TARJOUS

INFRA & LIIKENNE

Turun kaupunki
Kaupunkiympäristötoimiala / Kaupunkirakentamisen palvelualue / Kaupunkiympäristön toteutussuunnitteluyksikkö
Mika Laine / Suunnitteluinsinööri; mika.laine@turku.fi
PL 355, 20101 TURKU

# Maarian kirkkosillan T-4002 rakenteellinen tarkastelu

Kiitämme tarjouspyynnöstänne ja ilmoitamme olevamme erittäin kiinnostuneita hoitamaan otsikossa mainitun sillan asiantuntijapalvelun.

Sopimusehdot:

Toimeksiannossa noudatetaan ”Suunnittelupalveluiden puitejärjestelysopimus ajalle 15.4.2018-31.12.2020, lisäksi optiot vuosille 2021 ja 2022” osa 4b ”Siltatekniikka: yleis- ja erikoistarkastukset ja niihin liittyvä korjaussuunnittelu”.

## 1. Tutkittava rakenne ja taustatiedot

Maarian kirkkosilta (T-4002) sijaitsee Turun kaupungissa, jossa se ylittää Vähäjoen. Ylittävä väylä on Vanha Tampereentie.

Rakenne on kivinen holvisilta. Sillan kokonaispituus on 23,4 m ja hyödyllinen leveys 6 m. Sillan valmistusvuosi on 1928.

Lähtötietoina tarkastelulle toimivat Taitorakennerekisterin tiedot ja tilaajan toimittama aineisto.

## 2. Työn sisältö ja laajuus

Kantavuusselvityksessä (rakenteellinen tarkastelu) tutkitaan sillan kantavuus väyläviraston ohjeen ”Siltojen kantavuuslaskentaohjeen” (LO 36/2015) mukaisesti. Liikennekuormakaavioina käytetään ohjeen mukaisia ajoneuvoasetukseen 2013 perustuvia kuormakaavioita.

Nykyisen sillan rakenteellinen tarkastelu sisältää:

- Tarkastelu sisältää sillan päällysrakenteen ja perustusten laskennan.
- Kapasiteettitarkastelun ajoneuvoasetuksen mukaisille liikennekuormille painorajoitustarpeen määrittämiseksi olettamalla, että rakenteessa ei ole kantavuuden kannalta olennaisia vaurioita.
- Kivisen holvisillan päälle on mahdollisesti tehty teräsbetoninen laatta, mutta sen toteutus on epävarmaa. Rakenteen kantavuus tarkastellaan ilman betonilaatan vaikutusta.

Kantavuustarkastelu tehdään Ramboll UK:n käyttämän ohjelman perusteella. Ohjelman laskentaperiaatteet on esitetty tarjouksen liitteessä.

Päivämäärä 22/11/2022

Ramboll Finland Oy
Itsehallintokuja 3
PL 25
02601 ESPOO

T +358 20 755 611
www.ramboll.fi

Viite: tarjouspyyntö 21.1.2022 kokous (Mika Laine, Tuomas Turpeinen, Guy Rapaport)



Ramboll Finland Oy
Y-tunnus 0101197-5, ALV rek.
Kotipaikka Espoo

Tehtävään sisältyy sillan laserkeilaus ja laserkeilausaineiston käsittelyn, joka toteutetaan Ramboll Finland Oy:n toimesta.

Sillalle on tehty sovittu yleistarkastus vuonna 2021, jonka tiedot on päivitetty Väyläviraston Taitorakennerekisteriin.

Tehtävä on mahdollista toteuttaa talven 2022–2023 aikana, mikäli sillan laserkeilaus saadaan tehtyä ennen lumien tuloa. Mikäli laserkeilaus ei onnistu vuoden 2022 aikana, sovitaan projektille uusi aikataulu.

Rakenteellisen tarkasteluun ei sisälly vahventamissuunnittelua kantavuuden parantamiseksi, siitä sovitaan tarvittaessa erikseen.

Geoteknistä arviointi varten ei ole olemassa riittävästi lähtötietoja ja sitä ei sisällytetä tähän tarjoukseen. Geoteknisesta arvioinnista ja lausunnosta sovitaan tilaajan kanssa erikseen.

## 3. Aikataulu

Sillan rakenteellinen tarkastelu on valmiina tilaajan tarkastukseen 31.5.2023 mennessä, mikäli sillan laserkeilaus onnistuu vuoden 2022 aikana.

## 4. Projektiorganisaatio

Projektiorganisaatio on alustavasti seuraava:
- Projektipäällikkö: Ins. (tekn. yliopisto) Guy Rapaport (01)
- Kantavuusanalyysit (Ramboll UK):
  Andrew Parris (E), Carl Brookes (E), Alex Salter (02), David Vaughan (02), Lynne Mabon (02), Daniel Niziolek (03)
- Kantavuusanalyysin koordinointi: DI Tuomo Siitonen (03)
- Laadunvarmistus: TkL Ilkka Vilonen (E)

Myös muita Rambollin asiantuntijoita voidaan esittää käytettäväksi tässä tehtävässä.

Vastuuhenkilöllä on seuraavat pätevyydet:
Ilkka Vilosella on FISE Oy:n myöntämä ”poikkeuksellisen vaativa -vaativuusluokan betonirakenteiden suunnittelija” -pätevyys uudisrakentamiseen (siltasuunnittelija).

## 5. Palkkio

Palkkiomuodoksi esitämme KSE 2013 5.2.3 mukaista aikapalkkiota henkilöryhmittäin. Tarjouksessa mainittua tuntimääräarvioita ei ylitetä ilman tilaajan suostumusta.

Tehtävän palkkio on yhteensä 40 700 € (alv 0 %).

Työmäärät jakautuvat tehtävittäin seuraavasti (arvio):
Ins. (tekn. yliopisto) Guy Rapaport (01), projektin hallinta 45 h
Carl Brookes (E) 20 h
Alex Salter (02) 9 h

David Vaughan / Lynne Mabon (02) 127 h
Daniel Niziolek (03) 30 h
DI Tuomo Siitonen (03), kantavuusanalyysin koordinointi, 45 h
TkL Ilkka Vilonen (E), laadunvarmistus, 60 h

Sillan laserkeilaus ja mittausaineiston käsittely 8 000 €

## 6. Maksuehdot

Työ laskutetaan kuukausittain toteutuman mukaisesti.

Maksuehto on 21 vrk.

## 7. Muut ehdot ja lisätiedot

Ramboll Finlandin projektitoiminta perustuu ISO 9001 -laatujärjestelmästandardin, ISO 45001 -työterveys- ja työturvallisuusstandardin sekä ISO 14001 -ympäristöstandardin mukaiseen laatu-, työterveys ja työturvallisuus- sekä ympäristöjärjestelmämme, jonka Bureau Veritas on sertifioinut.

Laadunvarmistusmenetelmämme mukaisesti suunnittelija tekee dokumentoidun itselleluovutuksen, ennen kuin asiakirja toimitetaan tilaajalle.

Ramboll toteuttaa korkeatasoista henkilötietojen suojaa. Ramboll käsittelee projektin toteuttamiseksi tarvittavia henkilötietoja sovellettavan tietosuojalainsäädännön, erityisesti EU:n yleisen tietosuoja-asetuksen (Asetus (EU) 2016/679) mukaisesti.

Toivomme, että tarjouksemme sopii Teille. Lisätietoja tarjouksestamme antaa Ramboll Finland Oy, Guy Rapaport puh 040 824 5622.

Tarjouksemme on voimassa 23.12.2022 saakka.

Kunnioittavasti

Matti Airaksinen
Yksikön päällikkö

Guy Rapaport
Johtava konsultti

Intended for
Ramboll Finland, City of Turku

Project no.
1510055789

Date
04 November 2022

# T-4002 MAARIAN KIRKKOSILTA

# LOAD RATING ASSESSMENT FEE PROPOSAL

# T-4002 MAARIAN KIRKKOSILTA
# LOAD RATING ASSESSMENT FEE PROPOSAL

Revision History

| Revision | Date | Purpose / Status | Document Ref. | Comments |
|---|---|---|---|---|
| 1 | 12.04.22 | Final | 1510061951-FP-02 | |
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| 3 | 04.11.22 | Final | 1510061951-FP-02 | |

| Prepared By | Reviewed By | Approved By |
|---|---|---|
| Edward Fraser | Alex Salter | Andrew Parris |
| Prepared By | Reviewed By | Approved By |
| Engineer | Project Manager | Director |


Ramboll
Carlton House
Ringwood Road
Woodlands
Southampton SO40 7HT
United Kingdom

tel +44 (0)23 8081 7500
fax +44 (0)23 8081 7600
southampton@ramboll.co.uk

T-4002 MAARIAN KIRKKOSILTA
LOAD RATING ASSESSMENT FEE PROPOSAL

# 1. INTRODUCTION

This document details the proposed scope of works for Ramboll UK's involvement in the Load Rating Assessment of T-4002 Maarian Kirkkosilta. The structure is a single span stone ashlar masonry arch bridge carrying the highway over a watercourse in Turku. The structure comprises of a single span stone arch with a Reinforced Concrete cover slab. The substructure comprises mass stone abutments.

# 2. SCOPE OF WORKS

## 2.1. Load Rating Assessment

The load rating assessment of T-4002 bridge will be undertaken in accordance with the Finnish Transport Infrastructure Agency Load Capacity Calculation Guide for Bridge (LO 36/2015).

