A review of the data held on 3,437 masonry arch bridges in Northern Ireland

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ABSTRACT: Queens University of Belfast and the Department for Infrastructure (DfI), who are the local road authority in Northern Ireland, have undertaken a joint project to develop a new bridge management system to cover the inspection and maintenance of DfI bridges and associated structures. An initial review of the asset data held by DfI, including bridge properties and current and legacy inspection data has been undertaken for the entire network. This paper primarily focuses on 3,437 masonry arch bridges which make up nearly 53% of the total bridge stock in NI. It presents data which has been classified into groups in order to explore trends in condition rating of various structural component types. A discussion on the most prevalent defects and the overall condition of the bridge stock are also presented. This forms the basis for identifying the critical defects and structural components in order to target maintenance spend in a timely and effective manner in the future. The fundamental aspect of this research is the input and use of Structural Health Monitoring (SHM) data to inform a decision-making framework. The greatest limitation of SHM data is the lack of historical data. In order to make bridge inspections more efficient, economical and effective at a local and global level there is a need to establish baseline data sets. The analysis of historical data has led to the identification of key performance indicators for monitoring through SHM to allow for live automatic updates on bridge condition.

KEY WORDS: Bridge Management System; Masonry Arch; Inspection Data; Structural Health Monitoring.

1 INTRODUCTION

1.1 Background

The Department for Infrastructure (DfI) is a Northern Ireland (NI) government department which encompasses a range of strategic functions including acting as the local roads authority. It has undergone organisational and operational changes resulting in various variants of its name and branding. For the purposes of this paper references to the Department of Regional Development (DRD), Roads Service (RS) and Transport NI (TNI) all refer to previous incarnations of DfI.

Increasing traffic and climate change has compromised resilience of the network. Events such as the 2017 floods, which resulted in the loss of three bridges in a single night have confirmed the current reactive method of bridge management is no longer fit for purpose.

DfI owns and maintains over 6,978 bridges varying in construction type, age, span and function. These bridges are subject to regular inspections as per the requirements set out in BD63/17, Volume 3 Highway Structures: Inspection and maintenance document with the Design Manual for Roads and Bridges (DMRB). BD63/17 sets out the requirements for various types of inspection including Safety, General (GI), and Principal (PI), Special Inspections and Inspections for assessment as well as the frequency of those inspections.

1.2 Inspection records storage development

DfI have recorded bridge inspections since the early 1970's, originally in paper format. These records are sparse and incomplete and held in filing cabinets located at numerous buildings across NI. These have not been digitised and are often limited in the detail they provide with little information on specific defects and few associated photographs. This provided little opportunity for direct comparisons of various inspections.

In 1999, RS developed a Microsoft Access Database titled the Road Service Bridge Management System (RSBMS) to log all the data relating to bridge inspections. This included the bridge number, positional coordinates, construction type and span as well as the inspection data. Crucially this database allowed for photographs to be attached to a record and was reasonably user friendly and simple to update. Separate databases where held for the four geographic sub areas and access was controlled by permissions and log in details. Inspections where still undertaken in paper format and then manually uploaded onto the database on return to the office.

In 2017, DfI undertook a project to replace RSBMS with a more advanced online based system. This project initially mirrored the functionality and data storing capabilities of the RSBMS but moved to include the ability to remotely input inspections in the field as well as some other features.

Ruggedized laptops with an offline version of the database were introduced which allowed for inspection details to be logged on site as the inspection is being undertaken. On return to the office the inspector would connect the laptop to the network and upload the inspections to the online database. This allowed for the phasing out of paper inspections and streamline the data logging process. This database was called the TNI Structures Management System (SMSR). Multiple defect photos can now be uploaded and linked to specific inspections. Although an improvement, this is a laborious task which has resulted in low uptake by many inspectors.

Another fundamental change was the rating systems adopted for the bridge inspections. In the paper format and later the RSBMS system, bridge elements were given condition ratings from 1 to 4. Then the bridge inspector would make a judgment call as to the overall bridge rating again between 1 and 4. 1 indicated a structure with no significant defects, 2 displayed minor defects of a non-urgent nature, 3 had defects of a moderate nature and 4 which indicated that a structure had severe defects which required immediate corrective action to be taken.

