Predictive Models Of Deterioration Rates Of Concrete Bridges Using The Factor Method Based On Historic Inspection Data

AI Abu-Tair[1] C McParland[2] JF Lyness[2] A Nadjai[2]
[1]Faculty of Engineering Al-Quds University Jerusalem
[2] School of the Built Environment University of Ulster N Ireland

Summary: **Recent decades have seen rapid developments in structural research attempting to predict the service life of building materials and components. Earlier ideas, ambitions or visions among a few researchers, are today realities or within reach for engineering applications. The reasons for these developments include improvements in testing procedures, better analytical tools and methods, and a computerisation that has significantly facilitated the ability to analyse and process large data sets. Another important influence and driving force for continued research in this area has been the demand for reliable service life data from building asset/property managers, management consultants and building owners. The risk of deterioration of reinforced concrete structures has highlighted the importance of developing service life prediction models so that optimal strategies for their maintenance and repair can be developed. Many approaches have been suggested to estimate the service life of concrete structures. To date, they are usually based on the Factor Method, or a stochastic/probabilistic approach. In this paper, data on bridge deterioration of over 400 bridges in the UK will be used to provide predictive models based on the factor method.**

Keywords. Concrete Bridges, Rates of Deterioration, Service Life, Modelling, Factor Method.

1 INTRODUCTION

Reinforced concrete provides a relatively inexpensive and durable material that has become widely used in construction of roadways and bridges. Corrosion damage has become a major threat to bridge durability in the UK as in all parts of the world. The inherent risk of deterioration of reinforced concrete structures due to corrosion has highlighted the importance of developing service life prediction models so that optimal strategies for their maintenance and repair can be developed. According to Clifton (Clifton, J. R., 1993), the methods applicable to estimate the service life of concrete subjected to deterioration processes are based on: (a) experience; (b) performance of similar materials; (c) accelerated testing; (d) mathematical models that can describe the chemistry and physics of the degradation processes; and (e) the application of reliability and stochastic concepts. Different approaches have recently been developed to estimate the service life of concrete structures, to date they are based on the concept of delay time, the Factor Method, or a stochastic/ probabilistic approach. These models rely on sound engineering judgement or statistical information in order to determine the structure’s deterioration rate. A key factor missing is that no ‘actual data’, collated over the past number of decades, has been used in their development. An important influence and driving force for continued research in this area has been the demand for reliable service life data from building and other structures asset/property managers, management consultants and structures owners.

This paper reports the modelling of the deterioration of concrete bridges using a large database of concrete bridge inspection records (Christer, A. H. et al, 1993), (Mc Parland, C. B. et al, 2001), (Redmond, D. F. et al, 1997), (Rigden, S. R. et al, 1993), (Rigden, S. R. et al, 1996). The defect histories of 725 concrete members from 439 bridges in the UK were obtained from inspection record covering a period of over 50 years. Of the information recorded and stored in the database, perhaps the most relevant data was the component age and exposure conditions. Through their service life, the various components of a structure will undergo different stages of deterioration, starting with cracking, minor spalling, and extensive spalling which might lead to total failure. It is evident that if enough data were available it would be possible to establish the age at which a structural component will have deteriorated to a specific phase of its service life. This paper reports on a simple spreadsheet program, based on the principles of the Factor Method. The data collected from the inspection records is used to calculate the relevant factors associated with the Factor Method. Subsequently, a critical appraisal of the spreadsheet is offered in order to evaluate its suitability in the field of service life prediction.

