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Condition assessment of reinforced concrete bridges using nondestructive testing techniques

Cristina Romanescu[1], Claudiu Romanescu[2] and Rodian Scînteie[3]
[1]*Road Bridges Department, CESTRIN, Bucharest, 061101, România, bridge@cestrin.ro*
[2] *Road Bridges Department, CESTRIN, Bucharest, 061101, România, cromanescu@gmail.com*
[3]*CERT-CESTRIN, Bucharest, 061101, România, rodian.scinteie@gmail.com*

Summary

The transportation infrastructure in the Romania is deteriorating and will require significant improvements. A major component of maintenance is the ability to accurately assess the condition of the transportation infrastructure.

A realistic and reliable assessment of a damaged bridge structure must comprise the evaluation of bridge condition, load bearing capacity, remaining service life and functionality.

It is essential for a reliable condition assessment to have records indicating the initiation of defects and deterioration processes and of their propagation from the beginning of bridge service life. As such records seldom exist for older existing structures and it is imperative to supplant them by other information using NDT techniques. Nondestructive testing methods help quickly diagnose hidden problems and assess bridge condition.

This paper present defects, the factors having strong impact on the deterioration and different nondestructive testing techniques used in the assessment of concrete bridge structure and promote the ability of these methods to detect defects with varying precision.

Defects evaluation should be done for individual structural materials with respect to the damage type, its intensity and extent and to the affected structural element.

Bridge engineers involved in the routine or extraordinary inspection of bridges have to take correct and reliable decision about the defect type, the associated deterioration process, the relevant cause and possible propagation of the damage in the future. This evaluation should be not based only on the expertise, engineering judgment and experience of the inspector.

KEYWORDS: defects, NDT techniques, assessment, deterioration processes and mechanisms.

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1. INTRODUCTION

A defect means the absence of something necessary for completeness or perfection, a deficiency and an opposed to superfluity, a physical or moral imperfection. Also, a defect is a specific inadequacy in the structure or its components that materially affect its ability to perform some aspect of its intended current or future function.

Related terms are deficiency, damage, degradation, deterioration and disintegration. [2]

A deficiency is a lack of something essential for the ability of the structure to perform its intended function, as a result of an error in design, construction or maintenance. Damage is a physical disruption or change in the condition of a structure or its components, brought about external actions, such that some aspect of the current function of the structure or its components is impaired. The worst damage is disintegration witch means a severe physical damage of a structure or its components which results in its break-up into fragments, with the possibility of gross impairment of functional capability.

A worsening of condition with time may result in two ways: usually in damage and this is called degradation and in a progressive reduction in the ability of the structure or its components to perform some aspect of their intended function and this is called deterioration.

Nondestructive testing (NDT) has been defined as comprising those test methods used to examine an object, material or system without impairing its future usefulness. Ultrasound, X-rays and endoscopes are used for these kinds of testing. Nondestructive testing is used to investigate the material integrity of the test object. Often, in NDT and Quality control defect, flaw, imperfection, non-conformance are the terms used when the material tested deviates from ideality. Though all of them look similar, there exists a vast difference in their meaning and interpretation. The term ‘flaw’ means a detectable lack of continuity or a detectable imperfection in a physical or dimensional attribute of a part. The term ‘nonconforming’ means only that a part is deficient in one or more specified characteristics.

2. ASSESSMENT OF A DAMAGED BRIDGE STRUCTURE

Assessment of the condition of a bridge structure starts with the identification of the damages relevant for the evaluation of the bridge condition, its bearing capacity, remaining service life and functionality. For every detected defect or damage the inspector has to identify the type of damage, the severity or degree of damage and its extent.

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Causes for the majority of deterioration processes and associated damages on concrete bridges are generally known.

Many types of defects have characteristic visual signs on the surface. During visual inspection of structures such signs can give valuable information about defects themselves, their nature and cause. The time when signs become visible can vary from a few hours up to many years after the construction. [2]

Deteriorations lead to many problems such as functional, load carrying and long-term durability. The factors having strong impact on the deterioration of concrete bridge structure are:

- design;
- materials used for construction;
- construction methods;
- applied loads;
- environmental actions;
- maintenance of the structure in service.