Load rating assessment of the bridge will include the arch structure and abutments. Assessment of the cantilever structure supporting services, vehicle containment barrier, and foundations is not included in the assessment. A Finite Discrete Element model will be used to predict bridge behaviour at Ultimate Limit State and Serviceability Limit State. Appendix B and C provide additional information on Ramboll UK's approach to assessment of arches using FDEM methods.

The following assumptions, exclusions and caveats have been made in developing the fee proposal for the load rating assessment of bridge T-4002:

- The bridge appears to in good condition generally, this is to be confirmed through inspection and survey by Ramboll Finland.
- The geometry of the structure will be confirmed with a point cloud survey.
- The assessment will provide a load rating for the arch and abutments based on the LO36/2015 Finnish Assessment Standard, as defined above.
- The adjacent pedestrian structure is not part of the scope of this assessment.
- The cantilever structure supporting services is not part of the scope of this assessment.

### 2.2. Deliverables

Ramboll UK will provide an Assessment Report detailing the assessment approach, assessment results, overall findings, and recommendations.

## 3. PROGRAMME

Ramboll UK will complete the assessment by the required timeframe of May 2023.

## 4. RAMBOLL UK RESOURCES

In accordance with the framework agreement between Ramboll and the City of Turku, Ramboll UK provide the following list of staff and their proposed roles and grades for this project:

Project Director, Andrew Parris (E)

Project Manager, Alex Salter (02)

Technical Lead, David Vaughan/ Lynne Mabon (02)

CV's for these named staff are included within Appendix A. Other resource may be used where required to undertake specific tasks on the project.

## 5. ASSESSMENT FEES

A fee estimate to undertake the proposed assessment is € 16,975 with the following breakdown of staff hours and framework rates:

| Staff | Grade (SKOL) | Rate (€) | Hours | Total |
|---|---|---|---|---|
| Carl Brookes | E | 127.5 | 20 | €2550.00 |
| Alex Salter | 02 | 88.74 | 9 | €798.66 |
| David Vaughan / Lynne Mabon | 02 | 88.74 | 127 | €11,269.98 |
| Daniel Niziolek | 03 | 78.54 | 30 | €2356.20 |
| Total | | | | €16,975.00 |

## 6. TERMS AND CONDITIONS

The load rating assessment of T-4002 will be undertaken based on the current agreed terms and conditions between Ramboll Finland and the City of Turku.

T-4002 MAARIAN KIRKKOSILTA
LOAD RATING ASSESSMENT FEE PROPOSAL

## Appendix A – CV's

# ANDREW PARRIS

**Director Bridges**

Management of multi-disciplinary design teams and specialist in Bridge design, independent checking and construction of highway and railway infrastructure. Knowledge of UK National Highways DMRB and SHW, Eurocodes plus Rail standards and some international design standards. Experienced in the management of Engineers and Technicians in conventional and Design and Build contracts. His technical experience includes the design and checking of bridges (reinforced concrete, prestressed pre and post-tensioned concrete and steel composite), retaining walls, bored piled walls, diaphragm walls, reinforced earth walls and other civil engineering structures, technical approval of highway and railway bridges. He has extensive experience in the assessment, inspection and strengthening of modern and historic bridges and monitoring of both road and rail bridges. High-speed rail bridge engineering experience in Taiwan and UK – HS2.

Site based work has included the supervision of bridge and highway construction on several major highway, and railway schemes under NEC and traditional forms of contract.

## CONTACT INFORMATION

**Andrew Parris**

Andrew.Parris
@Ramboll.co.uk
+44 7785905156

Ramboll UK
Carlton House
Ringwood Road
Southampton SO40 7HT
United Kingdom

## YEARS AT RAMBOLL

8

## NATIONALITY

British

## CAREER

2013->>>

**Project Director, Ramboll UK**

Director, Bridges, in the Bridges South team at Ramboll Southampton. Lead the Advanced Bridge Asset Management team (ABAM) and provide technical leadership on D&B schemes too. Currently Project Director and technical Lead on a number of bridge assessment projects, Structures Lead on the Norwich Western Link Road Project and Deputy Viaduct Lead on HS2 Phase 1 North Cat III checking.

2008-2013
**Associate, Scott Wilson/URS**
Management of bridge design teams. Delivered the design of structures for the A421 M1 J13 to Bedford ECI scheme ahead of programme and under budget. Design review and amendment of structures and acted as DSR for Crossrail Pudding Mill Lane Portal. International work - bridge design and reviews for bridges on highway schemes in Kazakhstan and Azerbaijan. Due diligence reviews for projects in US/Canada and Mongolia. Prepared design concept for access bridge over SSSI/SAC river for windfarm.

1998-2008
**Principal Engineer, Halcrow**
Management of the Chichester Bridges Team. Provided the technical lead in production of calculations, drawings, reports and specifications for Local Authorities (WSCC – HaTS 1998-2003; LBWF;LBTH) and DTp/HA schemes ( M60 J5-8 Widening, Area 1 MAC) and Irish Road Projects (Cat II Checking). PM/PD on projects including D&B. Responsible for work winning. Inspection of Scottish Power Station coal handling structures following structural collapse. Due diligence reviews for UK and US schemes.

1988-1998
**Senior Engineer, Mott Hay and Anderson/Mott MacDonald**
Responsible for the design of a number of bridge and highway structures for DTp/HA schemes - A20 Folkestone to Dover Contracts 1,2,3 ; A34 Newbury Bypass; M3 widening (checking) and Assessments of road and rail bridges (Jubilee Line Extension and Taiwan HSR) . Structures involved reinforced concrete, prestressed (pre and post-tensioned) and steel composite bridges; reinforced concrete and bored piled retaining walls. Section Engineer on the A34 Newbury Bypass.

1983-1988
**Graduate Engineer, Rendel Palmer and Tritton/High Point Rendel**
Responsible for the preliminary design of highway schemes using MOSS (now MX) ; Design checks of contractor design structures for Tripoli Ring Road, Libya; Site supervision of A470 Taff Vale Trunk Road in South Wales; Water Resources department - A36 Salisbury Bypass, calculation of bridge openings and backwater flooding effects; Kilombero Ferry crossing, Tanzania, design of ferry guide cable anchor blocks, cost calculations and production of drawings. Bridge tender design for Dornoch Crossing.

1981-1982
**Student Engineer - Industry Year, Charles Haswell and Partners**
Ras abu Fontas , Desalination Plant, Qatar - Production of RC drawings for cable pits and other structures. Cable pit cover design.

## ACADEMIC TITLE
BSc (Hons), MICE, CEng

## EDUCATION
1999-2000
**AutoCAD - City and Guilds**
Chichester College, Chichester, United Kingdom

1988
**MICE**
Institution of Civil Engineers, London, United Kingdom

1979-1983
**BSc (Hons) Civil Engineering**
Polytechnic of the South Bank, London, United Kingdom

## COURSES/CERTIFICATIONS

**APM - PMQ, 2017**
Project Management qualification (ILX Course e- learning, classroom sessions and exam)

**Various Supplier visits ongoing and internal Technical and Management discussion groups,**

**Group ERP Training, 2015**

**NEC 3 PSC Training, 2014**

**Compliance training - H&S; Quality; Fitness for Work; Anti-bribery and Corruption legislation, 2013**

**MS Project (2010), 2013**

## COMPUTER SKILLS

MS Office - MS Project - Bridges Software SAM , LEAP, LUSAS (slight), AutoCAD

## LANGUAGE SKILLS

**English** (mother tongue), French

## PROJECTS

2021->>>
**HS2 Phase 1 (North) Cat III Checking**
**WSP**
**Deputy Lead Viaducts**

Acting as a deputy to the WSP lead for checking some 16 Viaducts (variety of structure types – post-tensioned, pretensioned, steel composite, steel truss) on Phase 1 North structures.

2020->>>
**Norwich Western Link Road Project**
**Ferrovial Construction and NCC**
**Technical Lead Structures**
Helped lead the successful tender and influencing the winning designs, particularly the 670 m long River Wensum Viaduct. Acting as Technical Lead for Structures in the detail design phase.

2019->>>
**Bridge Assessment Projects**
**Various Clients**

Acted as Project Director and Technical Lead on a number of complex bridge assessment projects. These included a fire damaged post-tensioned bridge in Bristol – technical lead in determining the redistribution of load effects, assessment, determine the repair strategy and detail design. Assessment of several multi-span post-tensioned bridges, including one carrying a railway with poor grouting to the post-tensioning (investigating various scenarios of bonding and non-bonding). Assessment of a cable stayed footbridge including dynamic effects and investigating solutions to counteract the lively behavior. Cat III Checking of complex multi-span post-tensioned viaduct that was to be demolished, including the deconstruction stages. Technical reviews of a number of special assessment and inspection reports on the A13 Lodge Avenue multi-span steel composite viaduct. UK based Project Director for Ramboll Finland bridge assessment schemes.

2018->>>
**DLR New Train Assessment**
**Docklands Light Railway Limited, United Kingdom**
**Project Manager**
Project Manager for the Assessment of existing structures for New Heavier Trains. Project planning, Client liaison, technical reviews and development of strengthening options.