2 FACTOR METHOD

Research into the service lives of structures has been ongoing for over two decades. The need for qualified predictions of the service life of structures and their members has increased. Deterministic and probabilistic approaches for such predictions were developed. However, up until the last decade, a sufficiently general and simple method had not been developed. Efforts

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towards this resulted in 1993 in the creation of the Factor Method. This approach is based on a concept developed by the Architectural Institute of Japan (AIJ, 1993) and Construction Audit Ltd (CAL, 1992). It is used as a method for estimating the expected service life when more detailed experimental prediction is not possible. Discussion papers by BRE (Bourke, K. and Davies, H., 1997), Teplý (Teplý, B., 1999) and others give details of this approach (Aarseth, L. I. And Hovde, P. J., 1999), (Bourke, K. and Davies, H., 1999), (Hed, G., 1998), (Hovde, P. J., 1998), (Leino, T., 1999), (Moser, K., 1999), (RILEM, 1997), (Robertsen, E., 1999), (Strand, S. M. and Hovde, P. J., 1999), (Vesikari, E., 1999).

The Factor Method is included in the ISO (International Organisation for Standardisation) document, ISO 15686 'Service Life Planning' (ISO, 1998). Chapter 7 in this standard indicates the intended level of use for this approach. It states that the Factor Method is a way of bringing together the consideration of each of the variables that is likely to have an effect on service life. Also, it can be used to make a systematic assessment even when exposure data does not fully match the anticipated conditions of use. The idea is that its use can bring together the experience of designers, observations, intentions of the managers, and manufacturers' assurances as well as data from testing institutions.

Aarseth and Hovde (Aarseth, L. I. and Hovde, P. J., 1999) state "The Factor Method allows an estimate of the service life to be made for a particular component or assembly in specific conditions. The method is based on a reference service life and modifying factors that relate to the specific condition of the element." Table 1 describes the factors used in this approach, see also Aarseth and Hovde (Aarseth, L. I. and Hovde, P. J., 1999). The factors have been designed to cover the main aspects affecting the service life. However, this does not mean that in some cases it may prove more suitable to include other relevant modifying factors. The value 1.0 is taken to be neutral, as it will obviously have no effect on the service life calculation. In the ISO 15686 document (ISO, 1998), 0.8 is used for the deteriorating effect, and 1.2 for the favourable conditions.

The relation for the service life prediction may be written as follows:

$$L = L_{ref} \times A \times B \times C \times D_1 \times D_2 \times E \times F$$ **Equation 1**

The reference service life, L_{ref}, is the expected service life in the conditions that generally apply to that type of element. Teplý (Teplý, B., 1999) states that it may be determined:

- by means of more accurate methods and approaches,
- based on the producer's data,
- based on the testing laboratory data,
- based on previous experience in similar structures and materials under similar conditions,
- on the basis of agreement in relevant bodies or commissions of the European Union in co-operation with national institutions,
- based on the data in the existing standards and other technical literature.

As discussed earlier, the Factor Method was developed as a tool to support service life prediction in cases where there is a lack of adequate or reliable data. Bourke and Davies (Bourke, K. and Davies, H., 1997) state that it must be used with care and understanding of the method and the project under consideration. However, the following quotation from ISO/CD 15686 (ISO, 1998) indicates the limitations of this method:

"The Factor Method does not provide an assurance of service life. It merely gives an estimate based on what information is available. It is less reliable than a fully developed prediction of service life. The distinction between estimated and a predicted service life should be made when a forecast of service life is given. The information taken into account should also be recorded, so that it is clear whether the estimate is particularly robust or not."

Factors		**Relevant Conditions (Examples)**	
Agent related to the inherent quality characteristics	A	Quality of components	Manufacture, storage, transport, materials, protective coatings (factory applied)
	B	Design Level	Incorporation, sheltering by rest of structure
	C	Work execution level	Site management, level of workmanship, climatic conditions during the work execution
Environment	D_1	Indoor environment	Aggressiveness of environment, ventilation, condensation
	D_2	Outdoor environment	Elevation of the building, micro-environment conditions, traffic emissions, weathering factors
	E	In-use conditions	Mechanical impact, category of users, wear and tear

Operating Conditions	F	Maintenance level	Quality and frequency of maintenance, accessibility for maintenance

Table 1: Deterioration Factors of Materials and Components (Aarseth, L. I. and Hovde, P. J., 1999).

