LIFE CYCLE ANALYSIS OF REINFORCED CONCRETE BRIDGES IN BALTIC COUNTRIES

Sander Sein¹, Jose C. Matos², Juhan Idnurm³

¹PhD student, Tallinn University of Technology (Ehitajate tee, 5, Tallinn, 19086, Estonia),
²Professor, Minho University (Campus de Azurem, Guimaraes, 4800-058, Portugal),
³Professor, Tallinn University of Technology (Ehitajate tee, 5, Tallinn, 19086, Estonia),
E-mails: ¹sander.sein@ttu.ee; ²jmatos@civil.uminho.pt; ³juhan.idnurm@ttu.ee

Abstract. During this paper the first part of Life Cycle Analysis based on visual inspection data of main types of reinforced concrete bridges in Baltic countries will be introduced and discussed. In a first step, the background of bridge management systems, visual inspections and most common bridges will be presented. During this step, an explanation of differences and similarities of Baltics visual inspections and data processing will be introduced. In a second step, principal component analysis with main outcomes for different Baltic countries and possible reasons for those outcomes will be discussed. Also a comparison of principal components for similar bridges in all Baltic countries will be shown. At the end, input for predictive models will be introduced. The main objective of this input is to show what elements deteriorate more rapidly and due to that have an influence for Life Cycle of reinforced concrete bridges.

1. Introduction

According to European Standard EN 1990, bridges belong to group where designed life-cycle should be 100 years (EN 1990). This is a long period and without correct interventions the structures will not fulfil the requirements to safety (ultimate limit state) and serviceability (serviceability limit state). For example in Estonia, although designers provide user manual with structural calculations, they differ from bridge to bridge and are not properly used by owners or operators. To overcome the problem of ageing structures not fulfilling the requirements and making right decisions to efficiently maintain them, bridge management system have implemented. Bridge management system (BMS) is a framework that helps decision making process by having systematic approach and giving rational suggestions. In order to maximize the benefits of the investments done in the past, also Estonia, Latvia and Lithuania have implemented BMS. Unfortunately all systems are moreover database oriented and additional benefit can be added with Life Cycle Assessment by integrating deterioration models to predict the performance of these structures. Over the past two decades, many models have been proposed including the ones based Markov chains (Thompson et al., 1998), linear or non-linear probability functions (Neves and Frangopol, 2005), neural networks (Miyamoto et al.2000) and lifetime functions (Yang et al. 2006).

In 2016 there are more than 3000 reinforced concrete bridges on national roads of Baltic countries, to be exact then 1370 in Lithuania, 907 in Latvia and 778 in Estonia. Most of the bridges are built in 1960-1990, which means that the average age of these bridges are more than 40 years. Since the bridges were constructed during Soviet era, where most of the design projects were based on catalogue products, then similarities in three countries are likely to present. For example mounted simply supported beam bridges (Fig.1) are widely present in all Baltics.

Another similarity in Baltic countries is that every country have started to collect conditional information of bridges in unified formulation. All these collections are mainly based on visual inspections and there have been more than two inspections per bridge. The first Baltic country that started developing BMS was Lithuania, in 1992. Although there are differences in rating and assessment levels, the main idea is to allocate funds. The time between main inspections is also different and it affects the amount of collected data. More specific description of Baltic bridge management systems are provided in next paragraph.

In this paper emphasis is made to describe the differences and similarities, which are both connected to concrete. Assuming that people involved in data collection have acted rationally, different mathematical tools are examined on the basis of Baltic reinforced concrete bridges visual inspection data. All the presented methods are based on the concept of life-cycle analysis (LCA). To be clear, then life-cycle analysis in this context is the study
of a system’s lifetime from construction to disposal. The decisions that could be made on the basis of LCA can differ from annual maintenance planning to long-term resource allocation (Sánchez-Silva, Klutke, 2016).

Fig 1. Simply supported beam bridge in Estonia, designed by catalogue.

Similarities are compared within the context of Principal Component analysis (PCA) and expert judgement. These are two possible ways of getting input info for predictive models to make decisions not based on element level, but also on system level. Similar weight factor approach have been used also in former Pontis (Thompson et al 1998). In Pontis the weight factors were used on every element combining it with expected replacement cost, which was intended to prioritize elements that have more influence on bridge condition. The approach with excluding replacement cost is still in use in Estonian BMS.