2018- >>>
**Volker Laser Projects**
**Volkerlaser Ltd, United Kingdom**
Project Director giving a technical lead to bearing replacement schemes for the Port of Dover ( Berth 8 Upper Bridge) and East Cliff Viaduct for VL/HE/AOne ( permanent and temporary works).

2016-2019
**Thames Tideway West: Cat III**
**BMB Joint Venture, United Kingdom**
**Civil Structures Technical Lead**
Technical lead for Civil Structures for the Cat III Checking of a variety of ground engineering structures (interception Chambers, connection culverts, drop shafts and ancillary structures, river walls) at Hammersmith, Putney, Wandsworth and Acton locations. Team leadership and reporting, work and programme planning, reviewing design and check comments.

2014-2018
**Shinfield ERR and M4 Overbridge**
**Hochtief, United Kingdom**
**Project Director**
Project Director responsible for leading the detail design phase of this 2km relief road to the village of Shinfield and new bridge over the M4. Responsible for the overall success of the project, and leading diverse teams covering highways, bridges, geotechnics and environment. Specialist bridge design input. £15m D&B project.

2017-2018
**Stamford Bridge Redevelopment - BRGUK Tender**
**BAM Nuttall Limited, United Kingdom**
Director for tender Design Services for Rail Enabling works for New Chelsea FC Stadium. Technical lead on structures and managing multi-discipline teams – Bridges, Geotechnics and Environment, commercial proposal and bid writing.

2018->>>
**East Cliff Viaduct Bearing Replacement - Temp Works, Cat III Checking**
**Volkerlaser Ltd, United Kingdom**
CAT III check of the steel jacking frame to be used to enable the replacement of bearings on the A20 East Cliff Viaduct Responding to technical queries from site and independent technical advice on various site related technical issues.

2016
**HS2 Tender Design Lot C1 CVV**
**LFM, United Kingdom**
**Design Package Lead**
Design Package lead for the 3.4 km long Colne Valley Viaduct (CVV). Develop tender design options with Bridge Architect and Construction JV – LFM. Manage the preparation of designs, drawings, 3D models , design optimisation, interface with OHLE and rail assurance. Reporting and presentations to LFM Board. Substantial input to the answering of tender questions and design costing.

2015
**M3 Lagan Viaduct Joint Replacement NI**
**HMG/BREAM, United Kingdom**
**Project Director**
Following a failure of the existing joint system Ramboll were commissioned to provide expert witness assistance and develop design options, prepare technical contract documents and site support. Responsible for project from the end stages of the expert witness work, developing contract and fee requirements, input to technical solutions and contract specifications. Site phase is set to progress from August 2016 onwards.

2015
**A26 Glarryford to North of Drones NI**
**BAM McCann JV, United Kingdom**
**Checking Team Leader**
Responsible for leading the Cat II checking process for a number of precast prestressed integral beam bridges and culverts on this 8 km new dual carriageway, contract value £40m.

2013-2015
**Hammersmith Flyover Phase 2 Strengthening**
**Transport for London, United Kingdom**
**Discipline Director for substructures**
Phase 2 Strengthening to 622m long post-tensioned spine beam bridge supported on single columns and pad foundations. Discipline Director for substructures and bearings. £80m D&B scheme being undertaken as part of Transport for London's Structures and Tunnels Investment Portfolio. Responsible for developing solutions for permanent strengthening of pier bases, developing the bearing replacement strategy to maintain the integrity of the bridge and ensure stability. Liaise with FMEA lead and PD to determine jacking methodology. Prepared the bearing specification and liaison with German bearing supplier over various technical matters and paint protection. Reviewing bearing test data and answering site technical queries.

2013-2014
**Queen Elizabeth Olympic Park Bridge F03**
**BAM Nuttall Ltd, United Kingdom**
**Project Director**
Led the successful bid and Cat II checking of the structural modifications to the existing temporary structure to make permanent with a new in situ concrete deck. £3m D&B scheme.

## TEACHING EXPERIENCE

2005-2006

**Prepared and delivered lectures on Greatham Bridge strengthening at Brighton and Surrey Universities., Brighton and Surrey Universities**

## MEMBERSHIPS

MICE
Engineering Council

# ALEX SALTER

Principal Engineer

Alex has fourteen years post-graduate experience with Ramboll in the design, assessment and strengthening of highway and railway structures. He has specialised in advanced computational analysis and has significant experience in the assessment, checking and strengthening of bridge structures. He is experienced in the design of bridges and has been involved in the development of tools for the determination of fatigue life and dynamic response of both highway and rail structures, including portal and cantilever motorway gantries.

Alex is the technical lead for Ramboll UK's gantry team, responsible for the structural design of Ramboll's gantry portfolio. Alex is part of Ramboll UK's Advanced Bridges Asset Management leadership team. Leading various teams in the review, assessment, inspection, monitoring and strengthening of existing highway and rail bridge structures.

Alex has extensive experience working on both Network Rail, National Highway and local authority projects. Alex provides technical support for the design and assessment of metallic bridges across Ramboll's Bridge department, specialising in fatigue and special assessment methods.

## CONTACT INFORMATION

Alex Salter

Alex.Salter@ramboll.co.uk
+44 7870 810732

Ramboll UK
Carlton House
Ringwood Road
Southampton SO40 7HT
United Kingdom

## CAREER

2018- PRESENT
Principal Engineer, Ramboll

## ACADEMIC TITLE

BEng (Hons), MSc Bridge Engineering, CEng MICE

## MEMBERSHIPS

Member of the Institution of Civil Engineers

## PROJECTS

2021 >>>
Advanced Manufacturing District Innovation Scotland – South – White Cart Crossing Bridge
Amey, Renfrewshire County Councl, United Kingdom
Design Team Lead and Project Manager
Design of a 120m span Bowstring Arch Bridge crossing the White Cart Water connecting the east and west of Paisley. Alex is leading the design through concept design stage through to detailed design of an inclined twin bowstring arch bridge carrying the carriageway and footways of the new interconnecting road as part of the AMIDS scheme to regenerate Pasiley south of Glasgow Airport.

2021 >>>
A13 Lodge Road Flyover
RMS, London, United Kingdom
Technical Reviewer
A13 Lodge Avenue is a twenty-four span Braithwaite 'Fliway' built in 1973 originally intended as a temporary structure. Ramboll have been appointed to develop a repair and maintenance strategy for the remaining service life of the bridge. Alex is responsible for leading Technical Reviews required as part of the ongoing works.

2021 >>>
Transpennine Route Upgrade
TRU Alliance, Manchester to Leeds, United Kingdom
Civils Assessment Lead (CRE)
Alex is a Civil Structures Assessment Lead for the W4 package of works responsible for structural assessments of metallic and masonry arch underbridges. Structures including wrought iron and steel riveted plate girders of U-Frame, Lattice and Braced form, along with single and multsipan arch viaducts. The use of special investigations and complex nonlinear assessment methods were required to demonstrate structural adequacy.

2020 - 2021
Heurekan Footbridge Assessment and Remediation
Helsingin kaupunki, Finland
Assessment and Remedial Design Team Lead
Assessment and design of remedial solutions of an iconic cable stayed footbridge in Helsinki, Finland. The solution included the design of a retrofitted Tuned Mass Damper to reduce the dynamic behaviour of the footbridge back within comfortable limits. The structure is a two-span footbridge deck comprising a steel lattice truss deck supported by cables from a slender tower.

2020-2020
Hopeasalmentien Metrotunnelin Bridge Assessment
Helsingin kaupunki, Finland
Assessment Team Lead
Assessment of a reinforced concrete overbridge crossing the Helsinki Metro line. Simply supported single span with three decks, complex junction road alignment over the structure. Alex led the assessment using Eurocodes and the Finnish bridge assessment code.

2019-2021
Gantry - M42 Junction 3a - 7 MS4 Remedials
Kier, United Kingdom
Assessment Team Lead
Assessment Team Leader and Project Manager for the assessment of 64 No. gantry structure along the M42 motorway. The gantries are being assessed determine their adequacy to accommodate equipment upgrades and extension of their design life.

2018-2022
Smart Motorway Programme
Highways England, Multiple Projects
Gantry Team Technical Lead
Alex is the technical lead for Ramboll's Gantry team. Responsible for the technical delivery on all Gantry projects across multiple highway schemes.

2017 - 2019
M5 Motorway Oldbury Viaduct
Kier, EM Highways
Assessment and Design Team Lead, Project Manager
Alex led the design of six new replacement gantries on the raised section of the M5 Motorway supported by the Oldbury Viaduct between junction 1 and 2. The gantries are attached to the reinforced concrete viaduct deck, Alex undertook the assessment of the steel composite superstructure to ensure it has adequate capacity to accommodate the additional loading from the replacement gantries and signage.

2017-2019
A605 Kings Dyke
Kier Limited, United Kingdom
Structures Design Team Lead
Structures team leader and CRE for the design of multiple bridge structures on a new bypass road in East Anglia. The designs comprise of box culvert structures to retain access tracks under the new road layout and a new road over rail single span integral structure formed from precast concrete beams and reinforced concrete abutments.