These overall condition ratings where then used to allocate budget and spend based on priority lists. This served its purpose for several years, but it was clear that this broad-brush approach would not readily identify which structures on the same overall condition rating needed allocated funds over others. To try and address this it was decided to move towards using a Bridge Condition Indicators (BCI) scoring mechanism [1]. BCI gives a measure of the condition of a bridge and its elements. This can be used to look at the change in these conditions over time in subsequent inspections. By using BCI scores, all bridges would be assigned an overall BCI score out of 100. Once the inspections were completed a report could be run to list all the bridges based on this score and then rank them in order. The lowest scores indicating the worst assets and therefore where the budgets should be spent.

Although this provided a greater level of detail and functionality there was several issues that affected its overall functionality. The paper details the initial analysis undertaken to inform on the development of a replacement SMSR which would address these issues as well as provide enhanced functionality.

1.3 Research Test Sites

The findings are based on the analysis of historic datasets held by DFI in relation to bridge inspections. At the outset an extensive data-cleansing exercise was undertaken to identify any anomalies in the data. As detailed by Stevens et al [2] the historic inspections dating back to 2000 were converted into legacy BCI scores so that approximately 20 years of records can be considered and longer-term trends in bridge stock could be inferred.

A new database is being developed which will utilise these converted inspections alongside current inspections in order to build up a better picture of the state of the bridge stock. As structures age and deteriorate the demands on finite budgets becomes greater [3]. It is necessary when prioritising budgetary spend on a deteriorating bridge stock to find an optimal long-term maintenance strategy [4]. Limited annual budgets for maintenance and capital spends within DfI necessitates that bridge managers need to select maintenance tasks based on a range of factors, but these factors are not necessarily always aligned with an optimal maintenance strategy. Originally bridges where assigned a state between 1 and 4, with 4 being prioritised for work. However, each year the budget available would typically not cover the repair or replacement work for all these structures so within this list professional judgement came into play on deciding which bridge to consider first. Other factors affecting the choice of schemes included emergency reactive works. An example being when a bridge has been damaged unexpectedly/suddenly by a car crashing into a parapet and it needs repaired immediately. This could not have be foreseen in the regular inspection cycles or deterioration models. Other factors affecting schemes progressing can be related to the complexity of the work involved, level of design required or the need for various permits or landowner agreements to be in place before work can commence.

A goal of this research is to identify trends in the existing bridge condition data which can act as key performance indicators (KPIs) for predicting the future condition across the network and enable strategic decision making for future investment. Ultimately this will inform of the identification of properties suitable for Structural Health Monitoring (SHM) systems which incorporate real time monitoring into the new database and provide early warning notifications that intervention work needs undertaken.

1.4 Datasets

DfI have collected a wide range of data on over 6,978 bridges, over 20 years. Of these bridges, 3,501 are classified as Masonry Arch structures which represents 53% of the total bridge stock, see Table 1.

Table 1. Distribution of DfI Bridge types in NI

Span Construction	Percentage
Masonry Arch	53.0
Reinforced Concrete Pipe	12.4
Reinforced Concrete Slab	10.8
Concrete Box Culvert	6.8
Concrete Beam (various)	5.7
Arch Other (Brick, Concrete, Jack)	3.4
Steel (Various)	2.8
Corrugated Steel Pipe	2.7
Composite Concrete & Steel	1.2
Miscellaneous	1.4

The current database, SMSR, stores all the current bridge inspection data following the BCI rating system [1], from 2016 to current, as well as storing the legacy condition rating data of inspections prior to 2016.

This paper presents an analysis of this data, focussing on the data held for 3,437 of the 3,501 Masonry Arch (MA) bridges. Due to missing records for the other 64 MA bridges, these bridges have been excluded from the analysis in this paper.

Of the 3,437 MA bridges, over 94% carry 'roads over rivers' an additional 2% are bridges over watercourses (Rivers, Culverts and Canals), over 95% are of single span and 99% are over 100 years old.

