GPR Application	Methodology			Processing		Results		Complementary Tests (NDT, coring, etc.)	Ref.
	Antennas & Acquisition parameters	Testing Set-up	Equipment	Filters & Algorithms	Software	Achievements	Inconveniences & Limits		
a) Masonry arch bridges									
[Masonry arch railway bridges] [brickwork and stonework arches] To provide information on the bridge condition and basic input parameters for structural analysis and assessment	450 MHz, 900 MHz and 1.2 GHz	Profile lines in longitudinal direction and profile lines in transverse direction along the intrados covering the full arch profile starting from the ground level	PulseEKKO-1000 radar equipment (Sensors & Software)	NP	NP	(i) The ring thickness was obtained at the spandrel walls; (ii) three distinctive sections or layers were identified	(i) There was no information available on the ring thickness at other locations	Infrared thermography & Sonic methods	[124]
[Historic stone arch bridge] To provide information of the bridge deck subsoil, hence interventions can be planned on purpose	Array of 16 polarized antennas (2 GHz) Array of 2 antennas: 200 and 600 MHz dual frequency antenna	Profile lines in longitudinal direction along the length of the bridge (10 cm spacing)	RIS Hi-BrigHT GPR antenna array (IDS Georadar) RIS MF Hi-Mod (IDS Georadar)	NP	NP	(i) Depth of the upper layer of asphalt and condition; (ii) damage detection (reinstatement); (iii) depth to the historic stonework; (iv) location of reinforcing bars	NP	Terrestrial Laser Scanning (TLS)	[132]

[Historic railway masonry arch bridge-brickwork] To estimate structural information such as wall thickness and composition and condition assessment regarding moisture and crack distribution	500 MHz, 900 MHz and 1.5 GHz	Horizontal and vertical profile lines at different parts of the bridge such as the south abutment, left and right wing wall, under the arch and from the top of the bridge 3D imaging (5 cm spacing)	A SIR-20 GPR system (GSSI) Manual antenna movement and a mounted survey wheel for distance positioning or with an automatic scanning system	Advanced tools like 3D FT-SAFT reconstruction and data fusion. Creation of high-resolution depth sections (C-Scans) FT-SAFT algorithm	NP	(i) Reflection horizons of different brick layers; (ii) bride edge; (iii) course of the abutment of the bridge; (iv) back wall of the abutment; (v) cracks up to 50 cm were visible; (vi) moisture distribution in the masonry	(i) A missing back wall reflection was detected at the thick wing walls and abutment, which seems to be an effect of high attenuation in the inner masonry structure due to higher water content	Spectral Induced Polarization (SIP)	[134]
[Medieval stone arch bridge] To determine whether voids, deformations or a tree's root network are present within the structure	200 MHz, 400 MHz and 1.5 GHz (bowtie antennas)	Longitudinal and transversal profile lines on the bridge deck Transversal and radial profile lines on the surface arch barrel	NP	Time-zero correction; Background removal; Automatic Gain Control	ReflexW	(i) Interface paved surface/silt material; (ii) delamination or weathered material; (iii) roots; (iv) arch barrel surface; (v) disorders (voids or delamination behind stones); (vi) bridge road/air interface	(i) Bad contact between bowtie antenna and the voussoirs surface during the survey	Electrical Resistivity Tomography (ERT) and Photogrammetry	[135]