2. Bridge Management Systems

Since the bridge management systems are developed under different conditions then before going into detail with visual inspections, a short overview of every management system is presented.

2.1. Estonia

Estonia, as with least experience in bridge management, started implementing unified inspections and management system in 2003 and fully using in 2005. The main development was done by consultant company Teede Tehnokeskus using program Pontis, which is a database containing bridge condition data, traffic needs, accident data, maintenance, improvement and replacement costs, available money, etc. From all this data, a prioritized list of bridge needs can be produced that optimizes the limited funds available. Not all of the available possibilities were used, but it was successfully in use until 2013, when Estonian Road Administration decided to take bridge management under its own responsibility.

BMS in Estonia is based on four different modules:

- Inventory module
- Inspection module
- Cost module
- Analysis module

Inventory module consists of metadata like bridge dimensions and construction information. It is based on national road registry and is updated simultaneously. Inspection module consists of inspection data like element conditions and inspection dates. Cost module is based on the unit prices collected during procurement process. Analysis module takes all previous information and gives ranking list based on bridge condition, age, traffic density and measurement requirements.

2.2. Latvia

In 1995 Latvian Road Administration started looking for BMS and evaluating own financial and technical possibilities. A few years later, in 1997, they made an agreement with the Norwegian Public Road administration about the establishing of such a system for the needs of Latvia. LatBrutus was established with the support of and in cooperation with the Norwegian bridge specialists and the programme was finished in 2002. It is still in use in unchanged form. The software consists of four different modules, as shown in Fig.2 (Adamsone, 2006):
Inventory module is formed for the collection of necessary data about all bridges in road network to obtain the necessary technical information. Module includes base data for inspections and maintenance. Inspection module includes inspection planning and data registration about bridge technical condition over their service time. Maintenance module is established to help to perform maintenance planning, prioritisation and execution with financing. Administration module is necessary for the overall division of users and reports (Adamsone, 2006).

2.3. Lithuania

The Lithuanian Road Administration started the BMS development in 1992 and last updated version is from 2016, but works are continuous. Lithuanian Road Administration have used local experts and academics in development process, additional specialists from Swedish and Finnish Road Administrations have been used to audit the program. The whole BMS is based on inspections and condition evaluation. Damages and deterioration processes are recorded. Also, information on the effect of damages on different requirements and intervention proposals with costs are described and recorded (Virsilas, 2006).

The BMS consists of nine modules:

- Inventory data
- Inspection data
- Allocation (Budget) module
- Price catalogue
- Optimization
- Reports, photos, drawings
- Maintenance module
- GIS
- Long-term planning

There are a number of modules, but overall idea is to assist main tasks of road administration (Virsilas, 2006).

The central element of all Baltics BMS is visual inspection and in next chapter the nature of visual inspection and differences in assessment is explained.

3. Visual inspections

Visual inspection is probably the most dominant evaluation technique for bridges (Gatulli, Chiaramonte 2005). It can provide basic and valuable information with qualified inspectors. Visual inspection have simple
routine and it provides an initial indication of the condition of the concrete to allow the formulation of a subsequent testing programme. It is also through such inspections that proper documentation of defects and features in the concrete structure can be effected. Visual inspection can reveal substantial information regarding the structure such as the construction methods, weathering, chemical attack, mechanical damage, physical deterioration, abuse, construction deficiencies or faults and many others. In SAMCO Final Report (Rücker et al. 2006), visual inspection is proposed as Level 0 qualitative assessment, which means that it is based on experience of the engineer.

On the other hand inspections are time consuming, because inspectors have to go to the field to check the structures. Another problem of visual inspection is that even experienced inspectors have differences in evaluation and it may have unreliable data (Kušar, 2014). To minimize the error from subjectivity it is important to present clear manual for assessment. By combining qualified experts with proper manual, satisfactory results can be achieved.

In Baltic countries, there are manuals for assessment, most of them describing elements and defects. Latvian State Roads in cooperation with Norway Public Roads Association have developed a manual has more than 300 pages (Iurka, 2003).

Visual inspection, as the most popular assessment method, have different types of inspections. In LatBrutus the inspections are classified (Adamsone, 2006):

- Commissioning inspection – transfer of the structure to maintenance, in other words it is could be initial inspection after construction or in the beginning of maintenance actions.
- Guarantee inspections – inspections that are done at the end of guarantee period.
- General Inspection – Annually or more frequently made inspections.
- Main inspections – inspections done at least once in five years.
- Special Inspection – is completed to test, monitor a known defect or condition.