The impact of every one of the influencing factors on the occurrence of defects and damages is included in table 1.

Table 1: Influencing factors and causes for occurrence of defects and damages

No.	Influencing factors	Causes for occurrence of defects and damages
1	Design stage	Standards and design norms used at the time of construction could be out of present interest
		Degradation of concrete due the inadequate detailing of specific parts of the structure
		Suffering unexpected severe damages because not taking into account the micro-climate conditions near or around the bridge
2	Materials used for construction	Serious durability or load bearing problems because the components of concrete and/or the reinforcement do not meet the design requirements
3	Construction stage	Inconsistent quality control during construction process may lead to severe durability and load carrying problems like excessive cracks and deflections, or even collapse
4	Applied loads	Excessive deflections of bridge than calculated because of excessive loads of passing vehicles
		Displacements of the infrastructures because of greater earth-pressure or global instability of the foundation
		Severe mechanical defects can be brought by collision with different objects
		Defects that remain visible for many years because of loading due to natural disasters
5	Maintenance of the structure in service	Deterioration of an existing structure is due the delayed or inadequate rehabilitation methods applied

The types of defects that may be assessed using NDT methods can be classified into three major groups:

- inherent defects - introduced during the initial production of the base or raw material.
- processing defects - introduced during processing of the material or part.
- service defects - introduced during the operating cycle of the material or part.

Some kind of defects which may exist in these three groups are:

- cracks on surface and subsurface, arising from a large number of cases;
- porosity;
- breakings;
- laminations;
- lack of bond;
- inclusions;
- segregation;
- fatigue defects etc.

The origin of defects in a material can take place during manufacturing stage, during installation or during in service. In the first two cases quality can be achieved essentially by good engineering practice.

However, the occurrence of some form of imperfections during manufacture is inevitable and there will be a typical distribution of imperfection sizes associated with a particular manufacturing process and quality. The ideal situation is where the inherent distribution of initial imperfection sizes is well separated from the distribution of critical defect sizes which may cause failure. Hence, the role of NDT is not only to detect the defects but also to give information about the distribution.

There are little benefits derived out of repairing the parts/components with defects for their delivery to the customer. Here, the industry should aim at produce parts / components without defects. In the subsequent section, it is shown how to achieve this objective.

On the other hand, in the in-service scenario, defects will be generated due to deterioration of the component/structure as a result of one or combination of the operating conditions like elevated temperature, pressure, stress, hostile chemical environment and irradiation leading to creep, fatigue, stress corrosion, embattlement, residual stresses, microstructural degradation etc. which, in turn, result in deterioration of mechanical properties, crack initiation and propagation, leaks in pressurized components and catastrophic failures.

NDT techniques are increasingly applied to components/systems for the detection and characterization of defects, stresses and microstructural degradation to ensure the continued safety and performance reliability of components in industry. NDT

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techniques improve the performance reliability of components through periodic in-service inspections, by way of preventing premature and catastrophic failures.

NDT also provide valuable inputs to plant specification and design i.e. to determine which components are the most likely to fail and then to ensure that those have easy maintenance access for repair or replacement. In in-service scenario, it is rather difficult to stop the formation of defects and the growth of defects already formed. [4]

NDT in the assessment flowchart is shown in Appendix 1.

There are three types of assessments, depending on the considered safety criteria for the existing road bridges: one exceptional heavy load (one time), bridge capacity is affected by on-going deterioration and new loads (heavier axle loads or higher speeds). The levels of detail may be element assessment (part of a bridge), bridge assessment (one bridge) and line assessment (number of bridges).

Typical assessment criteria for the three states are:

- ultimate limit - safety of persons an/or the bridge
- serviceability limit state - functioning under normal use, comfort of passengers and appearance
- fatigue limit state - relationship between safety and normal use
- durability limit state - environmental actions that causes degradation with time.

From the complexity point of view of procedures there are initial, intermediate and advanced assessments.

Initial assessment supposes site visit, study of documents and simple calculations (e.g. comparison between design load and required load, simple hand calculations, moment, shear force).