Looking at the overall spread of cumulative spans for the bridges nearly half of the bridges span between 1 and 3 meters, Figure 1.

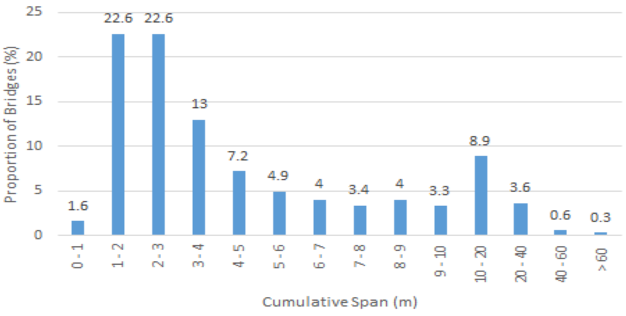

Figure 1. Distribution of Cumulative Spans for all 3,501 MA bridges in NI.

2 METHODOLOGY

2.1 *Dataset Cleansing*

The datasets for these bridge records have been amalgamated from various historic databases and paper records covering a 20-year period. This inevitably led to a proportion of the data being erroneously transferred across or logged incorrectly initially. An exercise was undertaken to clarify and correct these errors prior to the analysis. Examples of such errors include; the geographical coordinates of certain bridges placing them in the wrong location entirely, number of spans, lengths of spans being a factor of 10 out, and missing data.

A significant amount of time was spent on identifying missing data in the inspections. This included null returns for the component, defect, and extent and severity classification within individual inspections. In order to identify these missing pieces, all the data held on that specific bridge number was interrogated and where patterns in adjacent inspections to the missing data was evident, a judgement call could be made as to the value.

2.2 *Trends in occurrence of Component Types*

An analysis of the 17 years of legacy data relating to MA bridges between 2000 and 2017 was undertaken to understand factors which influence condition.

In this dataset a bridge component was a distinct part of the structure as listed in Table 2. Each time a defect is logged it is associated with a particular component.

Looking initially at the frequency with which a component was being logged it was shown that the bridge parapets were the most prevalent component, see Table 2.

Table 2. Distribution of defects for all MA bridges and Overall Priority 4 (OP4) MA bridges (2 decimal places)

Component	All MA Defects (%)	OP4 MA Defects (%)
Parapet	24.71	22.52
Deck Soffit	19.39	21.47
Wingwall	19.3	16.32
Spandrel/ Headwall	14.22	13.53
Abutment	9.4	13.42
Invert	3.81	4.32
Cutwater	3.15	2.76
Arch Ring	2.6	2.03
Pier Face/ Column	2.03	2.45
Apron	0.87	0.5
Surface	0.39	0.59
Parapet Upstand	0.08	0.07
Abutment Slope	0.03	0.03
Movement Joint	0	0

Focussing on the component frequency for bridges given an overall priority of 4 (OP4), it is shown that the trend remained predominantly the same with Parapets remaining the most prevalent. The relative percentages have changed with marginal increases in the deck soffit relative to the wingwalls and abutments percentage increasing, see Table 2.

Parapets are one of the most visible parts of the structure and tend to be more exposed to the elements and the associated deteriorative effects. These bridges are predominantly single span over rivers and over 70% are located on C or U-Class roads on the rural network. All non-motorway roads in NI are designated one of 4 categories, A, B, C and U in order of significance to the network. C and U class roads are typically minor roads within towns and most of the rural roads in the countryside. These roads often have sub-standard widths which increases the effects of spray from passing traffic as well as the potential for collision/ impact damage from agricultural and other traffic movements. Grass verges and hedges encourage damaging vegetation growth.

When defects begin to appear more frequently on the abutments and in turn the deck soffit, this is when the overall priority of the bridge increases and work is required. Abutments support the deck soffit, so it follows that an increase in defects in one is likely to lead to increased defects in the other.

