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International practice using NDE for the inspection of concrete and masonry arch bridges

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Abstract. This paper reviews international practice in the inspection of bridges, and looks at the NDE of post-tensioned concrete and of masonry arch bridges. Key continental European practice is compared with the UK and the USA. Given the wide range of languages and cultural backgrounds, there is remarkable similarity between procedures for bridge inspection. However, there is no one standard database used worldwide, which might give the opportunity to spot international trends in bridge type behaviour.

Non-destructive evaluation is growing into an established tool for the special investigation of concrete and masonry arch bridges. These trends are driven by Advisory notes from the Highways Agency, London UK and by the American Concrete Institute. In this paper, many key problem areas of concrete and masonry arch bridges have been identified and appropriate NDT techniques discussed. Some of the techniques used on concrete are capable of being transferred to new masonry, but not necessarily to old stone masonry arch bridges, with their special features such as large stone block size and the use of lime mortar. For stone masonry arch bridges, it is been shown that the most useful techniques are low frequency sonic echo, sonic transmission and sonic tomography. Ground penetrating radar (GPR) also has a role in the evaluation of masonry arch bridges. In the case of concrete bridges, the techniques of ultrasonic tomography, impact echo, impulse response and Ground penetrating radar (GPR) are particularly relevant. GPR has only a limited role in the investigation of post-tensioned concrete bridges, where the tendon ducts are metallic. Examples of NDE practice are given in the paper.

1. Introduction

Older long span bridges in the USA tend to be steel – especially on the railroads. Long span modern highway bridges in the USA are often post-tensioned concrete. Compared to the USA, there are relatively fewer very long span bridges in the EU. On the other hand, there are many historic masonry arch bridges in daily use on both the road and rail networks of the EU [19]. Since most masonry arch bridges tend to be greater than 100 years old, many were destroyed within the continental European countries involved in the civil wars in Europe during the middle of the 20th century.

These masonry arch bridges form an important part of the road and railway infrastructure in the EU. They are a critical part of the transportation system in the UK, since they comprise over 40 per cent of the bridge stock in current use. In total, there are over 70,000 masonry arch bridges in the UK [15]. The largest single owner of masonry arch spans in the UK is the railway operating company, Network Rail. Masonry arch road bridges were originally designed for horse drawn traffic and although they are carrying loads greatly in excess of those for which they were designed, they are showing little sign of distress.

Masonry arch bridges are so reliable, that they tend to be neglected compared to concrete bridges. However, with the increase in rail interoperability across the enlarged EU, there is increasing attention being paid to the evaluation and maintenance of masonry arch bridges – hence, the increased attention being paid to the NDT of these bridges.

During the reconstruction of Europe after WWII, most of the new bridges were concrete and many were post-tensioned concrete bridges, particularly in the UK, France and Germany. Post-tensioned concrete bridges have been constructed in the UK since 1947. In the case of highways, a major issue has arisen with the grouting of the post-tensioned tendon ducts. If water, chlorides and oxygen infuse into these ducts then the tendon corrodes reducing the strength, ultimately leading to structural collapse. The collapse mechanism is brittle and little or no warning may be given.

Post-tensioned concrete railway bridges are less vulnerable than highway bridges as they are not normally subjected to de-icing salt. None-the-less, railway bridges remain vulnerable [36], albeit the time scale to failure may be longer.

2. Bridge inspection protocols and management databases

The collapse of the I35W Bridge in Minneapolis created a flurry of concern worldwide regarding the inspection standards for bridges. In the State of Minnesota, a review was commissioned from Parsons Brinkerhoff [32] – which largely confirmed that current bridge inspection practices were appropriate. This has also been the reaction in the UK.

Bridge inspection protocols in the USA and the EU are summarised in Table 1 – the EU position is taken from various sources including the EU project "SustainableBridges" [19]. In the EU, there is remarkable similarity between countries and transport modes, given the wide range of cultural backgrounds: different languages; differences in cultures between the UK, continental "Western Europe" and the "former Eastern Europe", plus the difference between railway and highway cultures.

