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RISK BASED INTEGRITY ASSESSMENT OF CONCRETE STRUCTURES

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ABSTRACT

Damage process initiation and propagation in concrete structures is a time dependant phenomena, with the negative implication to the structure load bearing capacity, decreasing its overall resistance and as a final consequence, decreasing degree of structural safety and reliability. Previous, deterministic procedure of the assessment of concrete structures is extensive and conservative, leading to rather subjective engineer decision making, to the conclusions without right answer about the real degree of structural safety and to the implementation of non-optimal reparation procedures. In the paper, it is proposed the probabilistic approach which on the basis of previous analysis of structural critical elements and virtual structure failure mechanism, adopting corresponding limit state, determines the probability of reaching the limit state and based on the expected negative consequences, determines degree of risk which the structure is exposed to. As an example, the procedure is applied to the prestressed concrete highway bridge integrity assessment. The bridge was heavily damaged during NATO bombing of Yugoslavia and an urgent decision about the right measures for the bridge reparation was quickly requested. Applying Monte Carlo method for the proposed limit state of the bridge structure, degree of risk is calculated and the right decision was made.

Introduction

From the very beginning of its service life the concrete structure is exposed to the various loading conditions and excessive and adverse events – hazards (overloading, fire, explosions, floods, earthquakes and so on). As a consequence, the overall integrity of structure is jeopardized and some structural limit states could be reached. Risk is a probability that a particular adverse event (limit states) occurs during a stated period of time multiplied by the consequences. Damage initiation and development in concrete structures is time dependant process determined by the many factors as: aggressive environment, quality of the construction, loading history and the quality of maintenance. In the same time, damage progress affects the structural resistance, safety and reliability decreasing them during the time [2], [4].

Damage function

Having in mind mentioned, the right question concerning the concrete structure integrity assessment is: what degree of structural damage may be permitted and tolerable with no taking any protective actions to the structure or what is the limit of acceptable damage? The response to this question is very important not only from the point of view of the structural integrity assessment, but for making decision about the needs for structural repair and its remaining service life prediction (Fig. 1.)

Process of damage initiation and propagation - damage accumulation - has the negative implication to the structure bearing capacity, decreasing safety and reliability of structures:

$$r = R - S \qquad (1)$$

where

r - Reliability of structure
R - Resistance
S - Loading

The two parameters (R and S) characterizing reliability, change unfavorably inversely during the time - resistance decreases but loading increases until the structure limit state (R=S) is reached. A damage development in concrete structures takes place continuously observing it on large scale, but actually sudden drops happen since the accumulated energy releasing occurs from time to time. All in all, three significant states during this process may be pointed out: (1) damage initiation, (2) serviceability limit state and (3) ultimate limit state.

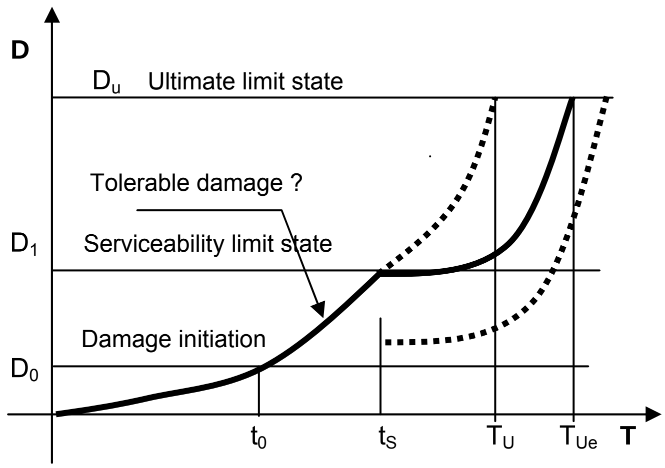


Figure 1. Damage vs time function

Integrity of concrete

Concrete deterioration and damage regardless to their cause, mainly appears visible as a crack. However, no mater how much the cracks appearing is negative and undesirable on the structure, it presents a visible warning and particular indicator of the structure state. It should be mentioned that the crack phenomenon in concrete structures (where the crack appears as a part of the structure natural state) has an essentially different meaning than the crack in the metal structures. Namely, a crack appearing on the concrete structures doesn't mean that structure critical state, proceeding to the structure total failure, has been reached. The cracks initiation in the concrete structures is due to a low resistance of concrete to the action of tension stresses (tension concrete strength is approximately 1/10 of the concrete compression strength). Soon after the tension concrete strength is reached (and the cracks initiated) the tension stresses are redistributed to the steel reinforcement. Further concrete deterioration advances depending of the quantity of imbedded reinforcement (expressed by ratio of reinforcement $\mu = A_s/A$) and there is a balancing "game" between lower rate of tension strain in the reinforcement (greater values of μ) and the raising rate of compression strain in concrete and vice versa (lower values of μ).