2.3 *Trends in occurrence of Defect Types*

Analysis of the composition of defects logged for all the MA bridges demonstrates vegetation is the most prevalent in the inspection records, Figure 2. This is perhaps not surprising, due to the favourable conditions these bridges over rivers provide to plant growth and the support and shelter the structures themselves provide. The next most prevalent are pointing missing and then cracks. Again, this is not surprising as these defects generally are related during inspections as they follow on from the effects of vegetation damage by invasive root systems.

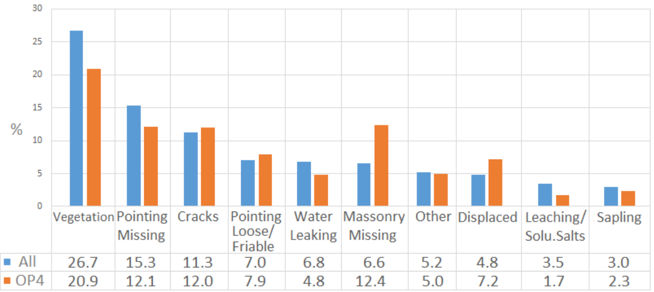

Figure 2. Comparison between defect prevalence for all MA bridges and OP4 MA bridges.

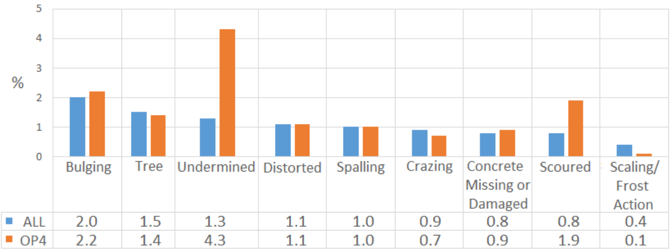

Figure 3. Comparison between defect prevalence for all MA bridges and OP4 MA bridges, with adjusted Y-axis for clarity.

The data for the OP4 bridges follows the distribution of defects in a similar way, however with a few notable exceptions. As bridges reach a poorer condition the proportion of missing masonry has doubled, see Figure 2. The proportion of undermining and scouring has more than doubled, see Figure 3. This demonstrates that the effect of these defects has a greater influence on the overall priority than the vegetation and pointing missing defects alone.

2.4 *Linking Component and Defect types*

When the defects are considered for each component it is shown that vegetation is present in most components followed by pointing missing and cracks, see Figure 4 and Figure 5.

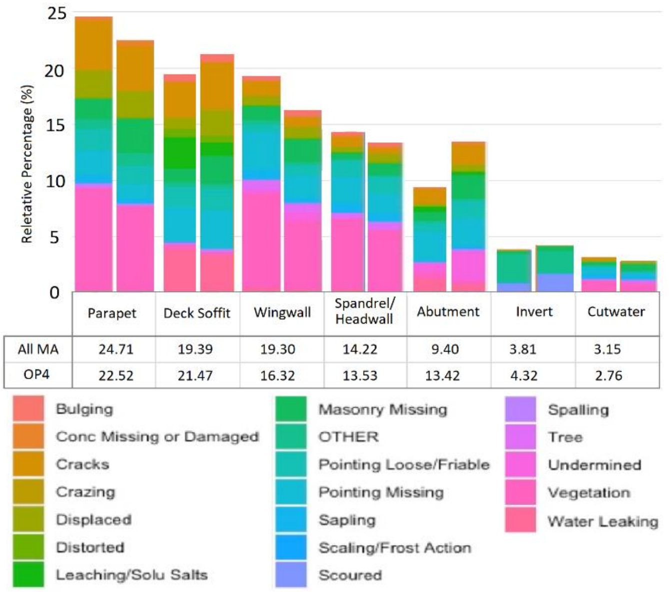

Figure 4. Comparison of Component defect breakdown for all MA bridges and OP4 MA bridges.