There is no EU institutional pressure to force convergence of inspection regimes, other than duty of care with interoperability. Even where there is pressure – such as Euro Codes for new build – there are National Annexes to protect local design practices. There has been some interest in reliability based approaches to bridge inspection [21], but although research has continued to date – these advanced concepts have not

Table 1
Interpretation of inspection regimes

Country	Transit type	Type of inspection	Time interval	Detail
Finland	Finnish rail	Monitoring	Continuous	Visual
		Annual	1 year	Visual
		General	5–8 years	Basis for next inspection
		Special	If needed 5–15 years	
		Intensified	Min, once per year	In case of serious defect
France	SNCF	Routine	1 year	Visual
			3, 6, 9 years	Detailed as needed
Germany	Rail (DB)		continuously	Visual G.L.
		Survey	6 months	Visual G.L.
		Investigation	3 years	Visual G.L. + simple NDT
		Evaluation	6 years	Touching distance + simple NDT
		Special	When needed	NDT depending on doubts
		Temporary structure	6 years	Touching distance
Poland	Rail (PKP)	Current	3 months	Visual
		Basic	1 year	Visual + simple tests
		Detailed	5 years	Visual + adv tests
		Special	When needed	High tech tests or proof load test
Sweden	Rail (Banverket)	Superficial	1 year	Visual
		Principal	6 years	Mainly visual
		Special	When needed	More adv tests
UK	Highway (Highways agency)	Safety	Weekly or monthly	Cursory
		General	2 years	Visual
		Principal	6 years	Close visual + Tap test?
		Special	6 months +	Cast-iron & repaired structures
	Rail (Network rail)	Routine surveillance	continuously	Duties
		Routine visual	1 year	From G.L.
		Routine detailed	6 years	Touching distance
		Additional	If any needs	As required
USA	Highway	Routine	1 year	NBIS – visual
		General	2–4 years	NBIS – visual + NDT
		Special	One off or continuous	NBIS safety critical

entered day to day practice. The 1990 s ambition of the (UK) Highways Agency (HA), the highway trunk road asset owner, to develop a reliability based system has not been pursued.

In the USA, bridge inspection practice varies from State to State and depends upon the age and state of the bridge concerned. The NBIS gives general guidance on inspection [32]. The general principles are similar to Europe.

There is no worldwide acceptance of a single database for bridge records. Helmerich et al. [24] report on the divergence across continental Europe. Table 2 lists some of the systems in operation. In the UK there are different databases being used by the rail industry, the Highways Agency (HA) and then the non-trunk roads authorities.

3. Special inspections – strategies and NDT tools

Once a bridge has an identified defect, that does not require immediate remediation, it is common to monitor the structure more closely. This is common practice in the airline industry, when the (US) Federal Aviation Authority (FAA) and (UK) Civil Aviation Authority (CAA) will issue directives to operators and manufacturers. The options available to the bridge engineer include: (a) more frequent and focused visual inspections; or (b) condition monitoring using either a low frequency system as often used on suspension bridges and post-tensioned concrete bridges [14], or a higher frequency acoustic emission (AE) system; or (c) a specific targeted one-off NDT inspection. Many bridge engineers prefer the targeted one-off NDT inspection.

There are a number of international initiatives with respect to Special Inspections and guidance on the use of NDT tools. Helmerich et al. [24] detailed the progress on the European Project [19] Sustainable Bridges – this EU initiative will be informative, but not mandatory. ACI Committee 228 [1] details a range of NDT test for concrete members, and is in the process of being updated. The BAM NDT Toolbox [38] is also contained in the EU Sustainable Bridges final report. Probably the most comprehensive NDT guidance is given by the (UK) Highways Agency in BA86/06 [4] – see Fig. 1. This Advice Note is largely mandatory for UK trunk road and motorway bridges and advisory on other bridges.

There remains an ongoing challenge to encourage bridge engineers to gain more confidence in these NDT techniques in the international bridge community.

Table 2
Bridge management databases

Country	Transit type	Highway administration: Bridge management system
Austria	Highway	BAUT
Denmark	Highway	DANBRO
Germany	Highway	SIB-Buawerke
Sweden	Highway	BatMan
Switzerland	Highway	Kuba
UK	Rail	SCMI
	Highway	SMIS – HA roads only
USA	Highway	Pontis

4. Advances in NDT

4.1. Background

The ultimate aim of most Civil Engineering NDT is to achieve the highest quality of visual imaging of the relevant internal features of a structure. Medical ultrasonics and NMR have provided excellent images and so has aircraft ultrasonic imaging of metallic structures. In the Civil Engineering NDT community, concrete has seen more developments than masonry, perhaps because the material is more widely used and there are more problems with aging concrete bridges.