[Historical brick arch bridges, mid-19th century] To investigate the presence of significant cracks or discontinuity in the masonry arch for failure analysis using finite element method	500 MHz and 2 GHz	Longitudinal profile lines above the bridge deck Profile lines above the abutments	Radar System (mod. Zond 12e 16-bit a/d conversion)	NP	NP	(i) Presence of external masonry walls and of heterogeneous internal filling material; (ii) presence of abutments and arch; (iii) presence of a crack; (iv) presence of lateral masonry walls; (v) internal filling composed of a different heterogeneous material, partially disturbed	NP	Thermographic, and vibrational tests	[136]
[Historic stone masonry arch bridge] To locate structural disorders, like cracks, as well as cleavages and their magnitude in the sandstone masonry rings forming the main arches of the bridge	900 MHz and 1.5 GHz	Profile lines in two different directions of acquisition: perpendicular and parallel to the blocks The profile lines were recorded from the intrados and the extrados of the arches	NP	Dewow (DC removal); Background removal; Gain function; Spiking deconvolution; f-k filtering	NP	(i) Several levels of cleavage in the main arches of the bridge; (ii) some areas having presence of water and/or chlorides in the masonry; (iii) damping of the radar signals most probably due to changes in water content contained in masonry blocks	(i) In most of the cases the damping was compensated with gain functions, but some profiles suffering too much damping could not as the noise was superior to signal; (ii) boreholes indicate a larger amount of cleavage than the ones detected with GPR; (iii) border effects: the first and last centimetres of each profile could not be interpreted; (iv) similar to the edges of blocks generating hyperbolic reflections, the spandrel walls of the arches create a significant interference (reflection) masking underlying reflections from possible cleavage	Photogrammetry	[138]

[Mediaeval Stone arch bridge] To know about the size of the ashlars, possible existence of structural elements between arches, and the homogeneity of the filling that was used to create a finite element model aiming to determine the stresses acting on the structure	Ground-coupled antennas: 250 MHz: 2 cm of trace-interval and 250 ns total time window 500 MHz: 2 cm of trace-interval and 100 ns total time window 800 MHz: 2 cm of trace-interval and 70 ns total time window	Longitudinal profile lines crossing the bridge	RAMAC radar (Mala Geosciences)	DC removal; Max phase correction; Band-pass filtering; Geometrical divergence compensation; Static corrections	NP	(i) Thickness of the masonry walls and arches; (ii) homogeneity of the filling (with some kind of layered structure between arches, while in the other parts it is, most likely, formed by coarse and non-regular materials); (iii) absence of structural supports or other inner elements between arches; (iv) absence of important cracks or holes in stonework; (v) foundations	(i) Reflection on the internal side of the arches (discontinuity ashlars-filling) is observed as a discontinuous and irregular anomaly. It is probably due to the constructive techniques used in this kind of bridges: a polished external face and an irregular internal face. The irregular surface provides a better contact between the ashlars and the inner filling, but the irregular characteristics of the surfaces produce scattering of the electromagnetic pulse, minimizing the reflected signal	Ambient vibration noise measurements & close-range photogrammetry (CRP)	[139] [140]
[Roman stone arch bridge] Characterization of infill, such as the thickness of the barrel vaults or layering, for predictive structural analysis	Ground-coupled antennas: 250 MHz: total time window of 30 ns 800 MHz: total time window of 100 ns	Longitudinal profile lines along the pathway of the bridge Profile lines in the vertical direction through accessible spandrel walls	X3M® GPR system (MALA Geoscience)	NP	NP	(i) Cross-section of the bridge (pavement, infill and foundations); (ii) thickness of the spandrel walls; (iii) steel bars within the bridge's deck; (iv) expansion joints along the concrete layer	(i) It was not possible to identify the infill distribution of the bridge due to the presence of steel bars within the bridge's deck	Terrestrial Laser Scanner (TLS), Sonic and impact-echo, and Multichannel analysis of surface waves (ambient vibration tests)	[141]