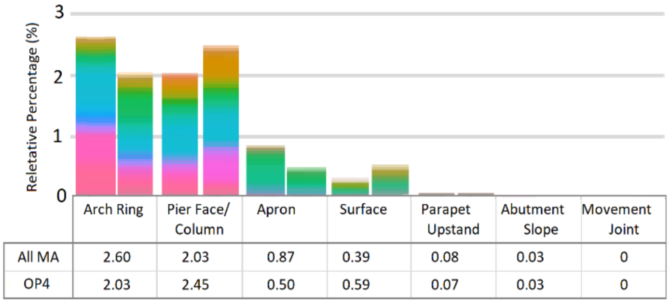

Figure 5. Comparison of Component defect breakdown for all MA bridges and OP4 MA bridges continued (Legend as per Figure 4).

It is interesting to note that for the worst conditioned bridges (OP4) that the increase in abutment and deck soffit defects coincides with a greater proportion of masonry missing and cracking defects respectively in each. Abutment, undermining defects proportion, has increased significantly along with scour to the Invert. This provides validation to the notion of critical elements and defects, for these structures. As such it would be important to understand the hydraulic properties of these sites in order to determine the impact they have on the structural behaviour.

3 ANOVA ANALYSIS

Analysis of Variance (ANOVA) was introduced as a way of examining the impact of both bridge and non-bridge factors on the deterioration of bridges by Huang [5]. In order to conduct this analysis, bridges that have no history of maintenance and have a biennial inspection were used. No history of maintenance describes the situation where an improvement in the bridge condition, for example from condition state 3 to condition state 1, are removed as this improvement could not have been possible without intervention taking place. In order to conduct this test, each state is taken in turn and the condition state reached next was determined. The ANOVA would test the null hypothesis that for bridges in a certain condition state, the mean values of the next condition state are equal among the categories of the factor being investigated. The alternative hypothesis states that the mean values are not equal. If the test is significant (i.e. p-value less than 0.05) then there is sufficient evidence to reject the null hypothesis in favour of the alternative. This means that the factor has a significant impact on the deterioration at that stage. (Only the results of the ANOVA are presented in this paper).

Firstly, the influence of the number of spans was considered. This analysis indicates whether a bridge that is single or multi span, has an impact on the initial stages of deterioration when moving from State 1 to State 2, but this declined as the structures condition worsened, see Table 3.

Table 3. ANOVA analysis summary

Feature	State	P Value
Single Span Versus Multi-Span	1	0.0114
	2	0.0623
	3	0.1060
Road Over River Versus Not Over River	1	0.97700
	2	0.00317
	3	0.66700
Road Over Water Versus Not Over Water	1	0.05490
	2	0.00139
	3	0.51200
Deck Widths	1	0.6830
	2	0.0121
	3	0.0379

Secondly the effect of the bridges function and whether it was a ‘road over river’ or ‘road not over a river’, was tested. No significant impact on the early stages of deterioration was demonstrated, although when changing from state 2 it did indicate a significant effect, see Table 3.

Whether it was ‘road over water’ or ‘road not over water’ also indicated a marginal impact on earlier stages of deterioration. The test was close to significant for state 1 and is significant for state 2, see Table 3. The p-value is not possible to determine at state 4 as there is no record of a bridge that is not over water remaining in this state, so therefore no comparison can be made.

Looking at deck width and its effect, the analysis indicates that the deck width does have a significant impact on the later stages of deterioration on state 2 and 3. It is insignificant in the early stage of deterioration in state 1, see Table 3.

In summary, these results show what factors have an impact on the deterioration of MA bridges. Using the results of this analysis will lead to a more informed decision when choosing bridges to monitor. In order to narrow the selection further it is important to understand the general condition of bridges across the network as detailed in the following section

4 OVERALL BRIDGE STOCK CONDITION

Understanding the general condition of the NI bridge stock is critical when establishing future monitoring and assessment programs. Currently (as of 29th May 2020) BCI Average scores predominantly lies between 80 to 90 followed closely by those between 65 and 80, see Figure 6. There are several inspections showing BCI average values less than 40 and some at 0 which will need explored further to determine if these are erroneous values as it is unlikely a bridge that is still functioning after an inspection would score this low. Some of these '0's are bridges on the Strategic Road Network (SRN) which are inspected separately under a management contract which presently does not record BCI values and so are logged as 0. However, if you discount these outliers the broader picture of the bridge stock is evident.