Other concerns have been raised regarding this method. These include the possibility of providing misleading output due to the subjective approach used in calculating the factors and the suggestion that this method provides a deterministic value rather than a range or distribution. Also, in relation to the factors used, Teplý (Teplý, B., 1999) states that in certain cases values may be out of proportion. With this in mind, each factor must be carefully addressed to eliminate this ambiguity. Indeed, Aarseth and Hovde (Aarseth, L. I. and Hovde, P. J., 1999) suggest a method to overcome this problem. Each of these criticisms has value, and the method needs to be used with due attention to the changing state of the art of service life prediction.

2.1 Developments of the Factor Method Towards a Probabilistic Approach

Since the adoption of the Factor Method several issues have been raised as potential modifications or improvements to the approach. In particular, Hovde (Hovde, P. J., 1998) presents an evaluation of this method and includes suggestions for further studies to reduce uncertainty and improve user-friendliness. In other research, Hed (Hed, G., 1998) presents a project where the Factor Method was assessed. This method has been suggested as an alternate means of estimating service life of components and materials. However, previous use of this method has not been well documented, nor has the development of the various factors used in this method been demonstrated. Only now are these concerns being addressed. As discussed by Aarseth & Hovde (Aarseth, L. I. and Hovde, P. J., 1999), one of the shortcomings in the Factor Method is that the service life is treated as a deterministic value. In reality service life has a large scatter and should be treated as a stochastic quantity (Siemes,T., 1997).

However, more recently, stochastic approaches to the Factor Method have been developed. Moser (Moser, K., 1999) describes this approach for a simple building component. Using probability density functions either from supplier’s data, testing or estimates employing variations of the Factor Method, simple examples are provided for this component. However, if this data is not available, a density curve of the estimated service life can be defined by professional estimate or by the recursive Delphi method, see Moser (Moser, K., 1999). This method uses first inputs by experts. After analysis of these results the experts are required to give a modified second input, which is usually more precise. This procedure has given good results in the absence of sufficient data.

Aarseth and Hovde (Aarseth, L. I. and Hovde, P. J., 1999) discuss a similar approach, described as the ‘step-by-step’ principle. The distribution function is restricted to the Erlang-distribution and based on estimates of most expected value, and the 1% and 99% fractiles for each individual factor. In this way the uncertainty is identified and estimated for these factors. It was suggested that the most uncertain factors should, if possible, be divided into sub-elements and more information gathered so as to reduce this uncertainty. The factors are treated as elements which are summed up to give the estimated service life. Also, these estimates are expressed in years instead of values close to 1. This was done to enable the consequences of each estimate to be seen at each step in the process. However, it proved difficult for experts to assess the estimates. Also, it seems doubtful whether this principle adequately covers the real variation of the individual factors.

Despite the criticisms of the Factor Method, it has not prevented its adoption for use in service life planning and whole life costing. The main reason for this is that no other suitable approach has been proposed. However, additional research is needed for reliable estimation of service life, especially into the reference service lives of structures and their members, but also to recalibrate and refine the modifying factors for different situations.

3 ANALYSIS OF DEFECTS IN CONCRETE BRIDGES

The database contains the defect histories of 439 concrete bridges in the UK. The life span of many of these bridges goes back to the early 1930’s with the associated inspection records covering most of this period. Indeed, a number of these bridges were constructed as long ago as 1889.

The data collected from the inspection records was organised into three tables. The main categories are given in Table 1 of a paper by Rigden et al (Rigden, S. R., et al, 1993). The defect conditions noted from the inspections are categorised as in Table 2 of the same paper (Rigden, S. R., et al, 1993).

The database package used was Microsoft Access. This has the advantage of being compatible with spreadsheet software so that statistical information can be produced from any analysis undertaken on the database. The tables were viewed to determine which fields could be queried in order to extract useful and meaningful information.

By combining the data fields from each table a further table was produced, see Table 2. A key to the headings used is listed below. This table contains the relevant data used to carry out the analyses.