[Medieval stone arch bridge] Zonification of coarse filling material and internal thicknesses to be used in finite element modelling and structural analysis	Ground-coupled antenna: 250 MHz: 5 cm in-line spacing and 220 ns total time Window 500 MHz: 2 cm in-line spacing and 100 ns total time window	Longitudinal profile lines along the pathway of the bridge	RAMAC GPR system (MALA Geoscience)	Dewow (DC removal); Max. phase correction; Band-pass; Geometrical divergence compensation (gain); Topographic correction	NP	(i) Shallow internal composition of the bridge: distribution of coarse filling and ring stone thicknesses	NP	Photogrammetry	[142]
[Medieval stone arch bridge] Zonification of backfill, pavement and voussoirs thicknesses to be used in modelling and strength assessment using finite elements	Ground-coupled antennas: 250 MHz: 5 cm trace-interval a time window of 220 ns with 566 samples/ trace 500 MHz: 2 cm trace-interval & time window of 100 ns with 677 samples/ trace 800 MHz: 1 cm trace-interval & time window of 55 ns with 554 samples /trace	Longitudinal profile lines along the pathway of the bridge Longitudinal profile lines through the intrados surface of the vault Profile lines in the vertical direction through accessible spandrel walls	RAMAC GPR system (MALA Geoscience) Odometer wheel attached to the back of the antenna	Time-zero correction; Dewow (DC removal); Gain function; Subtracting average; Migration; Topographic correction	ReflexW	(i) Voussoirs and paving thicknesses; (ii) zonification of filling and solid granitic ashlar in the interior of the bridge	(i) The profile lines conducted through the intrados surface of the vault and the vertical walls of the bridge were only possible when accessible	Photogrammetry	[143]

[Medieval and Roman stone arch bridges] Internal evaluation and characterization: thicknesses, damages, restorations, etc.	Ground-coupled antennas: 250 MHz: 5 cm in-line spacing & time window of 200 ns with 516 samples/trace 500 MHz: 2 cm in-line spacing & time window of 100 ns with 678 samples/trace	Longitudinal profile lines along the pathway of the bridge	RAMAC GPR system (MALA Geoscience) Survey cart with an odometer wheel	Time-zero correction; Dewow (DC removal); Gain function; Subtracting average; Band-pass (Butterworth); Topographic correction	ReflexW	(i) Pavement and filling restorations; (ii) arches reconstruction; (iii) mapping different materials in stonework; (iv) ancient profiles/shapes; (v) hidden arches; (vi) solid piers; (vii) voussoirs thicknesses; (viii) foundations; (ix) internal voids/cavities; (x) moisture	(i) Some bridges had ancient flagstone surfaces composed of irregular blocks, so the wheel should be calibrated onsite to avoid inaccuracies in spatial trace positioning; (ii) in some cases the filling-stone interface was not identified due to the irregular internal shape of the voussoirs ; (iii) complex reflections patterns due to internal heterogeneity; (iv) external factors affecting the signal: ringing, airwave events, and X Marks the spot	Photogrammetry, Terrestrial Laser Scanner (TLS) & FDTD modelling of the GPR signals	[128] [129] [130] [131] [137] [144]
[Stone masonry arch railway bridges] To understand (i) thicknesses in piers, abutments & spandrel walls, and (ii) geometry and properties of foundations, for calibrating numerical models for structural behaviour simulation	250 MHz and 500 MHz	Horizontal and vertical profiles at different parts: bottom zone of piers, spandrel wall, abutments, and wing walls Longitudinal profiles along the road pavement and surrounding terrain and transversal profiles between some piers	Malå GeoScience AB equipment	NP	GroundVision (MALÅ GeoScience) Reflex2DQuick (Sandmeier geophysical software) GPRSIM and GPRSLICE (Geophysical Archaeometry Laboratory)	(i) Internal interfaces of stone blocks and blocks' thicknesses	(i) Interpretation difficulties were found due to the low contrast between blocks and infill material; (ii) result processing is still lacking some tools and work has to be done in this area; clearly, more developed software, incorporating optimization tools, would be quite useful in order to be more practical and functional to achieve good results	Dynamic Probing Super Heavy (DPSH), Ménard pressuremeter (PMT) and flat-jacks GPR numerical modelling	[145]