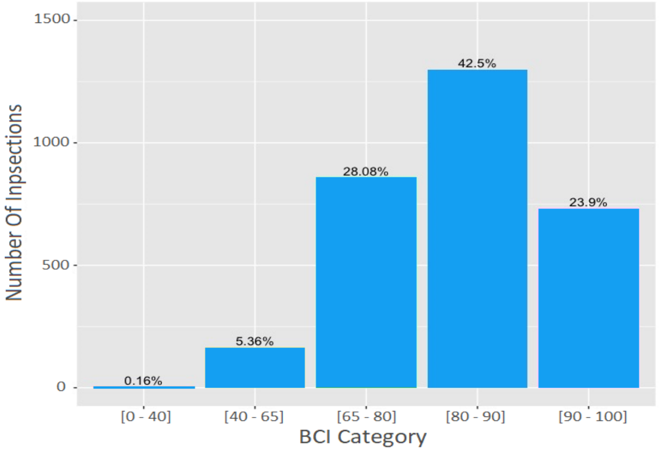

Figure 6. Grouped BCI Average scores for all current bridge inspections in NI

The current BCI Average inspection score for all bridge types in NI in Figure 7 highlights distinct bands in the data. The total bridge stock is separated into four different geographical areas, Eastern (ED), Northern (ND), Southern (SD) and Western (WD) see Figure 8.

Analysis of BCI scores for the 4 divisional areas provides a snapshot into the overall bridge stock condition in those geographical areas. It is beyond the scope of this paper to identify potential correlation between bridge condition data and environmental geographic condition such as ground condition or rainfall level, but this will be considered in future research. However, given the clear divisional divide the potential of engineering bias is considered an impacting factor. Although bridge inspectors are trained in the typical defects, judging extent and severity, ultimately what one person sees could be subtlety different to another. Perhaps one division is more risk averse and rates a defect higher than in another, due to local knowledge or experience. Currently within DfI line management undertakes a 5% check on the inspections carried out by the bridge inspectors annually which should help with consistency, but this is still within a divisional area. Figure 7 indicates bridges in WD are in a poorer overall state than in the other areas. ND and SD appear to be broadly similar with ED fairing a little worse overall but still better than WD.

Given this observation, allocating funding based solely on the BCI output would perhaps not be fully appropriate. Other factors need to come into play in order to maximise the effectiveness of the maintenance programme. However, a clearer understanding of the overall condition of the bridge stock combined with the KPIs derived from sections 2 and 3 will inform the development of predictive maintenance models and identification of suitable sites for SHM.