Intermediate assessment consists on further inspections (visual inspection, delamination check, crack measurements), simple tests (material properties like yield strength, concrete compression strength, simple load measurements) and detailed calculations (linear finite element analysis, plastic analysis)

Advanced assessment means laboratory investigation, load models, reliability-based, monitoring, refined calculations and decision analysis [3].

Deterioration may be categorized as early age deterioration (such as shrinkage cracking and settlement cracking over rebar), long-term deterioration (including pattern cracking due to alkali-silica reactions, and delamination from rebar corrosion), and in-service deterioration (such as midspan spalling due to overloading, and cracking and corrosion from defective expansion joints).

The nondestructive evaluation methods includes GPR and infrared thermography for locating delaminations and voids, impact echo techniques for determining the

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extent and depth of voids and locating embedded metallic materials, and radiography for locating voids and major corrosion of reinforcing steel.

2. DEFECTS WITHIN THE ROMANIAN BMS DATABASE THAT CAN BE ASSESSED USING NDT METHODS

An analysis of the Romanian Bridge Management System database pointed that the national roads and motorways network comprising 3171 road bridges are suffering of various damages induced mainly by the severe lack of maintenance and by the environment. The large majority of structures are affected by infiltrations and efflorescence, cracks, reinforcement corrosion, segregation and carbonation of the concrete.

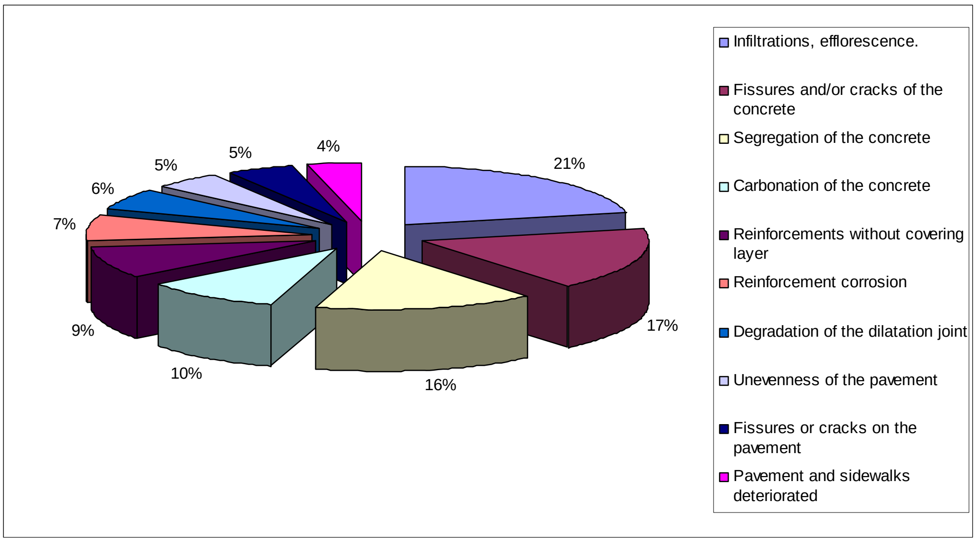

Figure 1. Diagram of the most common defects of the Romanian national roads and motorway bridges

As may be observed on the figure above, the main three degradations that have been seen on visual inspections for entire Romanian national network are: infiltrations and/or efflorescence, fissures and/or cracks of the concrete and segregation of the concrete. The causes for these degradations are mainly the same, the systematic lack of maintenance due to insufficient funds and the poor quality of concrete.

Diagrams for each of the seven regions within the Romanian National Roads and Motorway National Company are shown in Appendix 2.

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One may observe that all these defects can be assessed using NDT methods. A preventive evaluation may lead to the mitigation of the effects of these devastating degradations for the Romanian bridges. Infiltrations, carbonation of the concrete and the reinforcement corrosion occur simultaneously, within the same degradation process. Therefore it is considered very important to study the deterioration mechanism that stands as the base of phenomena, meaning the chloride ingress.

3. MODELS FOR DETERIORATION MECHANISMS

By using models of the most frequently occurring deterioration mechanisms the anticipated or remaining service life of concrete structures can be predicted with good probability.