2016- 2018
Northern Hub Electrification – Chapel Street Bridge Replacement
Skanska/BAM Joint Venture, United Kingdom
Assessment and Design Team Lead
Alex led the initial assessment team and through detailed computational analysis identified critical failures in the cast iron structure. Alex was appointed as CRE for this project. Alex led the design team and took the replacement design of Chapel Street Bridge from feasibility design stage through to the detailed design submission. This was undertaken within a shortened design programme and Alex helped to integrate the Network Rail, local planning authorities and third parties within the design process to ensure an expedited design approvals process was achieved to meet the required programme, this included IDR/IDC and DRN approvals. Chapel Street Bridge is single span skewed cast iron underbridge with five main arch ribs supporting cast iron lattice spandrels and deck plates. The replacement steel structure matches the existing arch rib alignment and utilises the existing substructure arrangement while providing improved highway clearance. The structure was successfully installed during a five day rail blockade and constructed between two adjoining metallic structures. The structure is located at the northern end of Salford Central Station on the lines into Manchester Victoria.

Alex also acted as the CRE for the masonry arch assessment works undertaken by Ramboll for the Chapel Street arch viaducts adjacent to the Chapel street bridge replacement, assessing for both long term and short term stability and movement of the arches during the replacement of Chapel Street Bridge. A similar assessment was undertaken for Water Street Bridge as part of the same package of works. Remedial strengthening of the arch was designed and installed as excessive movements and likely failure of the adjacent arches was identified within the assessment during the demolition and temporary stages of the replacement of Water Street Bridge.

2016-2017
NR- LNW Post Tensioned Bridges Special Inspections
Murphy, United Kingdom
Lead Bridge Inspector
Alex led the phase one and two inspection and investigation for the Post Tensioned Special Inspections of two multi-span rail bridges over motorways around Manchester. The inspections comprised of both internal inspections within the box cells and external inspections of the soffit, post tensioning anchorages and bearings. The phase two intrusive investigations identified the condition of the post tensioning systems within the structural reinforced concrete elements.

2015 - 2016
XTD67 Artillery Street Viaduct - Structures Strengthening Programme
Skanska
Design Team Lead
As design team leader Alex took the structural strengthening design of XTD67 Artillery Street Viaduct through options selection, single option design and detailed design. Alex was appointed as a Contractor's Responsible Engineer (CRE) for this project. Artillery Street is a five span wrought iron riveted girder structure requiring a full deck strengthening scheme along with strengthening and replacement of critical primary members. The structure is located at the southern end of London Bridge Station and required close collaboration and design integration with the London Bridge Station Redevelopment team and Network Rail's Thameslink Rail Systems teams.

2015 – 2016
Structures and Tunnels Investment Portfolio – Power Road Bridge
Transport for London
Structures Lead
Alex undertook the structural design lead for Power Road Bridge replacement scheme. A replacement of a four lane road over rail three span existing reinforced concrete bridge carrying the North Circular over a double track London suburban rail line. Alex led the design of a single span prestressed precast replacement bridge with a complex three stage demolition and construction process, allowing the North Circular ring road to remain open at all times. Alex led the design through an ever-evolving design and build process working closely with the temporary works design and checkers, the permanent works Category III checkers and the construction team to develop an efficient and practical design meeting all the complex site constraints and limiting disruption to the public to a minimum.

The working relationships he developed with Network Rail and Transport for London facilitated cross-party approvals during the design stages, resulting in efficiencies which saved several weeks from the existing approvals process. To ensure continuity and keep disruption to a minimum, Alex continued to provide design support during the construction stages, particularly during the demolition of the existing structure within Network Rail Blockades, where he worked on site to assist with decision-making

2014 – 2016
Structures Strengthening Programme.
Skanska
Design Team Lead
Lead Design Engineer and developing the structural strengthening designs through single option to detailed design stage. The project included 21 metallic structures on the Thameslink Rail Network between Blackfriars Station and New Cross Station. The structures were constructed from wrought iron riveted plate girders circa 1890. Alex led the inspection for assessments for undertaking detailed level 2 structural assessments, where required Alex specified intrusive investigations of key structural elements identify their condition and remaining structural capacity.

2012-2014
Thameslink Framework for Structural Strengthening Services
Network Rail, United Kingdom
Assessment Lead
Alex's led the masonry arch viaduct assessment, undertaking and leading the advanced computational team on the analysis of the arches. Three key packages of work were undertaken for Network Rail; to establish the RA rating of the masonry arch viaducts, the viability of employing the Kirow 1200 crane on the masonry arch structures and assessing the resistance of the spandrel walls to a new external walkway. The assessment used finite discrete element modelling analysis techniques which accurately model the non-linear behaviour of masonry arches. He led the deck plate assessment task for the Structural Strengthening team, developing and implementing a Level 2 assessment of sub-standard deck plates for critical metallic bridges on the assessment programme. Alex was a lead bridge inspector for the GRIP stage 3 and 4 strengthening options as part of the Structural Strengthening Programme.

2010 -2011
Reading Station - Cow Lane Bridge
BAM Nuttall Limited/Network Rail , United Kingdom
Design Engineer
Engineer working on the design of new bridge structures used in the reconstruction of existing bridges on the western approach to Reading Station as part of the station's redevelopment. The bridges are constructed in steel and concrete and have been designed to the Eurocodes.

# LYNNE MABON SIMPSON

Principal Simulation Engineer

Dr. Lynne Mabon Simpson has over 26 years of postgraduate experience in civil and structural engineering, mostly in the field of numerical analysis.

Lynne's key skills are;
- Bridges - Masonry arch bridges (inspection, advanced assessment, strengthening), plate girder bridges (special assessment), RC and PT concrete bridges (analysis for assessment)
- Buildings - Dynamics, particularly vibration due to pedestrian loading, 3D structural modelling
- Advanced structural analysis, including non-linear behaviour (large-displacements, cracking, contact, brittle materials, buckling), dynamics
- Finite element software - NISA2, DIANA, ELFEN, ANSYS, ESA-PT, implicit and explicit solvers, finite/discrete element technique

Lynne also has experience in the project management of projects involving complex Finite Element (FE) analysis.


CONTACT INFORMATION
Lynne Mabon Simpson

Lynne.Simpson@ramboll.co.uk
+44 7929 031657

Ramboll UK
Carlton House
Ringwood Road
Southampton SO40 7HT
United Kingdom


## EDUCATION

1996-1999 Ph.D. Bath University, Bath, United Kingdom
1992-1996 B.Eng. (1st class Hons.) Bath University, Bath, United Kingdom

## PROJECTS

### 2021

Dunaskin Bridge – Archtec, Cintec International Limited, United Kingdom

Archtec strengthening of a single span stone masonry bridge. The bridge is to be part of a route for heavy vehicles carrying equipment to a new wind farm.

Project Manager/Simulation Engineer/Design Engineer

Assessment of bridge and design of strengthening to carry all vehicles to Eurocode standards. Liaison with drilling contractors, main contractor and bridge owner and production and agreement of Approval in Principal documentation and report on strengthening design.

### 2014-2019

Wicklow Street, Buildwell Homes Ltd, United Kingdom

A residential development was proposed on a vacant site in London, situated partly over an existing Network Rail tunnel and adjacent to a railway cutting supported by a masonry wall.

Simulation Engineer

Discrete Element finite analysis was used to assess a cross section through the development.

- To predict likely displacements that may result in the tunnel lining from the proposed building.
- To calculate tunnel lining masonry stresses and compare the results with lower bound representative characteristic strengths.

2021

Shop Bridge Extension – Archtec, Cintec International Limited, United Kingdom

Assessment and strengthening design of a replacement of part of a single span stone masonry arch bridge.

Project Manager/Simulation Engineer/Design Engineer

Assessment of bridge and design of strengthening. Liaison with drilling contractors, main contractor and bridge owner and production and agreement of Approval in Principal documentation and certificates.

2018-2020

12-22 Finchley Road – Planning Work, 12-22 Finchley Road Developments Limited, United Kingdom

A proposed building scheme in London adjacent to an existing railway cutting supported by masonry walls and a railway tunnel.

Simulation Engineer

FEA has been used to model cross sections through the proposed construction, considering the construction sequence and proposed basement adjacent to the tunnel and cutting.

2018-2019

Hawthorn Viaduct LEN3/229 Assessment Cat III Check, Ove Arup & Partners Ltd, United Kingdom

Independent category 3 check of Hawthorn railway viaduct. A seven span masonry viaduct, with the main span exceeding the maximum span in assessment guidelines.

Checking Engineer

Non-linear FDE was used to investigate the behaviour of the structure and check the conclusion of the assessment engineer's analysis.

2017->>>

33-41 Wicklow Street, Buildwell Homes Ltd, United Kingdom

Design of a new residential development on Wicklow Street, London. The site is adjacent to a Transport for London rail line with retaining wall, and above a Network Rail tunnel.

Simulation Engineer

Finite Discrete Element Analysis of cross section through site to investigate the effect of the new building on the existing tunnel. The analysis includes an approximate construction sequence, including estimated loading from previous buildings, removal of previous building and loading from proposed building.

2016->>>

Winchester Cathedral vault modifications, Dyer & Butler, United Kingdom

Modification to a medieval stone vault within Winchester Cathedral for the construction of a new lift. Work involved surveying, monitoring, engineering analysis, structural design and heritage consultancy. The main activity was to cut a large opening through the floor and vault. It is believed to be the first time this has ever been done.