b) Concrete bridges									
Radar inspections performed on bridges designated for demolition. After the demolition radar results were verified. Thus, the accuracy and reliability of radar surveys was quantified under realistic circumstances.	Two horn antennae (1.2 GHz) mounted at the front of the vehicle: 200 or 40 traces/m and 512 samples/ trace Ground-coupled antenna (1.2 GHz): 300 or 400 traces/m and 512 samples/ trace	Mobile acquisition system with horn antennae (longitudinal profile lines) Manual acquisition with ground antennae over the bottom side of a bridge deck to detect tendon ducts Two horn antennas of the same type placed opposite to each other in air (2 cm spacing between parallel lines)	GSSI SIR-10 Horn antennae (GSSI model 4205) Ground antenna GSSI model 5100 Survey wheel A Trimble model 5700 RTK system	Band-pass filtering; Time-zero correction; Migration; Gain The calibration of the time to depth/thickness conversion were supported by one borehole	NP	(i) Asphalt concrete interface; (ii) top layer of rebar; (iii) tendon duct; (iv) bottom of concrete slab	(i) Gaps in the result for the concrete cover were mainly the result of resolution problems in sections with a small cover and of interpretation uncertainties in areas with additional structural complexity; (ii) no information about deeper layers of rebar was obtained with the mobile acquisition unit; (iii) gaps in the result for the pavement thickness were mainly due to a too small concrete cover resulting in overlapping reflections from bottom of pavement and rebar; (iv) the use of antenna arrays or automatic scanner systems can encourage the wider use of 3D techniques	NP	[154]
GPR validation tests on highway bridges	Dense multi-polarized dipole arrays (2 GHz ground-coupled antennas mounted on a trolley) Spatial sampling of 1 cm (100 radar scan/m)	One array with dipoles parallel to the scan direction, and the other with dipoles oriented in perpendicular 10 cm separation between profiles (scan width of 70 cm)	RIS Hi-Bright (specifically designed for investigating bridge decks and pavements)	(i) Automatic rebar detection algorithm; (ii) Automatic detection algorithm to extract and track the interface between asphalt and concrete	NP	(i) Thickness of asphalt overlay; (ii) depth of the asphalt – concrete slab interface; (iii) depth of the first layer of rebar; (iv) thickness of the concrete slab over the rebar; (v) depth of the bottom layer of rebar; (vi) drainage pipes; (vii) moisture and corrosion map	NP	NP	[157]

To measure the depth and size of cavities in concrete	2.6 GHz GSSI dipole antenna	Lines in the x- and y-direction were scanned (spacing not provided)	GSSI system	Data were not edited using any software filters	RADAN 7	(i) 3D view of the reinforcement; (ii) delamination and corrosion of the reinforcement	(i) Lack of resolution: the cavities are too close to the surface, causing the signal reflected by the delamination to merge with the signal reflected from the girder’s surface	Infrared thermography & Ultrasonic pulse echo	[161]
To assess the condition of two reinforced concrete bridge decks in order to analyse the potential of GPR to predict concrete repair estimates	Ground-coupled 1.5 GHz antenna mounted on a compact hand-pushed cart Bridge Deck 1: 256 samples/ scan, 120 scans/s & 157 scans/m Bridge Deck 2: 512 samples/ scan, 120 scans/s & 157 scans/m	Profiles acquired in the longitudinal direction Bridge Deck 1: 42 traverses spaced at 1 ft (305 mm) Bridge Deck 2: 12 traverses spaced at 2 ft (610 mm)	GSSI SIR System-3000 unit	Time-zero correction and amplitude normalization to eliminate undesirable anomalies	RADAN 6.5	(i) GPR reflection amplitude maps: areas of concrete deterioration	(i) The reflection amplitude value is highly dependent on various factors such as different depth to the top mat of reinforcing steel, different weather conditions at which data were acquired, various concrete properties, etc.	LiDAR technology	[166]
The study analyses potential, limitations and challenges of using and integrated GPR and IRT approach	1.6 GHz antenna (Model 5100B, GSSI)	Longitudinal 3D scheme on the bridge deck: passes at 0.3 m spacing for the GPR scans	GSSI SIR-3000 control unit	Numerical analysis based on detecting anomalies through analysing the amplitude of the GPR reflection	RADAN software The GPR data was integrated in GIS for enhanced visualization of the results	(i) Thicknesses of the asphalt layer and reinforced concrete deck; (ii) signal attenuation locations were identified reflecting the locations of potential defects (delamination); (iii) mapping: the locations of the defects were drawn in AutoCAD as lines	(i) The reflection amplitude value is highly dependent on various aspects such as moisture, corrosion and delamination	IR Thermography Geographic Information Systems (GIS)	[169]