But, whatever is the real cause of damage initiation the following important facts need to be considered in regards to the right concrete structure integrity assessment:
- Concrete material contains micro defects (preexisting microcracks) before the load is applied;
- After loading, concrete tension strength is quickly reached and the cracks appearing is a normal and expecting phenomena;
- Crack propagation and material deterioration is a consequence of farther unfavorable state advancing (increasing stress in reinforcement) in the more or less aggressive environment;
- Crack direction is always perpendicular to the direction of the principal tension stresses;
- Crack initiation and propagation (up to certain degree) doesn't mean a transition to the structure critical state;

The mentioned above, facing the engineers and experts with a very complex assignment of the right concrete structure integrity assessment. Namely, integrity assessment is in fact the calculation of the remaining structure resistance, taking in account all damage observed on the structure. In order to observe and to locate damage, it is necessary to perform inspection or long term monitoring of the structure. The inspections, usually performed periodically, are not only consisting of the structure visual examination, but of the application of the convenient NDT and destructive testing techniques. Mentioned presents already well established and known deterministic engineering approach to the problem. As it will be shown further, there is a reasonable basis for replacing this procedure by the new - probabilistic approach, which accepting certain level of risk that is, the probability of the some limit state to be reached, changes fundamentally the traditional attitude about structural safety.

Risk based integrity assessment

It is already well known fact that the variables characterizing the integrity of concrete structure are uncertain or random by its nature and it can be described by the variables of statistics and theory of probability. Thus, all parameters describing integrity of concrete structure have their own probability density function.

On the other side, concrete structures, as any other, are exposed to the probability of various external and sometimes excessive actions - adverse events - or hazards (overloading, fires, floods, earthquakes, vehicle impacts, explosions etc.) which could lead to the structure damage or failure. The risk is probability of appearance of some of this adverse event multiplied by the consequences and it is characterized by three basic aspects: (1) inevitability, (2) probability and (3) consequences. The all risks, which the structures are exposed to, are inevitable. It is possible to reduce them reasonably; they may be managed, but they cannot be escaped to the "zero" level. The risk reduction with the aim to increase the safety of structure, necessary comprehends the increase of financial investments. It is quiet reasonable expectation of the owner to get the higher level of structural safety with as less investment as it is possible. This is actually beginning of the optimization process for an engineer involved in structure integrity assessment, forcing him to take certain level of risk, that is, to accept certain probability of appearance of some "adverse event".

It was already mentioned that the failure (limit state) probability of structure is a time dependant function. The time dependant failure probability may be expressed as:

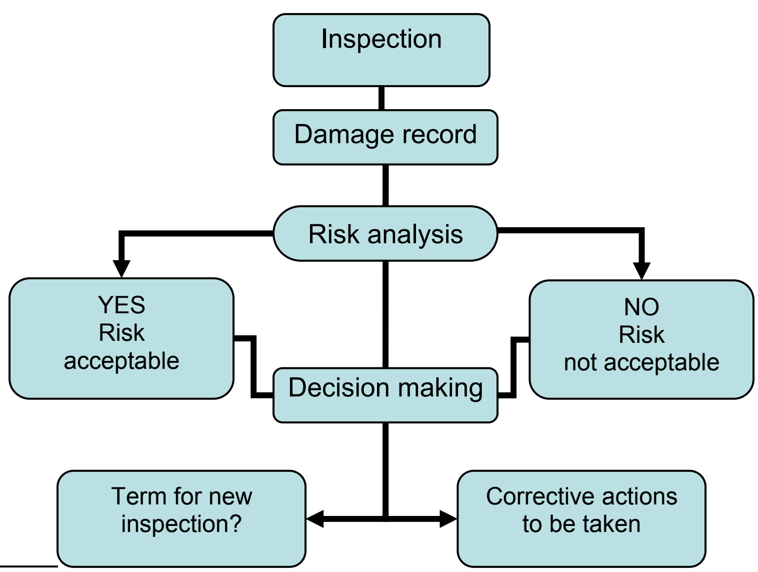
$$Pf(t) = P_r[R \le S] = P_r[R - S \le 0] = P_r[g(R,S) \le 0] = \int_0^{\infty} f_R(t)\, f_S(t)\, dt \qquad (2)$$