Simulation Engineer

Materially and geometrically non-linear Finite Element analysis of the existing vault, looking at displacement through the proposed construction sequence, including installation of propping, removal of hole, pouring of concrete surround and removal of propping.Reporting of results.

2016->>>

Project Artisan, Burberry, United Kingdom

Engineering consultancy for outline planning permission including reuse of an existing building.

Simluation Engineer

Finite Element Analysis of a quadrapartite masonry vaulted roof with tie rods, supported by cast iron columns. Careful analysis of the roof was required as the building is currently unused and there had been a previous collapse of part of the existing roof. The structural behaviour was investigated with a view to repair and reuse.

2013-2018

Thameslink Framework – 2013, Network Rail, United Kingdom

Strength assessment of masonry arch viaducts for Network Rail Thamelink Team.

Simulation Engineer

A major part of this project was the assessment and feasibility work on existing bridges, including a large number of masonry arches. Development of systems to put together Finite Discrete Element models quickly and effeciently for analysis of existing masonry arches, and subsequent analysis to determine load carrying capacity.

2012-2013

Network Rail Level 0 Assessment Tool for Masonry Arch Bridges, Network Rail, via. Mott MacDonald, United Kingdom

Development of a system for rapid assessment of Network Rail masonry arch bridges, using automated mechanism analysis to study thousands of possible bridge geometries and helping to develop a system for using that information.

Project management, analysis and reporting

Advice on system requirements, overseeing automated mechanism analysis, determining scope of assessed arches, comparing mechanism analysis with Finite Discrete Element analyses and expanding results to include multi-arch behaviour.

2012->>>

East Indian Railways, Bridges 5, 15, 34, 56 and 123, Cintec India, East Indian Railways, India

Monitoring of 5 masonry arch bridges and assessment for increased loading.

Project manager, project engineer

Preparation of monitoring specifications, assessment specifications, analysis and preparation of result reports. Liason with Indian engineers undertaking monitoring and inspecting the bridge.

2010-2012

The Lighthouse Building, UK Real Estate, United Kingdom

Situated within a conservation area, the Lighthouse Building was constructed around 1875 and is partially Grade II listed.

Structural analysis and reporting, liaison with checker

Linear elastic analysis to estimate the effect of retaining and existing historic façade whist removing the internal heavy masonry building and replacing it with a new structural frame situated above shallow cut and cover tunnels in a congested London site

## PUBLICATIONS

2012, Archtec – Strength Assessment and Strengthening of Masonry Arch Bridges, Mabon L, Brookes CL
Structural Faults and Repair 2012

2002, Assessment, Strengthening and Preservation of Masonry Structures for continuous Use in Today's Infrastructure, L Mabon
IABSE Symposium, Melbourne

# DAVID VAUGHAN

Principal Analyst

David is a mathematician and programmer, with 30 years of experience in numerical analysis, software development and software system design.

As an analyst, he regularly works with many advanced aspects of numerical analysis, particularly masonry and concrete materials and time-dependent behaviour. He has analysed a variety of structures, including masonry arch bridges and plate girder bridges. He is considerable experience using Diana, Ansys, Nisa2, and Elfen.

He designs and writes tools for the Advanced Engineering Group and others in the company, to allow large-scale and complex tasks to be carried out, and to enable repetitive tasks to be carried out quickly and reliably, with suitable auditing. He develops systems so that complex tasks, typically requiring a variety of commercial software, can be combined effectively and reliably. He has championed the effective use of Revision Control for analysis and software development in Ramboll UK.


CONTACT INFORMATION

david.vaughan@ramboll.co.uk
+44 (0) 78 7081 1272

Ramboll UK
Carlton House, Ringwood Road,
Woodlands, Southampton
SO40 7HT, UK

www.ramboll.co.uk


## Projects

Archtec (masonry arch strengthening)
Carried out and checked explicit discrete/finite element analyses in Elfen to predict the behaviour of numerous masonry arch bridges and evaluate strengthening strategies. This models local crushing, joint opening, and large-deflection mechanisms. Developed software to make the preparation and post-processing of models straightforward.

Level 0 Arch Assessment tool
for UK Network Rail's efficient assessment of under- and overbridges. Developed mechanism for automatically running ArchieM and recover results, allowing efficient parametric studies of hundreds of arch bridge configurations.

Thameslink
Bermondsey Dive-Under was a vertical re-alignment of Thameslink, designed by Ramboll, involving partial demolition, and incorporating new reinforced concrete multi-span arch structures into the remaining masonry. Carried out extensive non-linear analyses to justify the design.

Putney Bridge
Thames Tideway West involved ground works potentially disruptive to Putney Bridge in London. Carried out Category 3 check of demonstration that the masonry and concrete bridge would not be noticeably distressed.

Spandrel Walls
Carried out parametric studies of structural analysis of masonry arch bridges for a UK Network Rail national research programme to help manage risk associated with masonry arch bridge spandrel walls. Developed the system for generating geometry and analysis models, analysing, and harvesting results for large numbers of analyses.

Police station, Hong Kong
Assisted in a successful expert witness contribution to a legal case around the partial collapse of a masonry building during the course of structural works. The work involved clearly demonstrating the shortcomings of others' analysis work, and numerical illustrations to help present engineering concepts to a judge.

London Bridge Station
Carried out analyses and assisted with handling pointcloud data for the monitoring of London Bridge Station during the construction of the Shard of Glass. Involved discrete/finite element analyses in Elfen to predict the behaviour of masonry tunnels and vaults.

Northern Hub
Carried out various analyses, to predict structural behaviour of extensive masonry arch structures during the propping, partial demolition, and addition of new structures in this large rail project.

Leeds Station New Entrance
Building a new entrance was expected to increase loading on the masonry vaults under the station. Carried out 3d checks on the vaults with the strengthening scheme proposed.

Port Baku Chimney
Carried out non-linear push-over analysis of an historic 56m-tall masonry chimney, and designed and set out retrofitted strengthening, which was installed.

Lincoln Cathedral
Ramboll were involved in replacing a flying buttress. Used non-linear discrete/finite element analysis to predict the ultimate strength of the already existing and proposed structures.

Peninsula Yangon Building
A tall historic masonry façade was being heavily propped, ready for the interior to be redeveloped, but was showing signs of distress. Predicted behaviour and damage in the façade due to wind loading and a variety of ground works.

## KEY QUALIFICATIONS

MA (Hons), Mathematics
MSc, Computation

T-4002 MAARIAN KIRKKOSILTA
LOAD RATING ASSESSMENT FEE PROPOSAL

## Appendix B – Application of the Finite/Discrete element method to arches

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Carl Brookes
Technical Director, Gifford, Southampton, UK

ice
Institution of Civil Engineers

# Application of the finite/discrete element method to arches

C. Brookes BSc(Hons)

**During the last 10 years UK engineering consultancy Gifford has been assessing masonry arch bridges and using the finite/discrete-element method to predict their structural behaviour. In the majority of cases this work has followed bridge strength assessments based on traditional techniques where under-strength bridges are first identified. Over 200 bridges have now been investigated ranging from small rural bridges in the UK to massive structures used by Indian Railways, and a significant economic and environmental benefit gained through their continued use. This paper describes how the finite/discrete-element method has been applied and verified and covers the description of a development programme including full-scale laboratory tests, supplementary load tests on bridges in the field, and several monitoring programmes. The advantages this technique can provide over conventional arch bridge analyses, both limit analysis (mechanism) and traditional finite-element modelling, are described and how through partnering an innovative assessment and strengthening service is being delivered. The relevance of this approach to emerging serviceability limit state arch bridge assessment, which is seen as being particularly important for railways, is also discussed.**

## 1. INTRODUCTION

It is very likely that there are well over half a million masonry arch bridges in use throughout the world today, principally carrying road and rail. European railways alone account for 200 000 bridges (Orbán, 2004). These bridges form a vital asset. Their replacement cost is almost incalculable yet a worldwide insatiable appetite for economic growth is in some cases pushing their use to the limit.

Despite masonry arches being ancient in form, it remains notoriously difficult to accurately assess their strength. At all limit states their behaviour is complex, deriving their overall behaviour from the interaction of individual parts, blocks, bricks, mortar and fill. Several methods for assessing the strength of arch bridges have become well established, a vital activity where traffic loads increase, but their generalised use is limited and their application for designing strengthening difficult. Finite-element analysis, which has to be non-linear to predict strength, has also been successfully applied but the choice of tensile material properties can be problematic as this can artificially influence the outcome.

The finite/discrete-element method (FDEM), which involves the automatic computation of interacting bodies is, therefore, a natural choice for representing masonry and this type of non-homogenised structure. Like the conventional finite-element method, being a generalised approach also means that, subject to verification, any geometric form of masonry can be simulated. Consequently, there are no restrictions to the arch bridge form, and the number of spans, rings and piers that can be modelled. Furthermore, unlike many simpler strength assessment methods, there is no adherence to predetermined failure mechanisms – for instance, a set number and pattern of hinges.

The application of FDEM has marked a step change in the sophistication that can now be applied to the structural analysis of masonry arch bridges. Not only can it be used to accurately assess strength but also to determine bridge deformation, including important non-linear effects, making it possible to assess behaviour at both strength and serviceability limit states. Being a generalised approach, the behaviour of complex bridges can be assessed where, for example, a concrete saddle may exist, a bridge has been propped and, in the case of strengthening, retrofitted reinforcement is introduced.