Internatonal leaders in NDT imaging include: BAM, Berlin, Germany [25], Politecnico di Milano, Italy, the University of Edinburgh [20] and Olson Engineering. BAM has focused on issues related to data fusion, particularly with respect to concrete structures – fusing impact echo, shear wave ultrasonics and GPR. In order to achieve credible data fusion precision, robotic readings are needed. Hand operated systems did not give appropriate locational precision [29]. Results on data fusion of masonry structures have not been published. A substantial reference to the BAM NDT Toolbox is available on the internet [38].

Modal analysis and whole structure dynamic testing of masonry arch bridges [3] has proved difficult, but more effective on metallic and concrete bridges than masonry arch structures. Gentile [22] has given an excellent example of such an investigation on a concrete arch bridge; Aktan has reported on metallic and other structures [27].

Japan is a world leader in research and practice of Acoustic Emission (AE), where it has proved increasing successful on concrete beams and bridges [30], but more challenging to interpret on masonry structures [34].

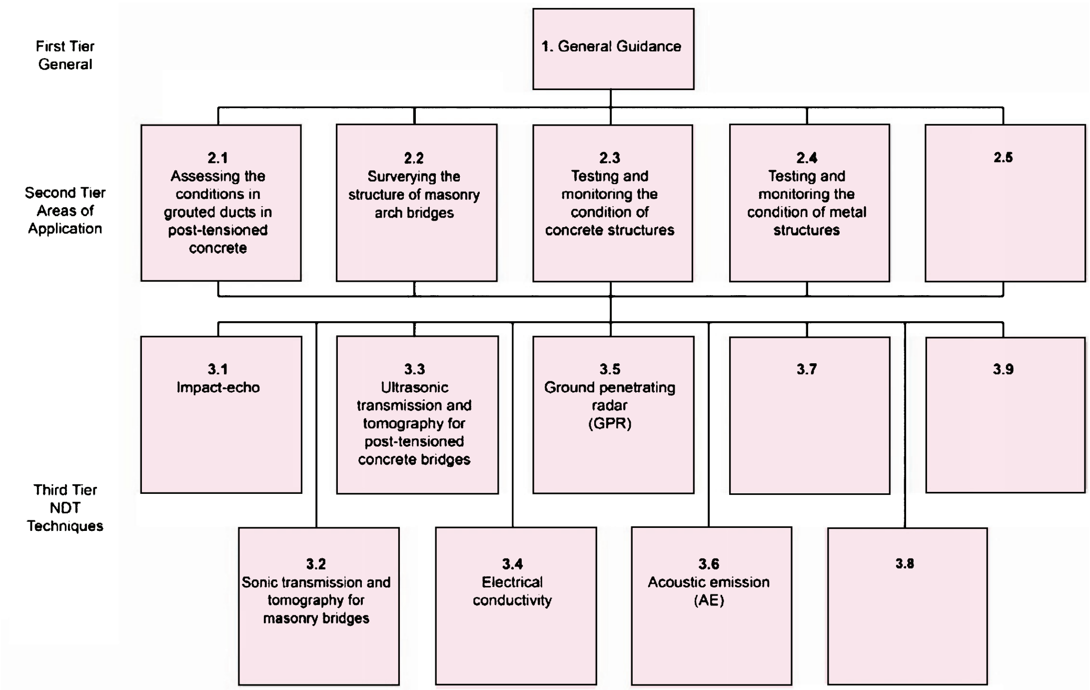

Fig. 1. Highways agency chart of NDT of bridges.