Using GPR to evaluate the deterioration of concrete bridge decks, highlight the basic interpretation assumptions, demonstrate successful applications and discuss limitations with the methodology	1 GHz	Three GPR sensors	RoadMap platform	NP	NP	(i) Deterioration determination (3D map) from amplitude values	(i) The ASTM standard should be updated to adopt some of the more recent developments that have occurred in the assessment of deck deterioration with GPR; (ii) GPR data should never be used alone to make a final decision on bridge deck condition. Confirmation with controlled coring data should be part of the process whenever possible; (iii) the bottom of deck reflection can often prove hard to detect, especially when the concrete is thicker than 15–20 cm. Shadowing from intermediate layers of rebar and variation in rebar density can alter the bottom reflection amplitude	Numerical modelling	[170]
Evaluation of two concrete bridges to characterize concrete deterioration and reinforcement corrosion	1.5 GHz ground coupled antenna Time window of 15 ns and longitudinal data resolution of the system fixed at 0.011 m	GPR scanning was implemented along the longitudinal direction of bridge decks (line spacing of 0.6 m)	GSSI SIR-3000 system Wheel encoder for positioning RTK GPS system	Migration (auto-focusing); automated rebar picking; data normalization (to a reference amplitude); amplitude correction due to depth variation; threshold (attenuation map)	MATLAB program developed for GPR signal processing	(i) Deterioration map: high attenuation probably caused by high chloride content and moisture induced by accumulation of deicing salt; (ii) rebar corrosion and concrete deterioration at early stages	(i) A multi-channel GPR system is not widely used in practice due to its high cost. With the common single channel GPR system, many line scans are needed to get a full coverage of a bridge deck	Acoustic scanning system	[174]

To evaluate the deteriorated depth of concrete bridge decks with asphalt overlays in an expressway network	1 GHz air-coupled antenna (4 channels at the rear of a vehicle): sampling rate set to 12 scans/m	A total of 12 lines of GPR scanning (4 channels × 3 lanes) in the longitudinal direction 500 mm (the centre-to-centre distance between antenna)	GSSI system	NP	Software RADAN	(i) Condition map of attenuation and concrete deterioration	(i) The low sampling rate for the air-coupled GPR in this study could introduce some errors in the attenuation and relative permittivity measurements. However, higher sampling rate decreases a survey speed, which could result in higher survey costs and more importantly, could increase a risk of a traffic accident on expressway	NP	[175]
This paper presents two case studies of applying GPR in assessing the actual condition of two bridges in the UK	Polarised 2 GHz antennas (array of 9 channels)	Merging on the same map datasets collected along both longitudinal and transversal scans Antennas spaced at 10 cm intervals	RIS Hi-BrigHT (designed specifically for the inspection of bridge decks)	Background removal; set start time-zero position; leading to some filtering and sometimes adjusting the gain	IDS GRED data analysis software	(i) Estimation of thicknesses of different structural layers of the bridge deck; (ii) location and spacing of upper and lower layers of rebar; (iii) possible moisture and delamination; (iv) detection of structural features and expansion joints	(i) To allow the traffic to flow at certain intervals, it was decided to divide the deck surface into 8 separate but interconnected zones and carry out the GPR survey separately	IBIS-S (interferometric radar system) FEM (Finite Element Model) – structural analysis	[158] [183]

Table S5. Bridges: relevant on-site GPR surveys (NP = Not Provided; Ref. = Reference).