where:

g(R, S) - limit state function
$f_R(t)$ - probability density function of structure resistance
$f_S(t)$ - probability density function of structure loading

The consequences of the failure of structure can be expressed as direct financial losses (price of reparation, demolition, disassembling etc.), environmental damage and losses of human lives. By that way, risk is getting a dimension e.g. number of human lives lost per an event. The notion of the limit state could be also extended to the any undesired structural state defined by an engineer as a critical for any particular structure. In fact, limit state is defined every time after inspection of the structure is carried out and a damage record obtained. It is important to mention here that even inspection of the concrete structure is not deterministic one, but risk based as well. It is well planed, directed to the most critical structural elements and scheduled according to the previously analyzed remaining structure bearing capacity. The risk analysis which follows encompasses all possible hazards, scenarios of all possible damage and fracture mechanisms appearing and the probability of reaching determined structure limit state. For all possible fracture mechanisms, one determines the probability of appearance and corresponding consequences, that is, a degree of risk evaluates (FMECA[1] method), followed by the final decision making.

The entire procedure could be presented by the following block-scheme:



[1] FMECA (Failure modes and effects criticality analysis)

Figure 2 Block scheme for risk based integrity assessment of concrete structures

Decision about the risk acceptability is the most delicate point in the risk based integrity assessment of concrete structures. Namely, the notions "risky" and "safe" are determined based on the general attitude of the particular society and they do not have the same meaning in the consciousness of - for example - a German, or an Avganistanian, or a Serbian. There are some attempts to get the general solution, as it is approach based on the principle of "life quality index" [3]. Practically, there are two ways to overcome this problem. One, which is basically qualitative, is based on the so called matrix of decision making. The matrix is formed of rows where the consequences are lined up gradually - from the fatal to the quiet negligible and the columns consisting of degrees of probability of the limit state appearing - from the very likelihood to that with the very low probability. The matrix is divided diagonally at three areas where the risk is (1) acceptable, (2) as low as reasonably possible or (3) unacceptable. Second way is concerned of the target risk determining. This is more complex, but more exact engineering approach leading to the application of some of optimization techniques (e.g. Life Cycles Cost Analysis).

Monte-Carlo method

Monte-Carlo method is a simple and effective tool for statistical analysis of the uncertainty in structural engineering and for calculation of probability of limit states. After structure inspection is performed and thorough integrity analysis carried out, the corresponding structure limit state is defined. For example, let's take the limit state to be defined as a state when a crack width $a \geq 2.0$ mm appears on the structure with the corresponding moment of deflection M_R. Let's assume the normal probability density function as a valid for the values of R and S, that is M(R) and M(S) with their known mean and standard deviations. Two sets of these values are than listed parallel to each other by the principle of generated random numbers from 0 to 1. Between two sets of numbers one identifies the number of cases (N_f) where $M(S) \geq M(R)$ as a limit state condition. Probability appearance of the assigned limit state may be than calculated as:

$$P_f = N_f / N \quad (3)$$

where

N = total number of random generated values

Example

During NATO air strikes against Yugoslavia the bridge over river Morava on the highway E-75 was completely broken down (right-side) and seriously damaged (left-side structure). Actually, the left-side structure was stricken with four missals provoking the serous bridge damage considering the overall bridge carrying capacity. The most serious damage the bridge structure suffered in the zone of piere S3, where as a consequence of the missle strike and explosion, the integrety of deck and lower chord of the box girder were complitely destroied in the lenth of ~12 m. and over 30 prestressing strends (16 ∅ 7 mm.) were cut off. The only remining undamaged element of the section was the uper-stream web of the box girder (Figure 3).