UK engineering consultancy Gifford has completed over 200 bridge assessments and bridge strengthening designs, mainly in the UK but also in the USA, Australia and India. This service was originally conceived for efficient, economic and sympathetic strengthening of arches, but the method of structural analysis can also provide accurate strength assessment of existing bridges and on many occasions has been used to show that bridges previously identified to require strengthening need no further engineering to support planned loads.

## 2. CONVENTIONAL ASSESSMENT

Methods of strength assessment have been categorised (McKibbins *et al.*, 2006) as semi-empirical, limit analysis and solid mechanics methods.

### 2.1. Semi-empirical methods

Most semi-empirical methods are based on the Military Engineering Experimental Establishment (MEXE) method which evolved from work undertaken in the 1930s for the military to rapidly assess arch bridges. It is often still used as a first pass strength assessment but its use is highly subjective and there are many limitations. It is of little value for any detailed work such as the design of strengthening.

### 2.2. Limit analysis methods

Most conventional bridge assessments are now carried out using computerised versions of limit analysis, also known as mechanism analysis. In its simplest form these methods consider a two-dimensional (2D) arch comprising a series of blocks of infinite compressive strength, which cannot slide against each other and cannot carry tension. A routine is used to establish the locations of hinges in the span, followed by calculation of reactions and then vector algebra to position the resultant line of thrust. The method produces a lower bound solution. In other words, if a load path can be found that lies entirely within the masonry then the modelled arch is capable of sustaining that load, even if it is not the true load path.

Limit analysis techniques have proved to be excellent tools for first phase strength assessments but several restrictions exist that are important in the design of strengthening. The most important of these is the inability to calculate strains and displacements. Consequently, it is not possible to determine the distribution of stress at operational load levels, it is difficult to assess the serviceability of bridges and, in the case of strengthening, it is not possible to determine the share of load between the existing bridge and the strengthening.

### 2.3. Solid mechanics methods

The established technique used to model continuum-based phenomena in solid mechanics such as deformability is the finite-element method (FEM). Not surprisingly this has also become the most popular solid mechanics method used for arch bridge analysis, and there are numerous well-developed industry quality computer programs available.

As is the case in limit analysis, most work is carried out using 2D representations, generally plane strain, but three-dimensional (3D) shell and solid models are used for special assessments.

Although these techniques can be good for determining displacements, strains and stresses at operational load levels, they quite often become difficult to use to predict ultimate strength and damage. This is generally because of the type of solver that is used, normally an implicit solver involving matrix factorisation (Owen and Hinton, 1980), and the effort required to ensure internal forces are in equilibrium with external loads, as brittle materials such as masonry soften and redistribute load. The solution to the equilibrium problem is normally to use a hypothetical masonry tensile strength but choosing a suitable value, large enough to achieve equilibrium conditions are met but small enough not to influence the result, can be a challenge.

## 3. DISCRETE ELEMENT METHOD

### 3.1. Description

Numerical techniques have been devised to represent discontinua where body or particle interaction defines overall behaviour (Cundall, 1971). Perhaps the most advanced technique that describes this behaviour is the discrete-element method (DEM). The relatively new finite/discrete-element method (FDEM) described by Munjiza (Munjiza, 2004) is a combination of FEM and DEM and provides a more natural approach to the simulation of many materials and structures. It has been applied to a diverse range of engineering and scientific problems from food processing to rock blasting. Through automated adaptive modelling, even the transition from continua to discontinua and the fracturing and fragmentation process can be represented.

FDEM is aimed at problems involving transient dynamic systems comprising large numbers of deformable bodies that interact with each other. Models involve typically thousands, but in extreme cases millions, of separate finite-element (FE) meshes automatically interacting with each other using DEM contact algorithms. The solution of the continuum equations associated with FEM is well established, the algorithms within DEM less so.

Contact detection and contact interaction lie at the heart of DEM. Contact detection is aimed at identifying discrete elements that can potentially come into contact with each other and eliminating those far away from subsequent contact interaction algorithms. Different algorithms have been developed for different packing densities, for example sparse and moving or dense and static. The chief aim here is to reduce computing effort. Contact interaction applied to the surfaces of discrete elements coupled through the detection process is where interface behaviour is calculated. Here interface laws are applied according to the surface characteristics of the contacting discrete elements, for example frictionless no-tension contact. During the solution of transient dynamic problems of even quite modest size, millions of contacts will be detected and resolved.

Another key aspect of FDEM is that the analysis involves all equations of motion, is therefore dynamic and uses an explicit central difference solution scheme (Owen and Hinton, 1980). This involves a time-stepping procedure that is conditionally stable, but unlike many conventional FE solvers that use an implicit solution scheme, does not involve computationally intensive matrix factorisation. Solutions are achieved only through the use of very small time steps. The critical time step size below which steps must remain for stability and accuracy is given by the time taken for a stress wave to travel across the smallest finite element. The efficiency of DEM contact detection and the avoidance of equilibrium calculations allows FDEM simulations to predict failure, collapse and post-failure kinematic behaviour.

### 3.2. Application to masonry arch bridges

Masonry is a non-homogenised material, can be regarded as a discontinuum and as such is ideally suited to FDEM. Simply, a masonry arch bridge is a special form of masonry structure, which is an important consideration when faced with complex bridge arrangements.

The approach that has been developed for arch bridges, applied using the implementation within the FE computer program ELFEN (Rockfield Software Ltd, 2003), uses smeared masonry compressive properties and explicit mortar shear and tensile properties. Each brick or block unit is modelled with a separate FE mesh and each unit becomes a single discrete element. It has been found that units can also be grouped together (Brookes and Mehrkar-Asl, 1998); a blocky arrangement of four or five bricks glued together can improve computational efficiency without any loss of accuracy. The masonry arch is then assembled using blocky arrangements in hundreds, possibly thousands of discrete elements. Figure 1 shows part of a meshed arch barrel. Other bridge parts, for example fill, surfacing, abutments, piers and backing, are similarly represented although the material models may be different.

FDEM arch bridge models will develop failure mechanisms consistent with limit analysis results if these are critical as well as providing displacements, stresses and strains consistent with solid mechanics.

Another key aspect to the use of FDEM and the adopted modelling approach is that representing masonry at a fundamental scale requires only commonly available and basic material parameters to be used in order to accurately characterise bridge structural behaviour. Non-linear material models are used to define the deformable behaviour of the masonry in compression and the fill in tension. A perfectly plastic von Mises yield criterion is generally used to cap compressive strength, and a Rankine yield criterion used to give a simple no-tension soil model.

The behaviour of mortar, as well as other contacting surfaces such as masonry to fill, is included by using interface material models. Interface models give the surface of discrete elements appropriate mechanical properties. Mortar is represented differently depending on the type of construction. Historic construction involving lime mortar joints is represented using a no-tension Mohr–Coulomb friction relationship. Modern masonry with cement mortar produces masonry with some tensile strength. In these instances good predictions of masonry behaviour can only be made by including mortar tensile strength and a fracture energy formulation to model the development of cracking. Generally, masonry arches are historic constructions and do not include cement mortar.

For most types of masonry the generic material characteristics, compressive strength, Young's modulus, mortar friction and mortar cohesion, necessary for FDEM simulations are readily available (BSI, 2001; Hendry, 1990; Highways Agency, 2001). They are no more demanding to obtain than those parameters required for conventional limit state analyses. An estimate for Young's modulus for different types of fill in compression is similarly available.

There are no limitations to the geometric arrangements of arches that can be represented with FDEM other than those associated with computational resource. As an illustration, Figure 2 shows a model of a deformed two-tiered arch arrangement. However, models are kept as simple as possible to reflect the confidence in material parameters, geometric arrangement and to be reasonably compatible with codes of practice rules through which most design and assessment work is undertaken. Hence, the large majority of simulations are 2D and plane strain.

Models always include abutments and the supported fill as the strength of arch bridges is often sensitive to the abutment construction, particularly flat arches with high span-to-rise ratios.

In assessment and design, live load is generally applied by explicit representation of axle loads using discrete elements. Weight is applied to these elements and the axles moved across the span with a prescribed velocity, as illustrated by the sequence of images in Figure 3. As transient dynamic solutions are obtained, regard has to be given to acceleration arising from sudden movement and inertia effects. Consequently, loads are applied smoothly and slowly to ensure near static responses are obtained and dynamic effects are negligible. Permanent loads are introduced through construction sequences which, depending on the barrel shape, may necessitate the use of modelled temporary formwork to support the barrel self-weight while the fill is added – a process that is always required when constructing real arch bridges. Figure 4 shows an elliptical arch barrel and modelled formwork. It has been found that modelled elliptical barrels always require the construction sequence to include formwork support to avoid collapse during initial dead loading.