4.2. *Examples of bridge problems appropriate for NDT*

Two examples of international problems in bridge engineering, are:

a. Voiding in post tensioned (P-T) concrete bridge ducts
b. Voiding in masonry arch bridges

4.3. *Ultrasonic and sonic tomography*

Ultrasonic tomography has been used successfully to identify voiding in metallic ducts in post-tensioned concrete bridge beams [26]. The upper diagram in Fig. 2 illustrates the procedure adopted in this work. A hand operated standard ultrasonic system was used to measure time taken by a pulse of ultrasound to pass through the beam under test – 56 kHz ultrasonic transducers were used for both excitation and reception. By measuring the transit time from excitation point to reception point and knowing the transit distance, one can compute the average velocity. The velocity would vary depending upon the density of the concrete. The presence of a void would lead to a long path length and reduced velocity. In order to construct a tomographic image the transmitting transducer is kept at a fixed point and the receiving transducer is moved all around the beam. When the cycle is complete, the transmitting transducer is moved to the next location and the procedure repeated. The data is then iterated using a fuzzy logic tomographic software package which identifies regions or zones of varying velocity. The lower part of Fig. 2 illustrates the ideal coverage of a rectangular beam.

Figure 3 illustrates a beam cast at the site of Stanger Science & Environment to replicate a P-T concrete beam model with included defects shown. Employing the above ultrasonic pulse velocity system and tomographic modelling strategy, the tomographic image of the internal construction of the beam is presented in Fig. 4. Note that the units on Fig. 4 are in kilometres per second. High velocities would represent the steel and very low or zero velocities would represent air voids – or ungrouted P-T ducts.

As ultrasonic transmission transducers (56 kHz) would not penetrate stone masonry, low frequency sonic tomography of masonry arch bridges was developed at the University of Edinburgh [11]. The principle of this technique is identical to that shown in Fig. 2, except that a 12lb instrumented sledge hammer (approximately 200 Hz excitation frequency) replaced the ultrasonic transmitting transducer. The data was displayed on

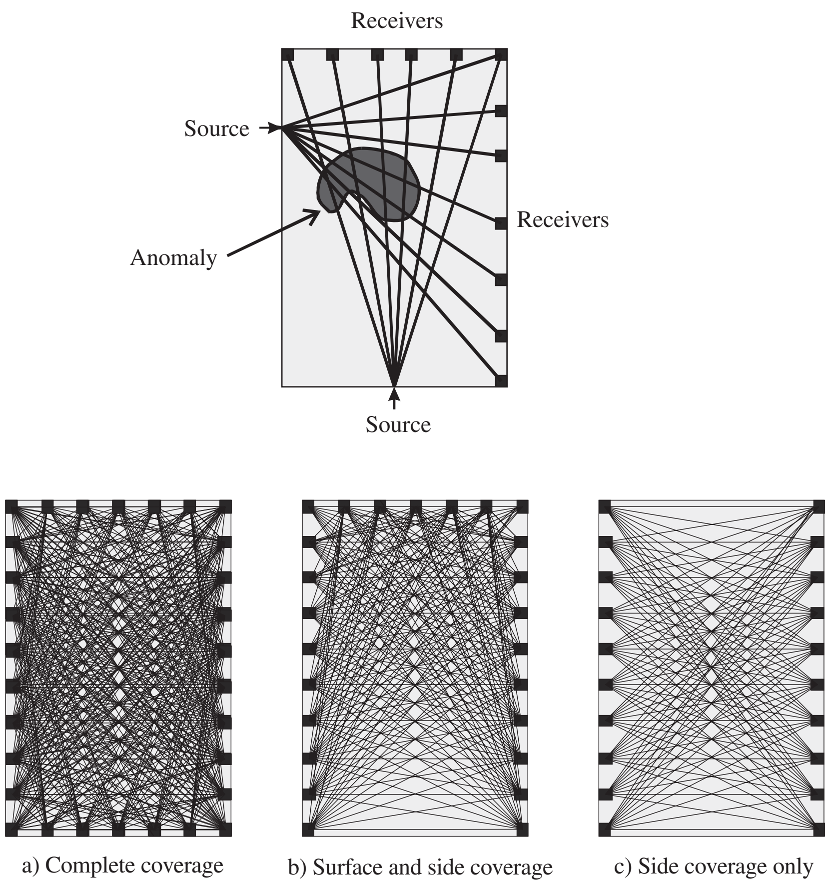

Fig. 2. Ray path coverage for different transducer arrangements.