Failures in the structures do occur as a result of premature reinforcement corrosion. Chloride ingress is a common cause of deterioration of reinforced concrete structures. Concrete may be exposed to chloride by sea water or deicing salts. The chloride initiates corrosion of the reinforcement which through expansion disrupts the concrete. Modelling the chloride ingress is an important basis for designing the durability of concrete structures. There are several mathematical models available which predict chloride ingress into concrete.

The most widely adopted technique for modelling chloride ingress in concrete is Fick's 2nd Law. If diffusion is assumed to be one-dimensional then the relevant equation is

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \qquad (1)$$

where C = chloride concentration at a distance x from the surface after time t

D = diffusion coefficient

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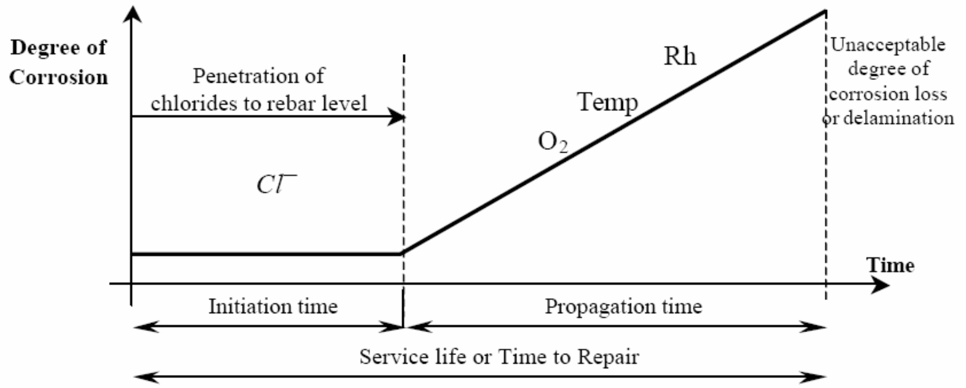

Figure 2. Schematic diagram of the corrosion process of steel in concrete

Assuming constant chloride concentration at the surface of the concrete, the commonly used solution to the above equation is

$$C(x,t) = C_s\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right] \qquad (2)$$

where *C(x,t)* = chloride concentration at depth *x* after time *t*

erf = the error function

CS = chloride surface concentration (assumed constant)

It is possible to evaluate effective diffusivity values, *D*, and the time for chloride initiated corrosion to begin by setting *C(x,t)* equal to a critical chloride corrosion threshold *Cth*. The assumptions made are that:

- one dimensional diffusion in a semi-infinite homogeneous body is representative of the chloride ingress process in concrete structures
- chloride surface concentration, *CS*, is constant through time
- the diffusion coefficient, *D,* is spatially and temporally constant

The first assumption neglects the effect of other processes which are important especially if chloride exposure is intermittent and the structure undergoes a number of wet-dry cycles. Structures are intermittently exposed to chloride attack, it well known that de-icing salts are applied only during part of the year, and that this process is repeated annually. Under these conditions, an alternative solution to Fick's 2nd Law has been used given by

$$C(x,t) = \frac{M}{\sqrt{\pi D t}} \exp\left(\frac{-x^2}{4Dt}\right) \quad (3)$$

where M = quantity of accumulated chloride on concrete surface per unit time in kg/m^2/year.

The third assumption concerns time and space variations of the diffusion coefficient. Temporal variations have been neglected because they are no so noticeable. Space variations are intricately linked with dependencies on temperature, water/cement ratio, cement type, humidity and workmanship and are known to be important.

That improves the understanding of transport mechanisms and deterioration processes in concrete structures. Permanent monitoring of the new and existing structures will increase our confidence in specifying probabilistic parameters for key deterioration variables, and in quantifying their systematic and random variability as a function of measuring and environmental influences.[1]

3. CONCLUSIONS

NDT methods should to be integrated into the condition assessment procedures and applied by the administrator of the road.

It is essential to improve the integration of deterioration modelling with reliability assessment through pragmatic and balanced approaches, in order to support technical and financial decisions that need to be taken.