Although the time required to develop FDEM bridge models exceeds that of comparable limit analysis representations, these models can still be assembled in 1 or 2 h. Furthermore, solution times, which are continuously tumbling as ever faster computers become available, are modest compared with similar FEM representations, with strength analysis completed in around 4 h for a typical bridge on a 3·6 GHz personal computer. This includes the calculation of permanent loads and the traverse of a single vehicle. To complete an assessment or design, several axle arrangements have to be considered to be sure that the

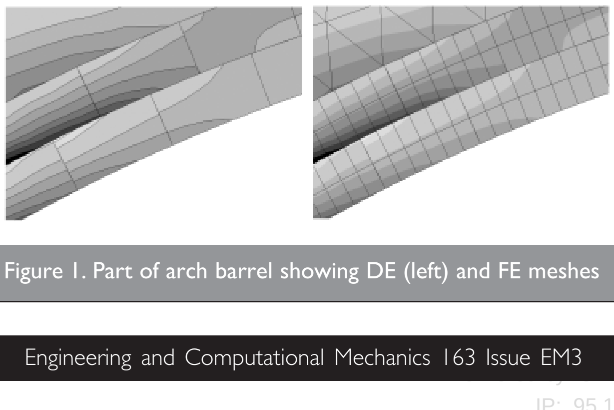


Figure 1. Part of arch barrel showing DE (left) and FE meshes

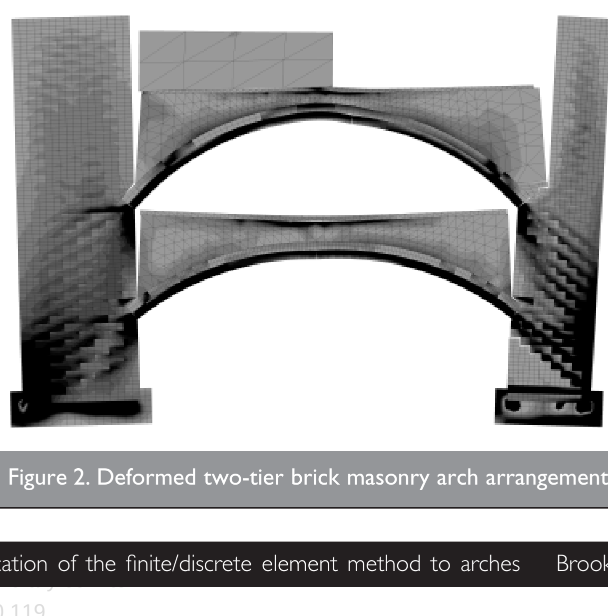


Figure 2. Deformed two-tier brick masonry arch arrangement

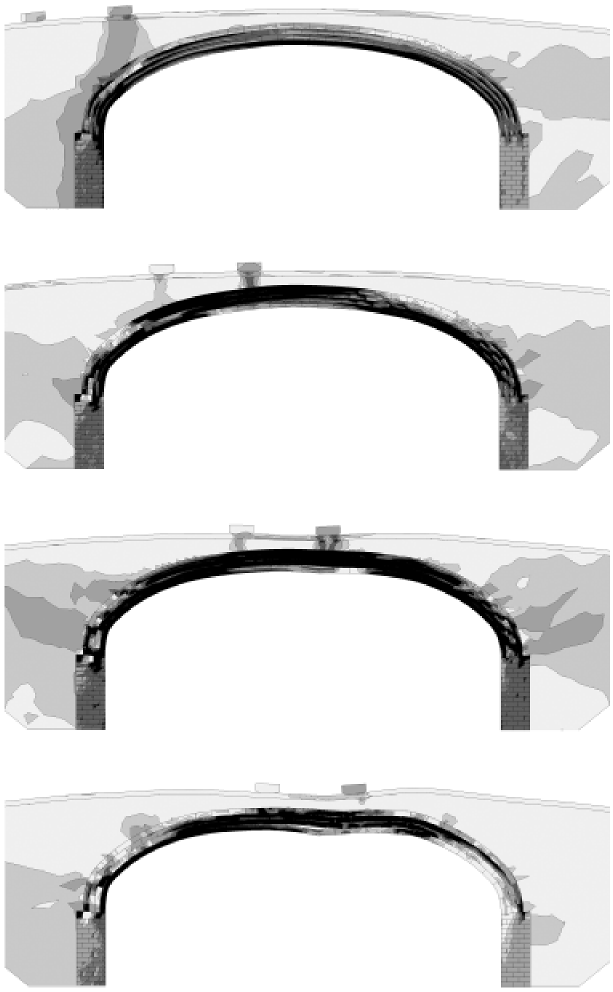


Figure 3. Sequence showing failed load assessment

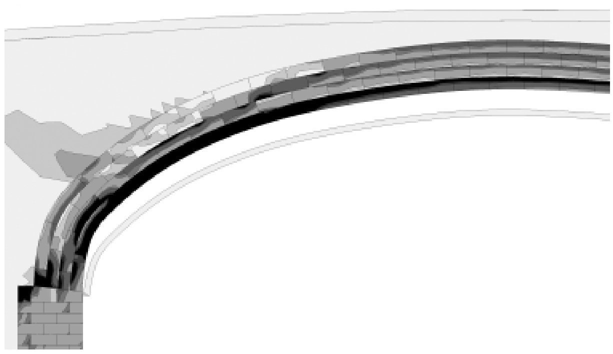


Figure 4. Modelled formwork to provide temporary support

critical case has been identified, so this could take several days. With relatively small problem sizes, around 5000 to 10 000 degrees of freedom, mass scaling techniques to accelerate the solution process are never used to obtain solutions, but are useful to quickly check the simulation process.

### 3.3. Modelling reinforcement

The FE technique is used to model steel reinforcement independently meshed from the masonry using a partially constrained spar formulation (Roberts, 1999). Modelling reinforcement is an important aspect to strength prediction where it is proposed for strengthening, but is seldom encountered in existing bridges. Connection between the reinforcement and the masonry FDEM representation is achieved through non-linear bond elements. These provide the transfer of axial shear force between the reinforcement, the grout used for providing bond, and the masonry. Modelling of reinforcement arrangements is completely automated without the need for topologically consistent element meshes, thus accelerating the modelling process and permitting rapid comparison of designs. Where reinforcement elements cross masonry joints, transverse shearing strength or dowel effect is ignored. This is a simplifying assumption and provides a conservative approach to estimating strength.

## 4. STRENGTHENING

### 4.1. Description

The method of strengthening that has been developed comprises retrofitting stainless steel reinforcement around the circumference of the arch barrel. The reinforcement is then grouted into holes drilled into the bridge with a coring rig from the road surface or, alternatively in the case of multi-span structures, from below. Once the work is completed there is no evidence of any major intervention to the bridge, a characteristic that is particularly important for historic structures.

Arches conventionally fail by the development of four hinges leading to a mechanism. The design basis for the strengthening is to locate reinforcement to improve bending strength where hinges are predicted to develop. By providing additional strength in this way the arch barrel is better able to resist live load, and peak compressive stresses in the masonry are reduced in comparison with similar unstrengthened cases. The same procedure is applied to more complex bridge arrangements including multi-span arches although failure mechanisms and reinforcement positioning require different locations to be considered in design. Figure 5 shows the simplest arrangement of reinforcement which in this instance is installed from above, and Figure 6 illustrates the installation process for a multi-span bridge.

Accurate 3D geometric modelling is required not only to develop the FDEM model but also for setting out calculations and the accurate positioning of reinforcement. Three-dimensional laser surveys are being used increasingly to provide the high-density survey measurements (point clouds), saving time and improving efficiency. Figure 7 shows a typical laser survey and the developed computer-aided design 3D

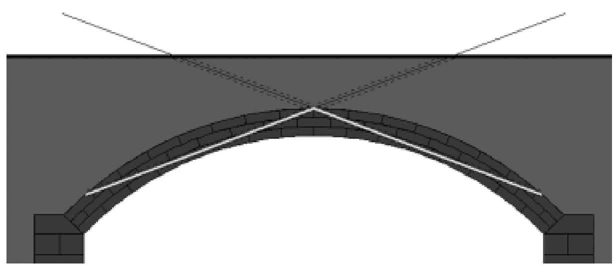


Figure 5. Arrangement of retrofitted strengthening reinforcement

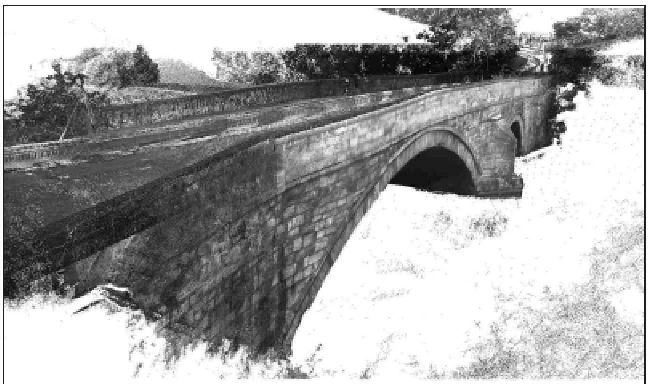
Figure 6. Installation of reinforcement, drilling from below

surface geometry model, including reinforcement and a zone where buried utilities have to be avoided.

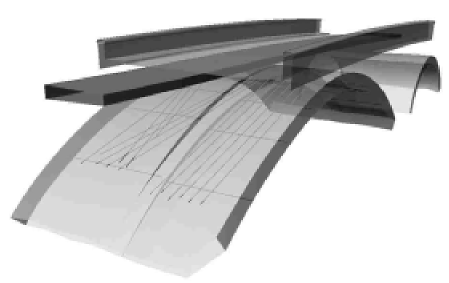
### 4.2. Benefits

In comparison with conventional arch bridge strengthening such as concrete saddling and lining, retrofitted reinforcment designed using FDEM simulation has several practical benefits, which includes the following.