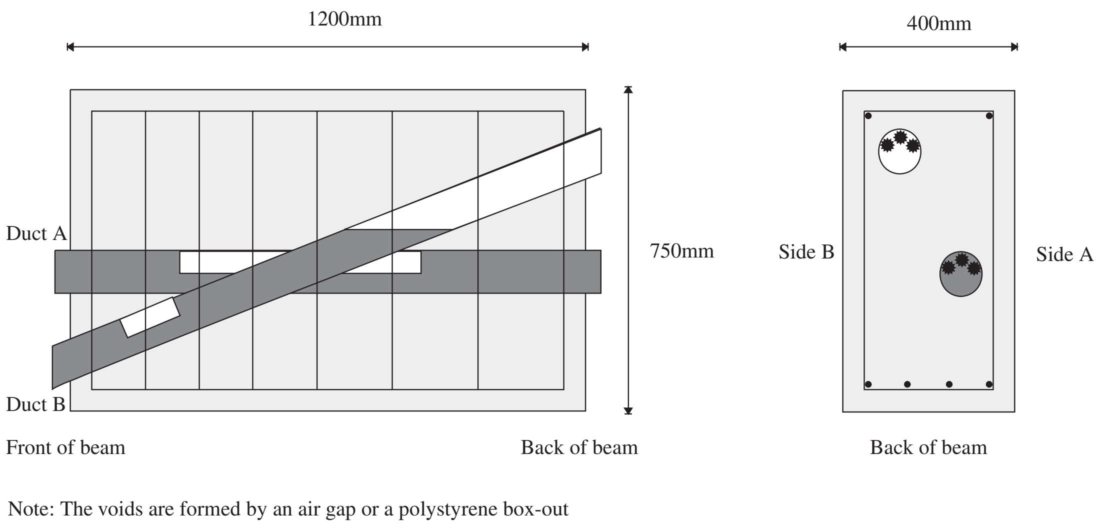

Fig. 3. Stanger Science & Environment P-T concrete beam model with included defects shown.

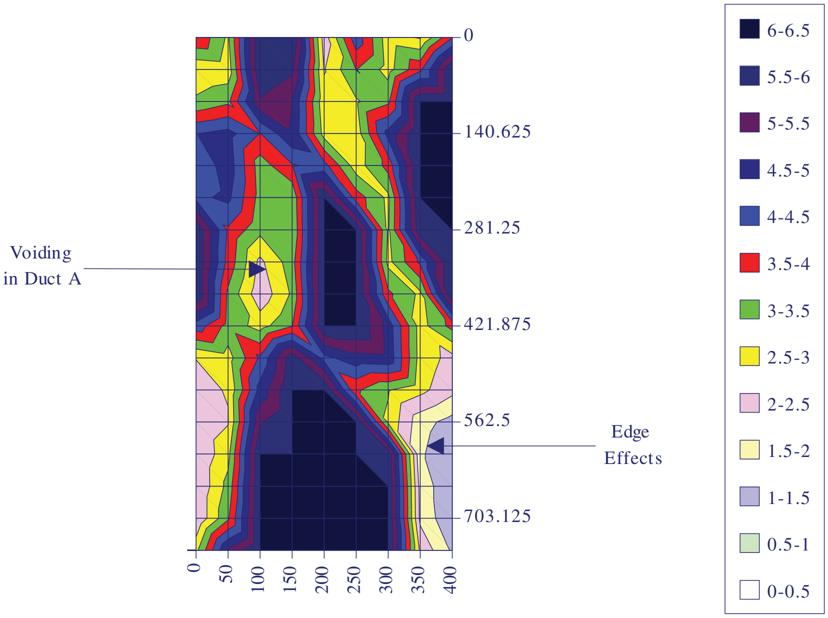

Fig. 4. 2-D tomographic interpretation of the ultrasonic tests on this beam.

a two-channel digital oscilloscope, thus transit times through the bridge could be measured and sonic velocities computed. See Figs 5 and 6, relating to North Middleton Bridge in the Scottish Borders, where A = abutment face, U = upstream wing wall; and D = downstream wing wall.