Database Query	Code; Year Built; Inspection Year; Type of Structure; Component Type; Exposure Condition; Urgency; Fault/Action Code; Age(years).

Code	Year built	Inyr	Type	Member	exp	urg	Fault	Age (years)
TC001	1937	1966	5	1	2	2	7	29

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TC001	1937	1970	5	1	2	1	11	33
TC002	1937	1970	5	1	3	1	8	33
TC002	1937	1976	5	1	3	1	9	39
TC002	1937	1982	5	1	3	3	9	45

Table 2:Typical Layout of Query Table

The database contains a wealth of information, with some data being more pertinent than others. To determine what data was useful, an extensive analysis of the database was undertaken. To begin, the data was analysed to determine the type of structures and number of members inspected. This gave an overall view of the data stored. The members were then analysed to investigate their degradation over time. The same approach was applied to investigate each individual structure. The relevant results of this analysis were reported by Rigden et al (Rigden, S. R., et al, 1993), (Rigden, S. R. et al, 1996) and Mc Parland et al (Mc Parland, C. B. et al, 2001).

Table 3 and Table 4 display the age at which the structure/member fails (as defined by the need for major repair) under the given conditions. They are a summary of the information obtained through preliminary analysis of the database. A number of significant trends became apparent through analysis of the database. The first step was to obtain a general view of the rate of degradation of all members that had been inspected over the last century. It was found that the majority of members had reached the end of their service life after just over 40 years (Service Life is reached when either failure occurs or major repair is necessary to keep the structure in service).

	Exposure 1 (Years)	**Exposure 2 (Years)**
Flexural	42.5	34.7
Compression	45.1	36.3

Table 3: Service Failure of Members under (1) Mild and (2) Moderate Exposure.

	Exposure Ignored (Years)	**Exposure 1 (Years)**	**Exposure 2 (Years)**	**Flexural (Years)**	**Compression (Years)**
Footbridge	40.1	43.1	37.0	37.9	43.5
Overbridge	27.8	26.4	26.5	33.1	20.4
Underbridge	45.4	53.5	39.2	45.2	51.1

Table 4: Service Failure of Structures

Various structures were analysed individually in order to determine the rate of degradation and make comparisons. Exposure conditions had obvious detrimental effects on the overall structure. Perhaps one of the most interesting findings of the analysis is the fact that under-bridges are most likely to perform longer than any other bridge structure. The reasons for this may lie in the construction type and the form of transport using these bridges; an under-bridge is a structure in which vehicles pass under.

The main cause of deterioration is most likely to be due to corrosion caused by chloride attack or carbonation. Much of the most severe concentrations of chloride levels from de-icing salt occur where bridge deck joints have leaked, allowing chlorides in water to seep through to the substructure. Rigden et al (Rigden, S. R. et al, 1996) reported that the main cause of defects in concrete bridges was due to leaking deck joints. Consequently, abutments and piers become contaminated and severe corrosion result. Spray from passing traffic can cause chloride contamination of roadside piers and abutments, but the concentrations tend not to be as high as that from defective deck joints. Members were analysed according to the structure type they were part of, flexural and compression members followed similar trends of degradation with the former deteriorating faster (Mc Parland, C. B. et al, 2001).

From the results obtained by the interrogation of the database it became apparent that there was a definite pattern in the way the information changed under certain conditions (Mc Parland, C. B., et al, 2001). It confirmed the belief that, for a given structure or member, the age and subsequent exposure conditions were key factors in determining the deterioration rate of the element. Using these factors it may then be possible to develop a model that could readily predict the deterioration rate of a given concrete structure.

4 DEVELOPMENT OF FACTOR METHOD USING A SPREADSHEET

The Factor Method has been discussed in previous sections. The processes involved in determining the estimated service life, L, of a structure are detailed. In earlier models factors were calculated based on deterministic rules, empirical methods or by subjective judgement. Later models attempted to use probabilistic approaches to determine the relevant factors. However, no ‘actual’ data, collated over the past decades, were ever used. The development of the Factor Method using a spreadsheet is based on this approach. The relevant factors used in the adapted Factor Method are calculated by simple probabilistic methods using data from the database.