Inspection results in Estonia and Latvia are taken from Main inspection category, but in Lithuania General inspection data is used. Overall information of visual inspections can be found in Table 1.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Estonia</th>
<th>Latvia</th>
<th>Lithuania</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of inspection</td>
<td>&lt;=4 years</td>
<td>&lt;5 years</td>
<td>6-8 years*, 1 year</td>
</tr>
<tr>
<td>Different states</td>
<td>1 Good – 4 Poor</td>
<td>1 Good – 4 Poor, 4 additional categories</td>
<td>Repair measure*, 5 No damage</td>
</tr>
<tr>
<td>Evaluation level</td>
<td>Element</td>
<td>Element</td>
<td>Element*, structural</td>
</tr>
</tbody>
</table>

* - only during Main inspection, but without inspection data.

The exceptions of different countries are mainly connected to evaluation levels. In more detail:

- **Estonia.** Only data from Main inspections are collected. There are 4 condition levels and 2 different letters to indicate damages with immediate intervention employment. Elements are assessed based on defects and unit areas. For example overlay with total amount 100 m² can have 50 m² in state 1, 40 m² in state 2 and 10 m² in state 3. Based on the element ratings, an overall Condition index is calculated. All defects need to be described and location is based on classified numbers.

- **Latvia.** Main and special inspections establish the cause of damage. There are 4 condition levels for the evaluation of damage degree and 4 different letters C, T, M, E to indicate the consequences of the damage, namely C – endangers load carrying capacity, T - endangers traffic safety, M- can increase the maintenance/traffic cost and E- can influence the environment/aesthetics. All the damages have also connected with maintenance activities. Assessment is made on element basis, which means that whole element can be in specific state. For example overlay can be in state 2.

- **Lithuania.** Data is collected during General (Annual) inspections. There are 5 condition levels and additional maintenance indication. Assessment is done structural based, which means that previously defined structure can be in a specific state. For example overlay can be in state 4. Additional assessment is made on system and bridge.

In conclusion, every country have found a suitable management system with supporting visual inspections and although variation may be found in decision making, the overall approach is similar. The different management of similar bridges should be investigated in more detail, because it could give objective information in how different administrations are making decisions. In this paper the input for further investigation is discussed.
4. Most common bridges

Traveling through Baltic countries and going under bridges is interesting in some areas, but most of the reinforced concrete bridges look similar, in spite of the deterioration due to environmental differences. The background of common bridges are closely connected to Soviet era and the regulations of bridge types. From 1947 to 1963 a number of design catalogues “Типовые проекты сооружений на автомобильных дорогах” (Design catalogue for roadway bridges) were produced and 13 of them were widely used in Baltics. For example there is catalogue prepared in 1958 for beam bridges with span length 7.5, 10.0, 12.5, 15.0 and 20.0 meters. In this edition the main girders were slim and tall T-beams with diaphragms, which were connected with special welding (Fig. 3).

These cross-sections are second most popular typology of all reinforced concrete bridges. There are three different typologies – ones built before 1956 with casted reinforced concrete and two others built afterwards, respectively with diaphragms and without (Fig.1) with mounted elements. Approximate subset of this typology is 35% of all reinforced concrete bridges.

The most popular bridge typology is simply supported slab. There are two different typologies – one cast in-situ and other mounted. There are also prestressed slabs. Approximate subset of this typology is 40% of all reinforced concrete bridges.

Third most popular typology is frame bridge in definition, but actually the bridges represent wider area of the typology. For example in Estonia the frame bridge is more likely to be underpass (Fig.4), but in Latvia and Lithuania there are bridges with stiff connections between sub- and superstructure (Fig. 4). This typology is also presented in Estonia, but it is not so popular. Frame bridges present around 10% of all reinforced concrete bridges.

In addition there are also continuous beams, Gerber beams, concrete truss and arch presented in Baltics, but the population of these bridges are lower and these typologies are not presented in this work.
Most of the catalogue products have similar defects and in same environmental conditions the degradation processes are also with same rate. With this input information it should be clear that the borderline of different countries shouldn’t affect the condition changes of different bridges, but to support the assumption additional investigation is needed.