Figure 3 Bridge over river Morave damaged during NATO bombing of Serbia

The bridge was constructed as a concrete prestressed continuous box girder with the spans: 41.4+52+62+52+41.4 m (Figure 4) and it was in service since 1982.

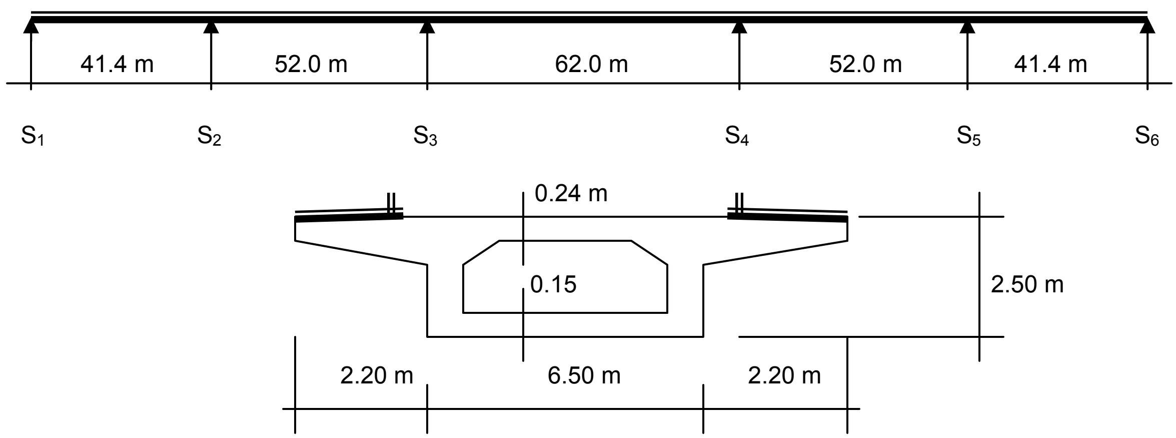


Figure 4 Bridge elevation and cross section

Soon after the bombing, forced by the pressing need to make the traffic possible urgently, a government commission for rebuilding and reconstruction decided to evaluate the bridge in existing state and make the light traffic (up to 5 t.) possible using one lane on the side of the bridge girder which was less damaged. The big hole on the traffic deck (damage T 4) should have to be over bridged with war-assembling truss bridge spanning 20.0 m and laid on the traffic deck with the supports on the peer S_4 and on the girder supported by temporary strut (Figure 5)

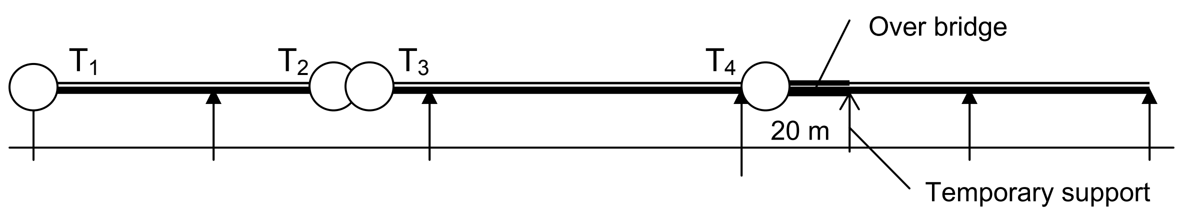


Figure 5. Damaged bridge structure

Damaged and partially over bridged and temporary supported structure has been analyzed on the basis of previous thorough bridge visual inspection and testing. At first, analytical model of the existing damaged bridge structure is defined taking in account only dead weight acting on the bridge. The damage T_1 is considered with no influence on the bending and share capacity of the girder and damage $T_2 – T_4$ are modeled reducing the full area moment of inertia to the real value. For example, the area moment of inertia at T4 is reduced up to 16%. The great reduction of the bending stiffness of the main bridge girder, gave as a consequence the particular bending moment redistribution, which is clearly shown comparing the damaged model with the corresponding but undamaged one. Particularly, the values of positive moment in the middle of the central span and the negative one at the support S_3 are significantly increased up to 26% or 10 % considering only dead load in both cases (Figure 6.) (Table 1)

Table 1.