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In the spreadsheet program, there are two forms. One is used to calculate the factors whenever the overall structure is being considered. The second form is used whenever individual members of a structure are analysed. Details of their development are given in the following sections.

4.1 Deterioration Rate of Overall Structure

Deterioration rate of Overall Structure is evaluated using Form 1. Table 1 of Form 1 displays the age at which a structure is most likely to deteriorate to a specific stage in its life cycle. These stages can either be defect free (1 – 3), cracking (4 – 6), spalling (7 – 9) or service failure (10 – 12). The values listed in this table are calculated from all the available data contained in the database. These will be used as the reference service life, L_{ref}, as mentioned in the Factor Method. To determine the expected service life, L, of a given structure two factors are first calculated. These are factors F_1 and F_2. Factor F_1 is based on the structure in question, as each structural type deteriorates at a different rate. This factor is calculated as follows:

- First, the database is queried so that only data related to the specific structure is used in the calculation.
- Next, the selected data is filtered into four categories depending on which stage of deterioration they relate to.
- The average and standard deviation of each category is calculated.
- The averages are then divided by the relevant values of L_{ref}, (Appendix A: Form1, Table 1).
- The resulting factors are averaged to provide an overall factor, F_1.

Factor F_2 is calculated in a similar way. The only difference is that the data from the inspection records is filtered depending on both structural type and exposure condition.

The final stage in the process is calculating the expected service life, L. This is done by multiplying each average in Table 1 of Form 1 by both factors F_1 and F_2. The resulting values are displayed in Table 2 of this form.

The overall process involved in determining the expected service life of individual members is similar to that previously mentioned (See Form 2). The major difference is that there are now three factors to be calculated. Factor F_1 is based on the structural type, F_2 is based on the member type and F_3 is based on the exposure condition. As before, the reference service life for each phase is multiplied by the appropriate values of F_1 – F_3 to provide the expected service life.

5 DISCUSSION OF THE RESULTS

The adaptation of the Factor Method using a spreadsheet offers a number of benefits to the user. The advantages of using a spreadsheet to develop this model can be listed as follows:

- It is user-friendly. Someone with limited knowledge in this field could competently use this approach. Other models of the Factor Method have proved to be quite difficult to use because they are often based on complex mathematical equations and distributions.
- Once the appropriate data has been entered the relevant information is displayed immediately. This avoids the need to search the database.

Other advantages in using this approach are apparent:

- There is a substantial amount of data available to provide reasonably accurate results.
- As more data is made available, the likelihood of obtaining a more accurate and consistent set of results increases. Also, with the availability of more data, more factors, such as those used to describe operating conditions, may be calculated. This would increase the overall effectiveness of the model.

With the development of a model, there will always be a number of shortcomings reducing its overall effectiveness. These include:

- Although there is a large amount of data that can be extracted from the inspection records, in some cases the amount of information available to be used is limited for certain types of structures.
- The data needs to be analysed further to remove records where unusual events occurred.
- In some cases, a data set containing relatively few values was used to determine a factor. Such factor would be sensitive to ambiguous data.
- For each stage in the deterioration process a factor was calculated. These four values were then averaged to provide an overall value for the factor. This process dilutes the effectiveness of the factor. This was due to insufficient data being available to calculate individual factors for each stage of the life cycle. The above

method provides an overall value to be used in this case. Whenever more data is made available, then this approach will be reviewed.

6 CONCLUSIONS

This paper highlights the need to model the deterioration process of concrete structures. The age and exposure conditions of concrete structures are important as part of the modelling process. They can be used to provide a classification of the deterioration of a structural element along with the associated urgency of maintenance required.