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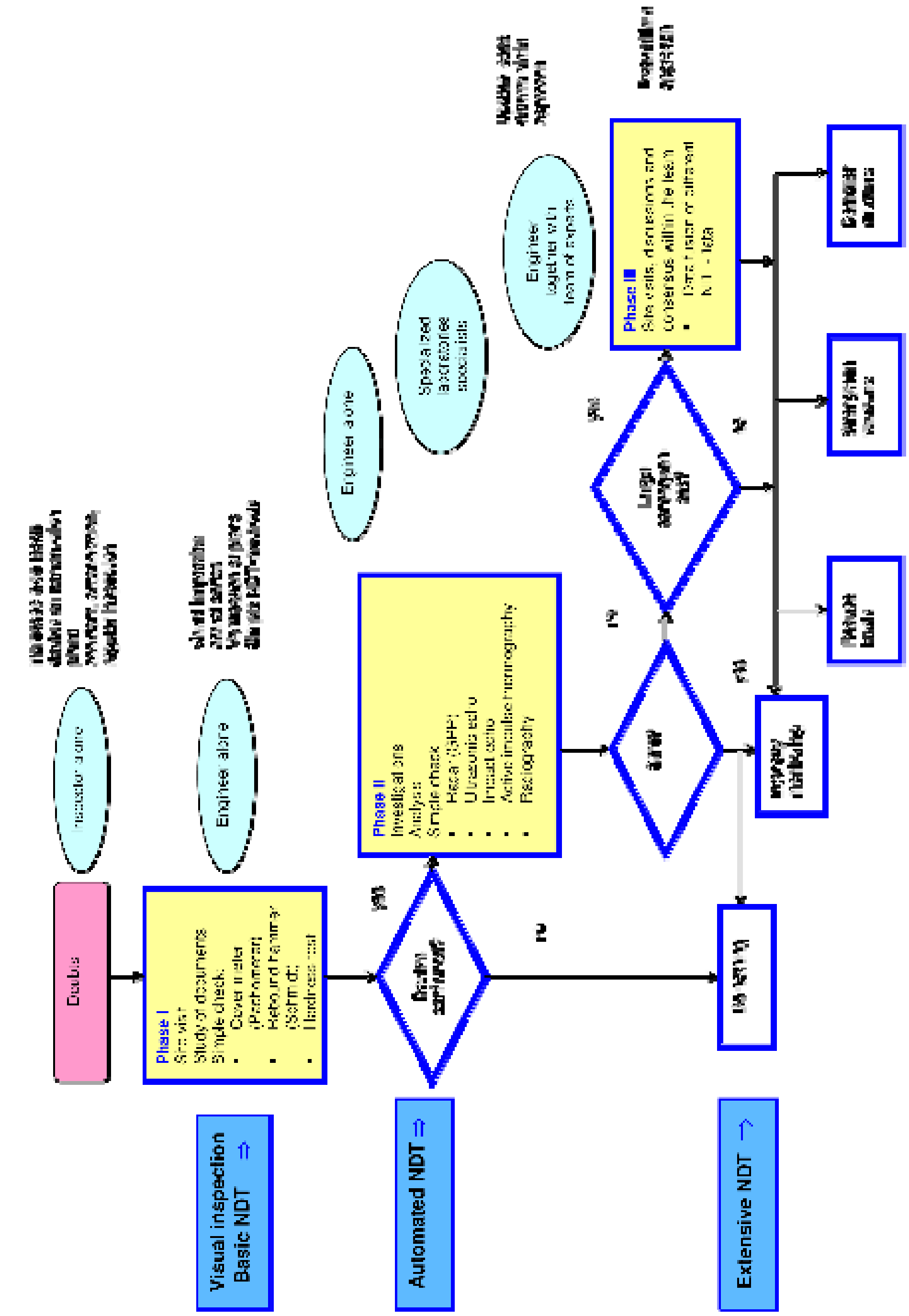
Appendix 1. NDT assessment flowchart