By using a fuzzy logic tomographic software program, areas of very low velocity can be identified – Fig. 6. These low velocity areas indicate voided masonry and coincide with a cellular construction for reducing the mass on the bridge foundations. This is a key area as Colla [10] showed that many stone masonry arch bridges were deliberately constructed with a hollow cellular structure to minimise the loading on the foundations. Modern structural engineers are often tempted to grout up voids!

Fig. 5. Elevation of North Middleton masonry arch bridge.

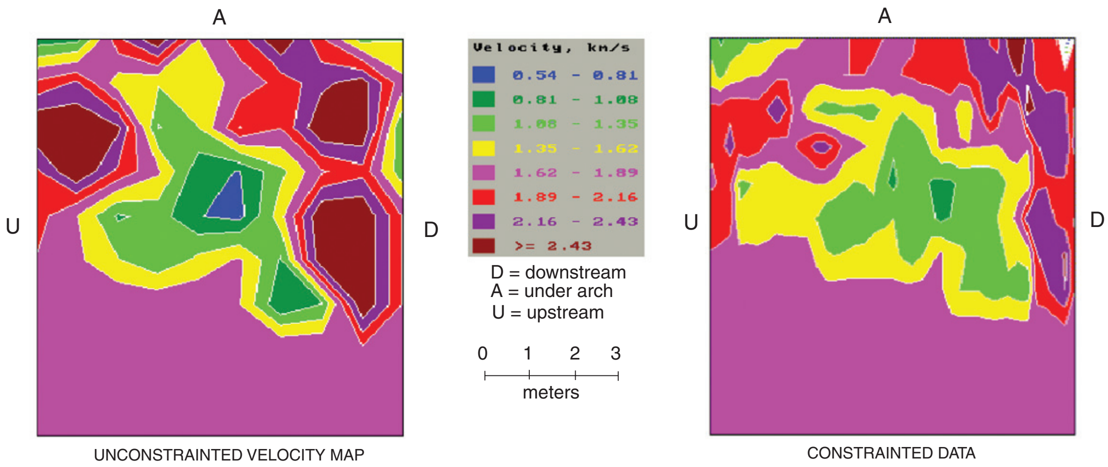

Fig. 6. Sonic tomographic reconstruction of data taken from the abutment of North Middleton bridge.

5. Detecting voids in post tensioning ducts in concrete bridges – international practice

Following the collapse of Ynys-y-Gwas Bridge and other P-T bridges [36, 37], the UK took the problem of tendon corrosion in grouted duct post-tensioned concrete bridge beams very seriously. A moratorium was imposed on any further construction [18] of P-T concrete bridges. This moratorium was lifted once new construction procedures were introduced using plastic ducts [12]. The argument was that these new bridges could in the fullness of time be examined using radar [8, 13, 23]. Meanwhile, for the older P-T bridges with metallic ducts – radar was used to identify the ducts with judicious drilling prior to visual inspection [35]. This UK strategy was pragmatic, but expensive, risky and of low statistical significance. The lifting of the moratorium on the construction of new P-T concrete bridges in the UK was dependent upon there being effective NDT inspection techniques for these bridges, which were now using plastic tendon ducts. The latest UK thinking on the NDT of P-T concrete bridges is summarised in BA86/06 and in Table 3.

France used to use the high energy X-ray techniques, which can give excellent results but have high health risks in urban areas.

Like the UK, Germany has used the drilling and inspection technique. More recently researchers at BAM [2] have focused on NDT techniques using advanced off site signal processing of impact-echo. They have also used radar (not applicable to metallic ducts) and shear wave ultrasonic arrays to enable data fusion. Their general conclusions are that for data fusion, robotic positional accuracy is needed to overlay the data. Contrary to the findings of Sansalone & Streett [33], the BAM group found that impact-echo testing alone was unsuccessful in detecting voids reliably in the metallic tendon ducts on full scale post-tensioned concrete bridges.

In the USA, considerable confidence is shown in the impact-echo technique on post-tensioned concrete bridge beams. However, US companies have the most experience of using this technique. Early US work is summarised in ACI 228.2R-98. The update to this ACI 228 document is due in 2008.

Japan has focused on refining and developing the impact-echo test interpretation using the SIBIE technique [31]. The procedure looks very promising and is licensed to Japanese industry. The technique has not been adopted in Europe or North America to date.