Following the development of the Factor Method, many researchers have considered different approaches to incorporate it into design and maintenance programmes. Previous models that were developed proved to be complex; it is believed that this problem has been overcome to an extent by using a spreadsheet.

On the negative side, the classification is only as accurate and suitable as the data provided by the previous records. Although it may not be the most accurate model currently available, it does provide realistic results. As more records are made available then the accuracy and relevance of the information for the structure and / or component will become more prevalent.

Overall, the model developed provides a useful tool to the engineer when an inspection is to be carried out. The information shows what to expect before the inspection begins. It will also help the engineer in determining the most appropriate maintenance and repair techniques to use.

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Form 1: Deterioration Rate of Overall Structure

From analysis of the database, the age at which a structure is most likely to deteriorate to a specific phase is given below.

Phase	Age (Years)	s.d.
Defect Free	*25.5*	*18.6*
Cracking	*31.0*	*17.5*
Spalling	*37.5*	*18.0*
Failure	*39.9*	*21.2*

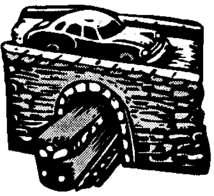
Table 1 Values of L_{ref} for each Phase

Note: The age will be used as the Reference Service Life, L_{ref}

Please Complete the Following Sections

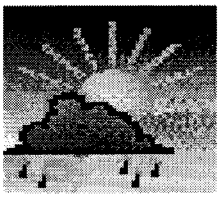
Section 1: Structure Type

	Structure
1:	*Footbridge*
2:	*Overbridge*
3:	*Underbridge*
4:	*Others*



Section 2: Exposure Condition

	Exposure
1:	*Mild*
2:	*Moderate*
3:	*Severe*



1

Enter Corresponding Number in Box Provided.

3

Output

Footbridge subject to severe exposure.

The following output is likely:

Calculated Factors

Factor	Value
F_1	*1.01*
F_2	*1.32*

Note: Expected Service Life, L, is calculated as follows:

$$L = L_{ref} \times F_1 \times F_2$$

Expected Service Life, L

Phase	Age (Years)
Defect Free	*34.0*
Cracking	*41.3*
Spalling	*50.0*
Service Failure	*53.2*

Table 2 Expected Time to each Phase.

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Form 2: Deterioration Rate of Individual Members

From analysis of the database, the age at which a member is most likely to deteriorate to a specific phase is given below.

Phase	Age (Years)	s.d.
Defect Free	*25.5*	*18.6*
Cracking	*31.0*	*17.5*
Spalling	*37.5*	*18.0*
Failure	*39.9*	*21.2*

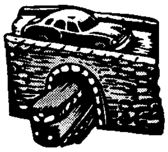
Table 1 Values of Lref for each Phase

Note: The age will be used as the Reference Service Life, L_{ref}

Please Complete the Following Sections

Section 1: Structure Type

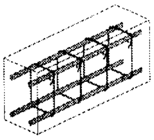
	Structure
1:	*Footbridge*
2:	*Overbridge*
3:	*Underbridge*
4:	*Others*



2

Section 2: Member Type

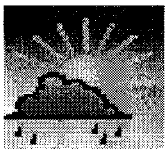
	Member
1:	*Flexural*
2:	*Compression*
3:	*Others*



2

Section 2: Exposure Condition

	Exposure
1:	*Mild*
2:	*Moderate*
3:	*Severe*



3

Enter Corresponding Number in Box Provided.

Output

Compression Members from an Overbridge subject to Severe Exposure.

The following output is likely:

Calculated Factors

Factor	Value
F_1	*0.87*
F_2	*0.80*
F_3	*No Data*

Note: Expected Service Life, L, is calculated as follows:

$$L = L_{ref} \times F_1 \times F_2$$

Expected Service Life, L

Phase	Age (Years)
Defect Free	*17.7*
Cracking	*21.6*
Spalling	*26.1*
Service Failure	*27.8*

Table 2 Expected Time to each Phase

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