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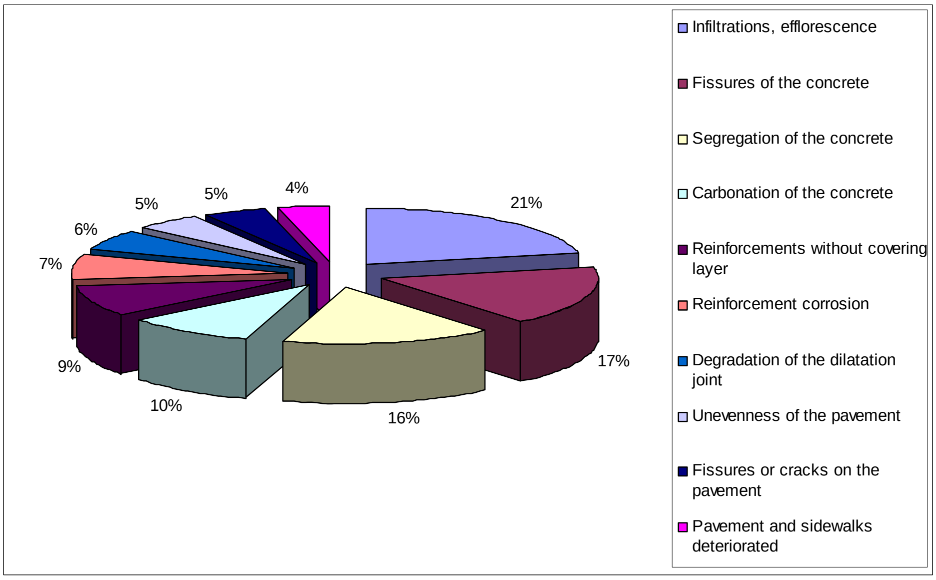
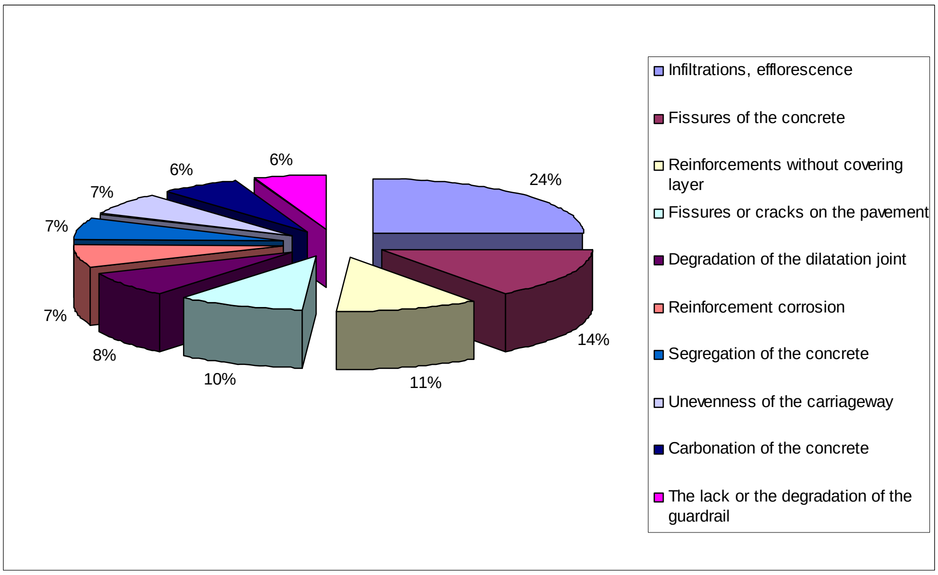
Appendix 2. Diagrams of the most frequently defects within the Romanian BMS database for every seven Regions