5. Principal component analysis and results

During one visual inspection of one bridge more than 20 inputs are entered with condition ratings for elements and it means there are big amount of data produced in inspection module of every Baltic country. Even in Estonia, where BMS is implemented only 12 years ago, there are more than 44000 rows of data each containing at least 4 variables. Not all the data is used during simple analyses, but during LCA of bridges all collected data is used when computing degradation models it takes a lot of time and computing resources to get the results.

There are number of different methods to reduce the dimensions of the database using statistical techniques starting from basic factor analysis and more advanced multivariate techniques without losing information. In this work the highlighted multivariate analysis is principal component analysis (PCA).

Principal component analysis (PCA) is technique which main purpose is to reduce the dimensionality of a data-set, and redefine the input variables as principal components (PCs); being a linear combination of the original variables, but having a magnitude less than the original dataset while preserving most of the information (Hotelling, 1933; Jolliffe, 2002; Mardia et al., 1979; Johnson, Wichern, 1992). In this work only first PC is under investigation.

The first principal component \( Y_1 \) is defined as (Eq.1):

\[
Y_1 = \alpha'_{1}x = \alpha_1x_1 + \alpha_2x_2 + \ldots + \alpha_nx_n = \sum_{j=1}^{p} \alpha_{1j}x_j 
\]

Where \( \alpha'_{1}x \) is a linear function of the elements, \( x \) having maximum variance and \( \alpha \) is a vector of \( p \) coefficients \( \alpha \). The first PC is the direction along which the data set shows the largest variation (Ringnér M., 2008).The sum of the square of the PC coefficients i is equal to unity, and thus the influence of any coefficient on the analysis is apparent in comparison to each other (Eq.2).

\[
\sum_{j=1}^{p} \alpha_i^2 = \alpha'\alpha = 1 
\]

The PCA was conducted on five most common reinforced concrete bridge types in Estonia and Lithuania using raw data of visual inspections completed between 2005 and 2015. It has to be noted that it is often considered wise to use the correlation matrix for a PCA, as the standardized variates are dimensionless and can be more readily compared (Jolliffe, 2002). However, when the variables are measured in the same units and have a low variance, using the covariance matrix is sometimes appropriate, and can be beneficial when statistical inference is important. In this case dimensionless raw data is used. In every specified typology there was different number of element groups. Additionally, in some groups there was little information available on the condition of drainage, deformation joints or bearings, so these elements were excluded. Element groups are presented in Table 2. Another limitation of input data was that bridges with intervention were excluded.

Unfortunately Latvian data had to be excluded due to condition ratings that are only entered when there are consequences for defect. Putting all the information without rating would needed a high capacity of manual work and effort have been made to eventually include the data in final results.

<table>
<thead>
<tr>
<th>Table 2. Classification of element groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Structural Elements</td>
</tr>
<tr>
<td>----------------------------</td>
</tr>
<tr>
<td>Overlay</td>
</tr>
<tr>
<td>Barriers</td>
</tr>
<tr>
<td>Handrails</td>
</tr>
<tr>
<td>Drainage</td>
</tr>
<tr>
<td>Slopes</td>
</tr>
<tr>
<td>Deformation joints</td>
</tr>
<tr>
<td>Other (river bed, snow nets, signs etc)</td>
</tr>
<tr>
<td>Waterproofing</td>
</tr>
</tbody>
</table>

In previous works by Hanley et al (2015, 2016) it has been pointed out limitation that PCA should only be conducted on continuous variables that conform to a Gaussian distribution (Qian et al. 1994), and that its application to condition ratings of a BMS, is inappropriate. On the other hand as long as there are inferential techniques that require that the assumption of multivariate normality, there is no necessity for the variables in the data set to have any associated probability distribution (Jackson, 2003).
Overall results of all bridge typologies are presented in Table 3, where only names of PC and most significant structural component is presented. Results show that most variance of all databases are hidden under non-structural element groups. One example of Lithuanian and Estonian results comparison is presented in Fig. 5.