Joints	27	29	31	33	35	37	40	42	44	46
M_0	-20135	-61591	-13955	16843	31880	34070	16677	-14199	-61880	-40846
M_1	-25570	-67947	-16397	18316	37121	41408	29889	2925	-40845	-20292

As a next step in the process of bridge evaluation, the same analytical model is analyzed applying the live load consisting of the two real three-axle truck weighted 28.0 t each (56 t in total). (Figure 7.)

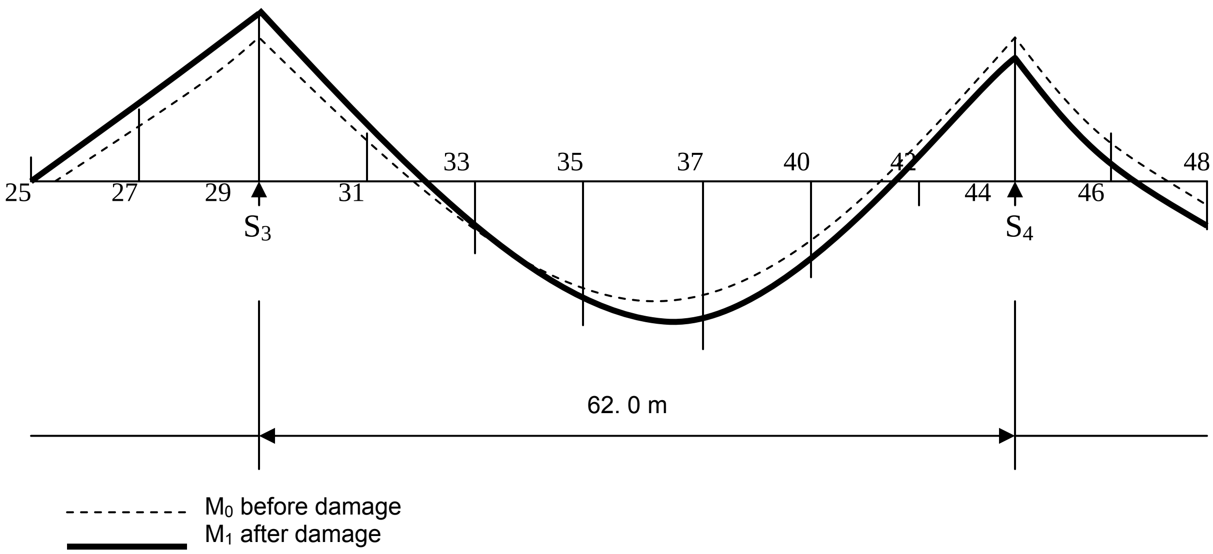


Figure 6. Moment diagram for dead load before and after damage

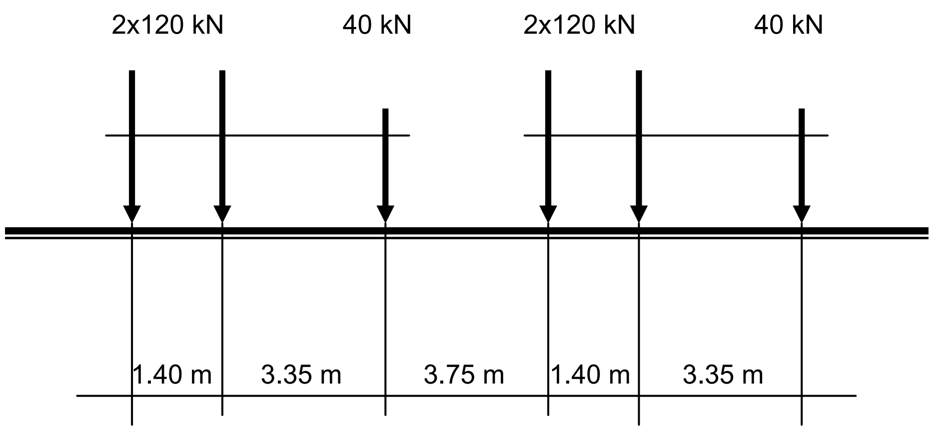
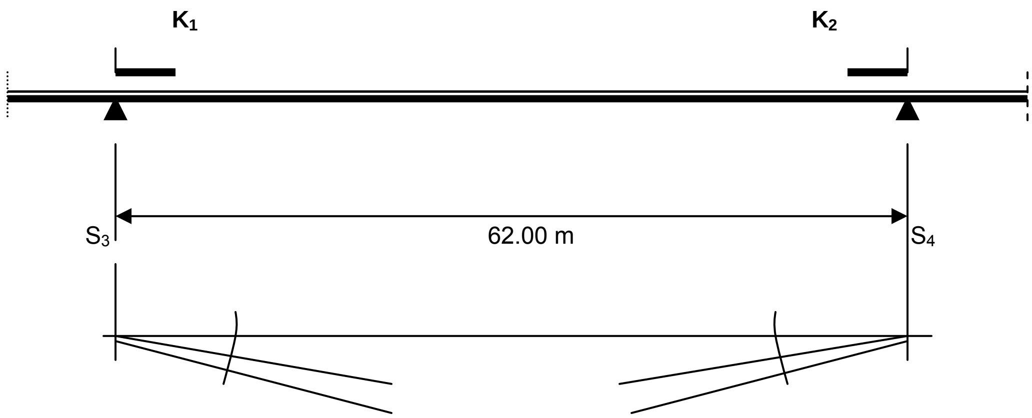


