. It was confirmed in previous laboratory test that EM sensory technology enables to measure the actual stress at steel tendon including relaxation phenomenon (Kurokawa, et.al., 2002).

This actual bridge monitoring was conducted to verify the capability and reliability of EM sensory technology for long-term structural health monitoring on external cables prestressed concrete bridge by utilizing pre-fabricated sensors and site-fabricated sensors. By assuming a real application on existing bridge, the stresses measured by site-fabricated sensors at span P2-P3 within 240 days from May 2002 to January 2003, are selected and shown in Figure 8.

The long-term pre-stress losses phenomena were observed in a period between primary-pre-stressing within span P2-P3 and secondary-pre-stressing in the adjacent spans. Pre-stress losses as the consequence elastic deformation due to secondary pre-stressing were clearly observed. The average pre-stress losses in the period between primary pre-stressing and secondary-pre-stressing within 180 days, for tendon 2E1 is 41.2N/mm^2 and tendon 2E6 is 43.1N/mm^2, respectively. Those values have a good agreement with considerable designed pre-stress losses i.e., 20.0N/ mm^2 pre-stress losses due to concrete elastic deformation and 20.0N/ mm^2 pre-stress losses due to concrete creep and shrinkage.

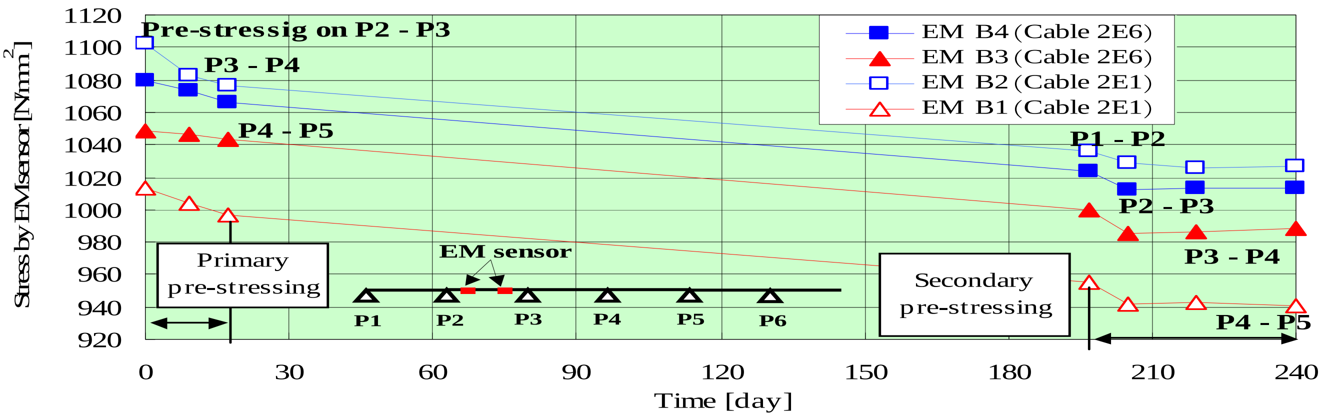


Figure 8. Life-span monitoring result at span P2-P3

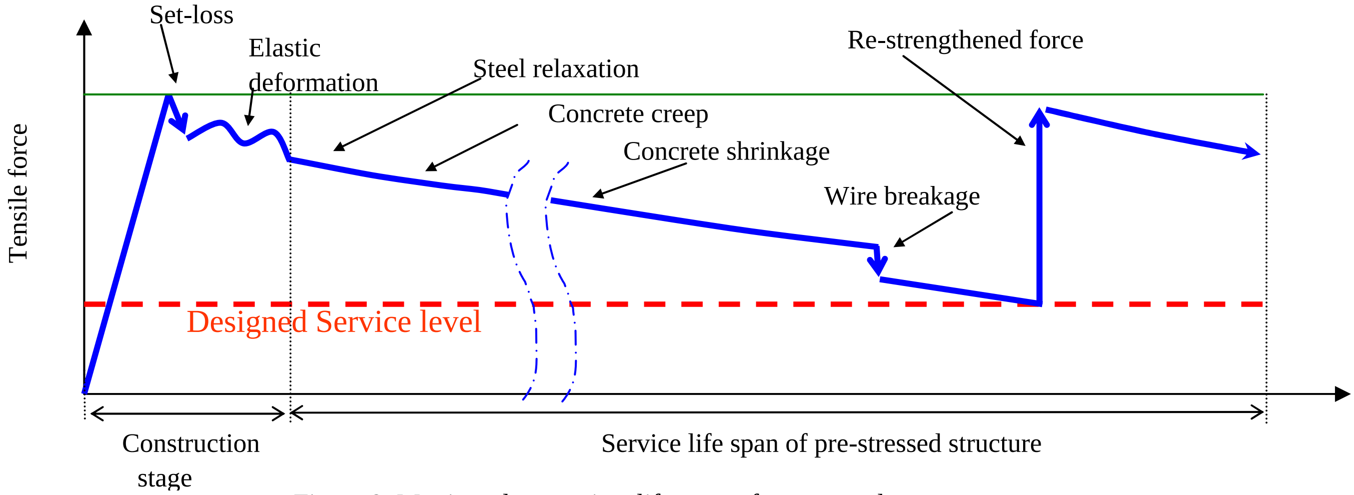


Figure 9. Monitored events in a life-span of prestressed concrete structure

4.4 *Structural Health Assessment*

The structural health condition can be assessed based on the field-retrieved actual stress data by utilizing EM Sensory technology (Sumitro, et.al., 2005). The pre-stress introducing during construction can be controlled by EM sensor instead of using load-cell temporarily. Figure 9 describes schematically the monitored events of steel tendon due to numerous deterioration factors of pre-stressed concrete.

At the beginning of service life, after suffering set-loss and elastic-deformation caused by near-by cable pre-stressing, the actual stress changes can be clearly investigated. Then pre-stress losses due to steel relaxation, concrete creep, and concrete shrinkage can be continuously monitored. Furthermore, as the most serious peculiarity of pre-stressed concrete structures such as grout-imperfection and earlier-occurred of corrosion phenomenon which effect to wire breakage, can be also monitored by utilizing long term structural health monitoring system.

A retrofit or re-strengthen strategic can be decided based on the real-time actual-stress quantitative information for a specified service level. Moreover, the stress can be re-strengthen to achieve to a newly designed structure performance level to extend the life span of pre-stressed concrete structures.

5 CONCLUSION

In order to maintain safety level due to evolution of loads and materials, it is necessary to perform an overall long-term structural health monitoring system from construction stage and during its life-span. By investigating the reliability of field-monitored data, it is concluded that EM sensor is the most reliable, stable and practical method for long-term monitoring of prestressed concrete structures. It enables to measure directly the residual pre-stress of steel tendons to assess structure performance and to provide reliable information for repair and/or re-strengthen strategy.

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