There is still no international standard for the inspection of grouted duct post-tensioned bridge beams. However significant, if relatively slow, progress is being made towards an internationally acceptable and common approach to NDT inspection, through the various countries' advisory notes and the ACI 228 Advisory Note.

International practice for testing of concrete bridges and P-T concrete bridges with potentially voided metallic tendon ducts – has focused on employing higher frequency inpact-echo testing along with ultrasonic testing in conjunction with tomographic modelling. Newer developments include impulse response testing [16] and multi-sensor array shear wave testing [17].

Table 3
NDT of post-tensioned concrete bridges

Investigation method	Cost of method	Metal ducts	Plastic ducts	Effectiveness of technique
Visual inspection	Low	No	No	Technique if ineffective as bridges rarely show distress before catastrophic failure.
Load test	Relatively high	No	No	Ineffective procedure and dangerous as the structure could fail before any meaningful deflection response is obtained.
Stress/strain measurement	Relatively high	No	No	Generally ineffective as Cavell [9] has shown that post tensioned bridge strain variations due to loss of pre-stressing can be similar to variations resulting from temperature gradients throughout the year. Thus this technique is not sensitive to the defects in post tensioned bridges.
Impulse radar	Intermediate	No	Yes	Effective with non metallic liners such as in the joints of segmental bridges and in the newer post tensioned bridges. Radar will not penetrate post tensioned metal ducts.
Impact echo	Intermediate	Yes	Maybe	Potentially useful in identifying voiding in non metallic and metallic post tensioned ducts. Essential to ensure that impact frequency is sufficiently high to identify the defect.
Manual drilling of tendon duct with visual inspection using endoscope	Intermediate	Yes	No	Statistically limited and potentially dangerous if the tendons themselves are drilled. Advantage is that a direct physical observation can be made.
Radiography	High	Yes	Yes	High powered radiographic techniques give good image of voiding but requires closure of the bridge and may not be used in urban areas due to risk of radiation.
Ultrasonic tomography	Intermediate	Yes	Yes	Promising technique that could identify voids by producing a 2-D or 3-D image of the beam cross-section.

6. Voiding in masonry

In general there has been less NDT research and practice activity on masonry arch bridges compared to the activity relating to concrete. To some extent this is a reflection of the reliability and durability of masonry arch bridges. However, considerable work has been undertaken by the historic masonry conservation community led by Binda [5–7]. Key areas of activity have involved correlating sonic tomography with radar investigations. Infrared thermography has been used to determine delaminations in brick masonry and renderings in cathedrals and bell towers. In Italy, these investigations have then been combined into an interpretation, rather than the datafusion used by BAM on concrete. NDT research in the UK has focussed on sonic testing and ground penetrating radar [11]. The research undertaken at the University of Edinburgh was incorporated in detail by The (UK) Highways Agency into an Advisory Note on the NDT assessment of bridges: BA86/06 – which summarises UK practice.

International practice on unreinforced stone masonry has focused on using GPR and low frequency impulse hammer sonic testing, along with tomographic modelling, to investigate voiding in masonry arch bridges. Some use is made of infra-red themography. In the case of brick masonry, the above techniques are employed plus some limited useage of impact echo testing where there is good quality mortar and shallow depths of masonry.

7. Conclusions

Bridge inspection practice on the highways and railroads was reviewed from an international perspective. It was shown that there is remarkable similarity between procedures for bridge inspection across the EU and USA. In general, bridge inspections are limited to visual appraisals until specific defects are identified. However, failure critical bridges showing signs of distress may be monitored with continuous condition monitoring systems, including acoustic emission. In general bridge engineers prefer one-off specific and well targeted appropriate NDT techniques.

In terms of NDT inspection, higher frequency ultrasonic compression (P-wave) and shear wave (S-wave) tomography was shown to be a powerful technique for detecting voids in metallic duct post-tensioned concrete bridge beams. Lower frequency sonic testing involving: sonic echo; sonic transmission and sonic tomography, was most effective for testing stone and brick masonry arch bridges. Ground penetrating radar (GPR), acoustic emission (AE) and Infra-red thermography have been identified as having a role in identifying hidden features and defects.

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