Figure 7. Live load – trucks, axle forces and distances

Using already defined analytical model, live load is applied in every span at the most critical position and the moments, vertical displacements and the slops are calculated consecutively.

In order to make the evaluation of the existing structural state as much exact as it is possible, the bridge load test using the real trucks is carried out. The testing load has been increased gradually moving the trucks one by one at the most critical position from the span to the span. The changes of the relevant vertical displacements and slops are measured consecutively. Every time when the critical position has been reached the bridge was unloaded and appearance of residual deformations is controlled. In addition, the measured values obtained by load testing and the calculated values obtained from the analytical model are compared in order to identify the real structural model. As a most susceptible value (even for the very slight move of the truck along the bridge) the change of slops at the supports for the middle span is used as a decisive comparative parameter for system identification (Figure 8.).



I step	α_{c1} = 2. 4970 x 10^{-4}	α_{c1} = 2. 7460 x 10^{-4}
Measured	α_{m} = 2. 9967 x 10^{-4}	α_{m} = 3. 7700 x 10^{-4}
II step	α_{c2} = 2. 6170 x 10^{-4}	α_{c2} = 3. 0990 x 10^{-4}

Figure 8. Calculated and measured values of slops for the span S_3S_4

Since the load carrying capacity of the span S_3S_4 was the most decisive for bridge evaluation, the failure analysis and risk assessment is considered taking in account possible traffic jam and the probability of the worst event when the heaviest trucks close one after the other could be found in the span. With the scheme of the most unfavorable truck considering the very short distance between the axles, the value of continuously distributed live load is found and assuming uniform probability density distribution series of random numbers are generated and the corresponding values of moments are calculated. The limit state (failure) is defined as a state of stress when the zero stress in lower chord of the box girder is reached taking in account dead and leave load action. Considering uncertainty as a consequence of the great number of cables cut off in the area T4, only 50% of the full prestressing force is assumed as a residual but still active part of the prestressing. Considering cumulative dead load, 50% of the total prestressing force and the leave load action, based on the stress condition equal zero,, the limit value of moment is found with the mean value: M = 7000 kNm and variance: σ = 0.25. The uniform probability density distribution is assumed and corresponding random numbers (moments) generated as well. Comparing directly two sets of moments obtained by that way, it was possible to identify the total number of events indicating failure. Based on the mentioned procedure, probability of failure was found as P_f = 0.45 or 45%. The very high level of risk obtained was decisive for the authority to make a decision that the bridge at first has to be repaired.

Conclusions

Compared to the traditional but more conservative deterministic approach to the integrity assessment of concrete structures a new, probabilistic - risk based approach is proposed. The new concept takes in account the uncertainty and randomness in determining the necessary values (property of materials and characteristics of integrity) calculating the probability of reaching a limit state. The limit state is chosen based on the previous structure inspection and virtual structure failure mechanisms analysis. The entire procedure is presented through the example, where the heavy damaged bridge structure is analyzed and the probability of structural failure calculated.

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