<table>
<thead>
<tr>
<th>Group No</th>
<th>Type</th>
<th>Principal component</th>
<th>Structural component</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Simple span beam</td>
<td>Handrails</td>
<td>Abutments/bearings</td>
</tr>
<tr>
<td>2</td>
<td>Slabs</td>
<td>Barriers, handrails</td>
<td>Abutments</td>
</tr>
<tr>
<td>3</td>
<td>Slab in fragments</td>
<td>Handrails</td>
<td>Deck plate</td>
</tr>
<tr>
<td>4</td>
<td>Simple span and cantilever beam</td>
<td>Handrails</td>
<td>Main girder</td>
</tr>
<tr>
<td>5</td>
<td>Frames</td>
<td>Other elements</td>
<td>Abutments</td>
</tr>
</tbody>
</table>

As seen in Fig. 5 in both countries the most significant element group is No 3. Handrails followed by other non-structural element groups. Handrails are in bad condition and most of them have been unchanged from construction. The use of de-icing salts are also affecting the condition. Since the condition may be bad, then handrails are repaired/repainted without bigger intervention and this information is not stored in management system database.

Lithuanian data has better distribution of factors and the reason may be hidden in assessment on structural level in annual inspections. In Estonia the element data had to be averaged before analysis and by averaging the more variance have converged. Second bigger difference can be found in structural components, where Lithuanian data shows that most variance is retained in Abutments (13), but Estonian data shows Bearings (16) and Main girder (15). The reason of different results is that there weren’t data collected for these groups in Lithuania.

In other typologies similar pattern occurred – group where most variance is retained has higher value in Estonia and due to missing information some groups could not be compared.

Using Eq2 the sum of first PC is unity and one solution is to put weight factors to every element according to PCA. It would be possible to calculate bridge deterioration models based on element deterioration models. Since the main variation is retained in non-structural elements, then before using PCA results for decision making it is important to consider additional circumstances as risk of failure and influence to overall load capacity, because non-structural elements have less influence than structural elements.

To take additional circumstances into account the second possible solution is expert judgement, which is widely used in many countries. To give additional value to PCA results a questionnaire was held in Baltic countries in February 2017. Questionnaire main purpose was to avoid taking only principal component analysis results for decision making process and experts were kindly asked to assign weights from 1 (Not important) to 5 (Very important) to element groups in two different situations:

- Please assign the following weights considering the risk of failure. Risk of failure is the possibility to total failure, in case an element or group of elements fail.
- Please assign the following weights to every element considering the importance to carrying capacity. Importance of an element is the level on which the capacity of that element influences the total capacity.

During the questionnaire 19 answers were collected and results are shown in Fig. 6 and 7.
Fig 6. Average ratings taking into consideration the risk of failure

Fig 7. Average ratings taking into consideration the influence to load carrying capacity

Overall results are as expected – structural elements have higher values. Unfortunately, weight factors are not as expected because a lot of experts have rated non-structural elements also as important elements to both risk of failure and load carrying capacity, which could be addressed by short scope and lack of knowledge. It is necessary to make an additional questionnaire with more explanation of the background and some examples.

6. Input to Life Cycle Assessment

There are two different type of weight factors, one based on statistical technique and other based on expert judgement. With combining these two different factors it is possible to attain results to element groups to get overall result to bridge. In this paper only linear comparison is presented, although there are number of decision making techniques like analytical hierarchy process, analytic network process and multi-attribute utility technique.

An example is made based on results from Fig.5 and Fig.7 with both results having importance factor of 0.5. Since in Estonian database there are mode elements represented then these results are used. Combined results can be seen in Fig. 8

Fig 8. Combined results of PCA and Expert judgement
Results show that first PC highest value Handrails are still most important element group in simply supported reinforced concrete beams. The weight is reduced, but 34% of LCA still relies on condition changes of Handrails. The results can be changed in putting different importance factor to PCA results.

Difference with determined weight factors and combined PCA, expert judgement is taking into account that depending on structural type, same element group can influence life cycle of structure and decision-making differently.

7. Conclusions

There are four important conclusions to be drawn from the comparison of Baltic countries bridge management and reinforced concrete bridges:

1. In all Baltic countries there are working bridge management systems with similar modules and purposes, but with different visual assessment levels and condition states. It is possible to compare collected data with multivariate analysis, but Latvian data needs additional work.
2. Similar reinforced concrete bridges are constructed during Soviet era on the basis of design catalogues presented from 1947 to 1963. Most common bridge typology is simply supported slab with subset of 40% of all reinforced concrete bridges.
3. In comparison of most principal components similar element groups are represented as most important. There are differences in weight factors and represented element groups. In addition to PCA a questionnaire was conducted and results were combined with PCA.
4. Different element groups affect Life Cycle Assessment differently and using combined weight factors it is possible to give appropriate input for deterioration models.

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