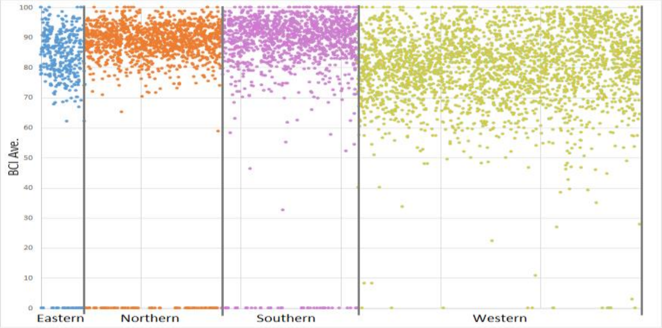

Figure 7. BCI Average scores for all current bridge inspections in NI

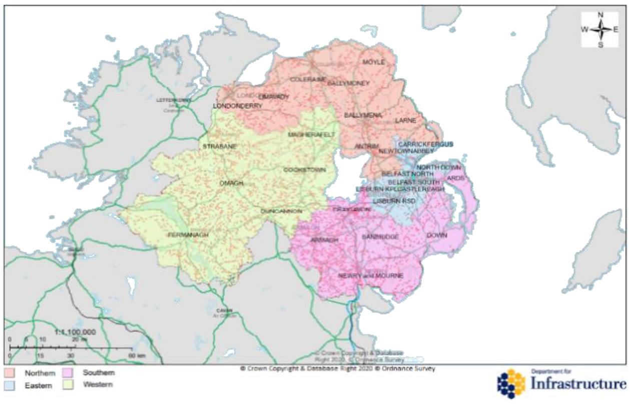

Figure 8. Geographical boundaries in NI

4.1 *Structural Health Monitoring*

SHM provides an invaluable contribution to ensuring the safety of transport infrastructure assets but the deployment of such systems can often be cost prohibitive when using the current (short term) funding models. To maximise the potential of such systems there is a need to understand the network wide performance of bridges and identify suitable clustering techniques to monitor behaviour which is representative of a group of structures. The cost of repairing damage in large structures increases rapidly as the damage approaches criticality. However, without monitoring, the prediction of deterioration and hence early intervention is extremely difficult. Further analysis of the full BCI history will be undertaken to establish the optimum intervention time and identify the most cost effective means of integrating SHM. As transport networks begin to operate closer to capacity the increased volume of live loading poses a higher risk to human life during visual inspections (VI). VI's are essential for the ongoing collection of data across all transport networks, but as resources become limited and risks increase, the quality of data becomes compromised. The analysis undertaking in this paper aims to ensure targeted SHM systems collect not just Big Data but useful data which can be easily sifted to provide meaningful insights.

5 CONCLUSIONS

Analysis of the general bridge type and overall condition across the network was undertaken to establish which structures represent the biggest weakness in the road network. MA bridges were selected as the bridge type to be assessed based on the proportion of MA, uncertainty around material and construction properties, and their average age. This paper has shown the initial data analysis for MA bridges, the prevalent defective components and defect types and how they interact and change with deteriorating overall priority. It has shown that the most prevalent structures are MA bridges spanning between 1-3m over water with a single span. The current data establishes vegetation as the most prevalent defect noted and parapets the most reported component over all the bridge conditions. When considering only the OP4 MA bridges, scouring and undermining proved to be significant factors. These bridges tend to be older structures with typically unknown foundation depths or conditions, this poses a significant management problem for DfI. The ANOVA identified function and construction type as significant factors in deterioration at various stages in a bridges lifecycle.

When abutment/foundations are undermined this induces stresses on the structure, encouraging cracks and masonry to loosen and fall out, hence why an increase in masonry missing is seen, this in turn allows for the roots of vegetation to take hold. An example of this is when a sapling or ivy initially starts to grow in some loose or missing pointing, after a few years this turns into a tree or large root stocks with thick roots which exacerbate the problems and increase the severity.

An early warning of scouring would be beneficial to intervene before these subsequent defects present themselves at a significant level that can cause severe damage. The most cost-efficient intervention point needs to be determined for these bridges and the decision made whether it is worthwhile proactively monitoring and repairing susceptible structures before they reach a point needing more extensive repairs or a more reactive approach.

The paper has also looked at the current overall bridge stock condition for NI and identified trends in regional differences. It has also postulated whether these are geographical features or human factors before highlighting areas for future research and consideration.

6 FUTURE RESEARCH

Another aspect of this research is the installation of SHM on several representative test sites for the network. A MA bridge, a reinforced concrete bridge and a half joint bridge are proposed.

Based on the criteria set out in this paper a MA bridge with a history of scouring/ undermining was selected. The site chosen is downstream from several other bridges with a history of scour/ undermining and a DfI Rivers gauging station which will provide up to date river data. Scour monitoring equipment will be utilised along with river data in order to develop a better understanding of scour patterns on these structures.

Additional analysis of the maintenance spend has highlighted half joint bridges as a potential bridge type for SHM. Although these represent a small proportion of the total bridge stock, they represent a significant maintenance and inspection problem for DfI. Half-Joint bridges are susceptible to deterioration around the joint which can be hard to inspect and can require special attention [6]. In Northern Ireland they are typically located in areas over railways and motorways and as such are difficult and expensive to inspect on a regular basis. Often these bridges require specialised access arrangements including temporary traffic management while obscured elements are difficult to inspect.

The final site will monitor a listed reinforced concrete bridge in Belfast. This bridge has a range of structural defects which can be monitored and reviewed which are applicable to many other concrete structures in the network.

7 ACKNOWLEDGMENTS

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