Bucharest Region



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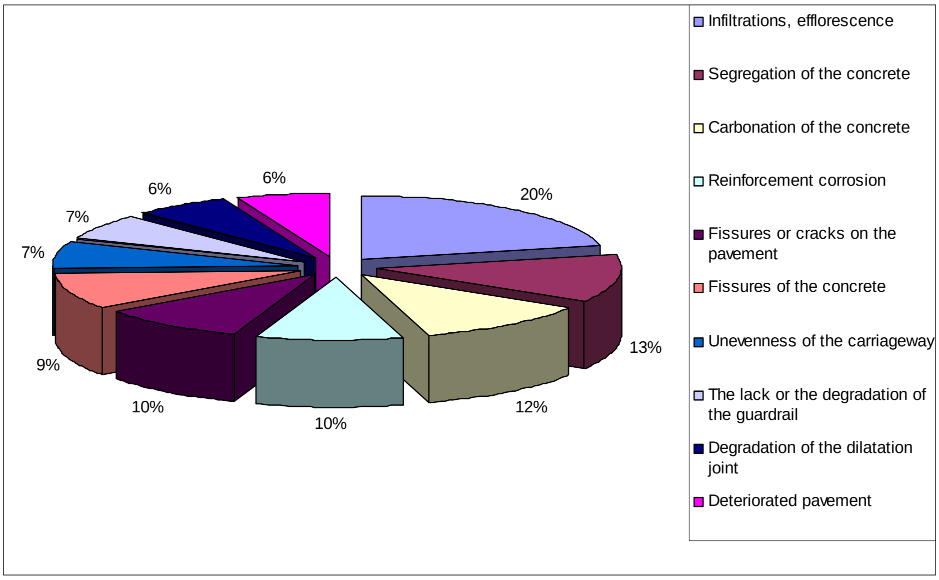
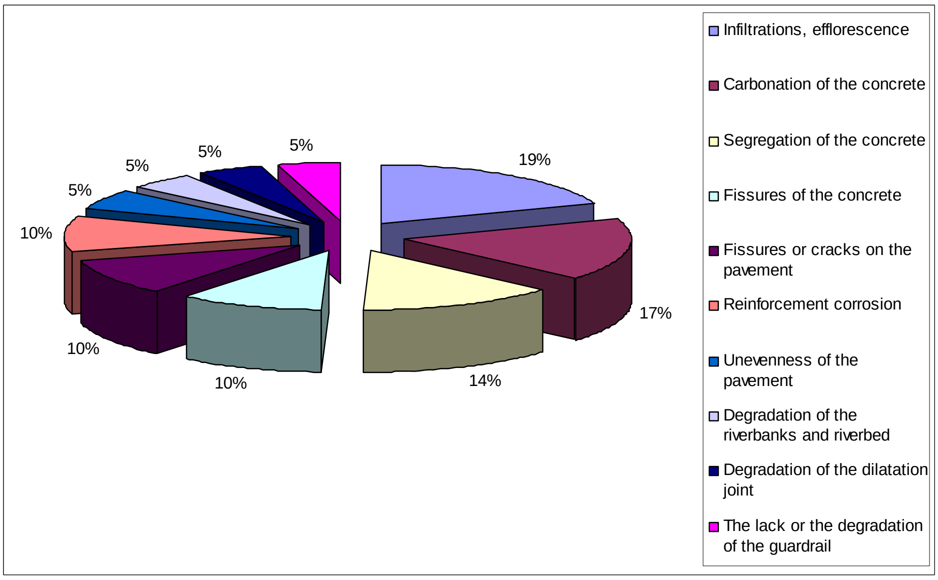
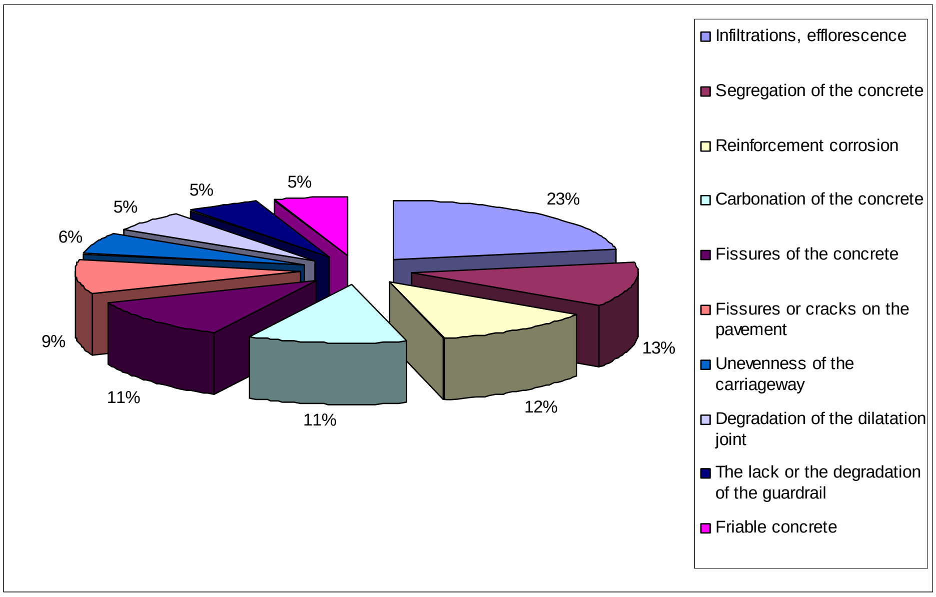


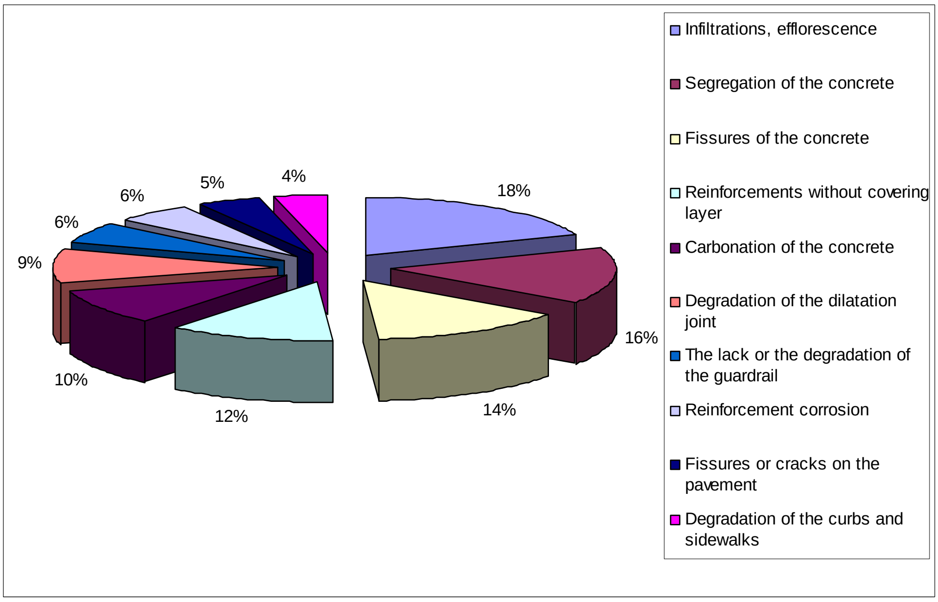
Timisoara Region



Cluj Region



Brasov Region



Iasi Region

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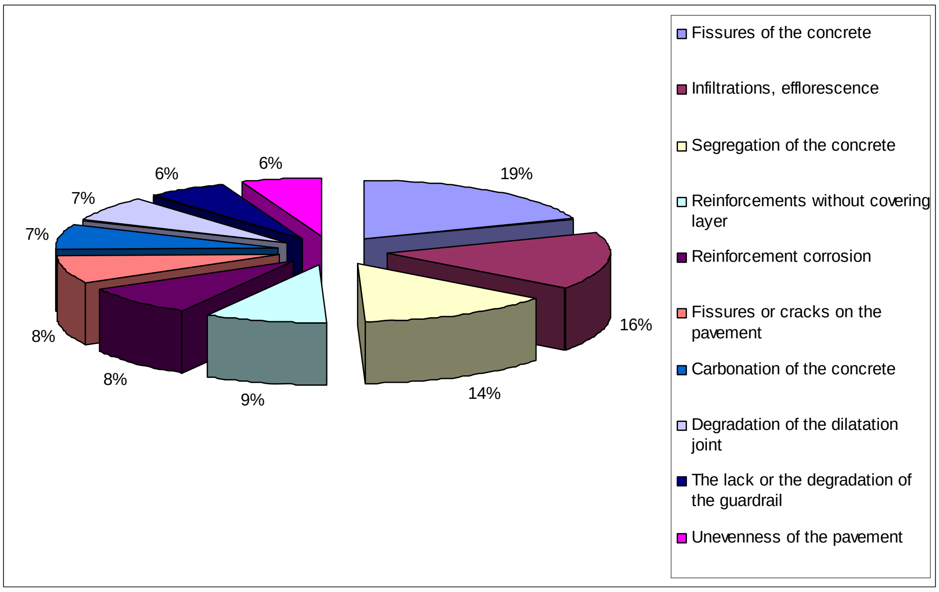

Constanta Region

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