(*a*) Good assessment of existing strength and bridge behaviour is obtained and the results can be used to justify safe and continued use of an existing bridge, providing an alternative to bridge replacement.
(*b*) Where a weak bridge is identified, detailed prediction of bridge behaviour allows accurate matching of strengthening to the loading requirements, thus minimising any intervention.



(a)



(b)

Figure 7. (a) Three-dimensional laser survey and (b) computer-aided design 3D surface geometry

(*c*) Strengthening is invisible, which is particularly important for historic and heritage bridges.
(*d*) Construction is small scale and fast to implement.
(*e*) Disruption to bridge users during strengthening is much less than conventional strengthening such as concrete saddling.
(*f*) Provides a more sustainable bridge strengthening solution with lower environmental impact, embodied energy and carbon emissions.
(*g*) Because displacements and strains are predictable, assessments and strengthening designs can be based on limit states other than purely ultimate strength.
(*h*) Each reinforcement bar installation provides a core of information that can be used to confirm the materials and internal arrangement of the bridge.
(*i*) In many instances all these factors equate to reduced cost.

### 4.3. Working with codes of practice

Assessment and strengthening services have to be provided within a framework which embraces as far as possible national codes of practice. Unfortunately, outside of the UK, there are few rules to help engineers assess arch bridges. For example, live loading is almost always developed for beam arrangements of bridges where load support is primarily through bending, and masonry strength assessment is often permissible stress based. In earthquake regions bridge rules again tend to be geared towards steel and concrete construction. Arbitrary and outdated rules can also be a problem. In India the railways have a code of practice for the design of masonry arch bridges which imposes almost arbitrary performance limits on deflection.

The use of FDEM to simulate arch bridges is a performance-based method, useful for limit state assessment and design, but cannot be directly used for rules that have been developed for linear, often inaccurate, working stress approaches. In these instances to satisfy bridge technical authorities, hybrid analyses are run alongside the more realistic and reliable limit state work. The results allow additional checks to be made with local code of practice rules and guidelines.

## 5. VERIFICATION

The process which has been undertaken to verify the FDEM analytical methods employed in arch bridge assessment and strengthening design has included a number of key strands, and comparisons, that are listed here.

(*a*) Conventional methods of arch assessment.
(*b*) Published data from full-scale tests of unstrengthened arches carried out by others.
(*c*) Full-scale tests by the Transport Research Laboratory (TRL) of bridges strengthened using retrofitted reinforcement specifically commissioned as part of the verification process.
(*d*) The results obtained by monitoring bridges in the field including the comparison of performance between before-and-after strengthening.

Additionally, a philosophy of fixing material parameters for whole series of tests where similar masonry construction has been employed (compressive strength of bricks, mortar type, etc.) has been adopted. This prevents an individual arch analysis being adjusted to gain better correlation with tests within a series without influencing all the others. Similarly, the analysis of strengthening follows on from verified and fixed unstrengthened analyses.

A small sample of the verification work (Brookes, 2004) and recent field trials illustrating the accuracy and flexibility of FDEM arch simulation follows.

## 6. FULL-SCALE ARCH TESTS

### 6.1. Unstrengthened arches

In undertaking comparisons with full-scale tests of arches the two key objectives were to demonstrate the accuracy of numerical solutions and the appropriateness of simplifying assumptions. Full-scale arch bridge tests have been selected where boundaries and loading are two-dimensional so that the validity of comparing their results with 2D FDEM analyses has not been compromised by 3D behaviour. Skew arch barrels and spandrel walls are examples of bridge features that generally give rise to 3D structural behaviour.

Comparisons with full-scale tests (Brookes, 2004) have included those carried out by the Transport and Road Research Laboratory (TRRL) on redundant bridges in the 1980s, and laboratory tests by TRL and The Bolton Institute in the 1990s. Figure 8(a) shows the arrangement of the arches used by TRL as well as those used later to test the strengthening. Figure 9 compares test results, vertical displacement measured at the position of the load, with FDEM predictions for arches in two conditions: with brick masonry rings unbonded (partially ring

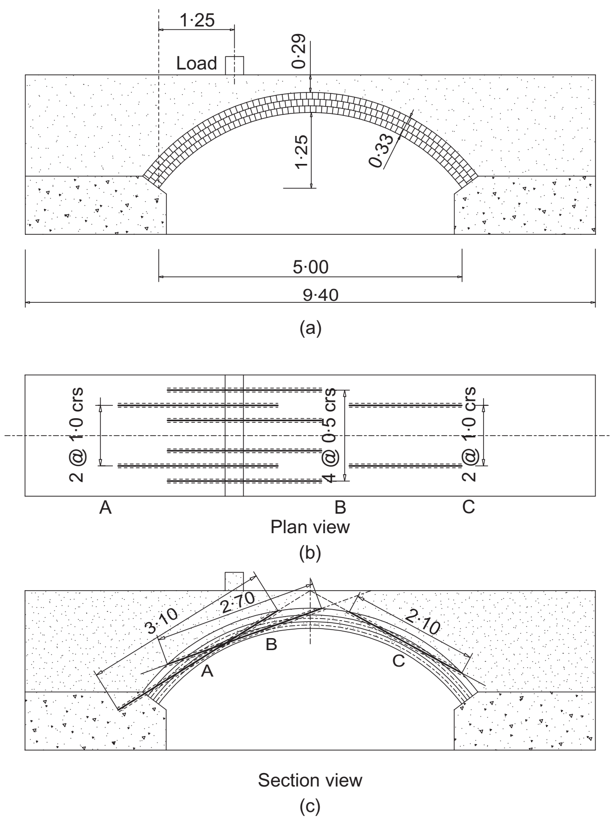



Figure 8. Strengthened arch bridge test arrangement (dimensions in m)

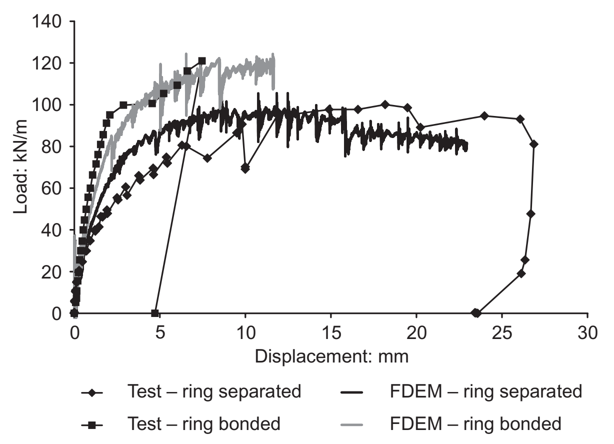



Figure 9. Full-scale arch test, predicted and test comparison

separated) and with rings bonded. Unbonded and bonded conditions were constructed to be representative of arch barrels in poor and good conditions, respectively. The figure shows good agreement in both strength and displacement response with strength predicted to within 5%.

### 6.2. Strengthened arches

In order to test the practical implementation of strengthening, to further validate the FDEM method of structural analysis, to help quantify key strength parameters and to illustrate the degree of strengthening that could be achieved, two full-scale tests of strengthening designs were carried out at TRL (Brookes, 2004). The arch arrangements were based on earlier unstrengthened arch tests. Figure 8 also shows the reinforcement arrangement used in the first of these tests. The second test was very similar but used slightly more reinforcement and used spaced bundled reinforcement, in place of single bars. Both tests used partially ring-separated barrels to be representative of arches in poor condition and those most likely to warrant strengthening.

The reinforcement arrangements were configured for a stationary point load test and, therefore, were arranged asymmetrically with respect to the span. In practice, with moving axle loads, reinforcement arrangements are generally arranged symmetrically to cater for any axle load position.

Figure 10 compares the graphs of load plotted against displacement results obtained by the FDEM simulations with those obtained from the two strengthened tests. Again measured displacement is at the position of the load. The figure shows strength predictions to be within 2% of test results. There is also very good stiffness correlation, displacements remaining within approximately 5% of test values throughout loading.

Making comparisons between strengthened versus unstrengthened tests, illustrated in Figure 11, shows the failure load of both strengthened arch barrel tests to have been increased by a factor of approximately 2. The reinforcement has delayed the formation of hinges and added considerable strength to the arch barrel, and the arch failed in a gradual and a ductile manner. In practice the characteristics of the arch barrels are improved sufficiently for the intended loading.

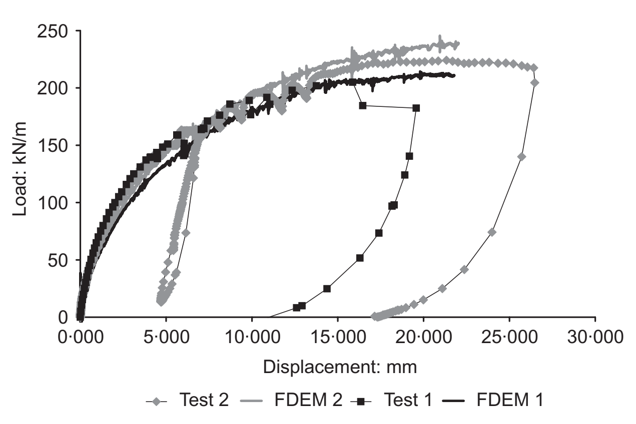



Figure 10. Strengthened arch, predicted and test comparison

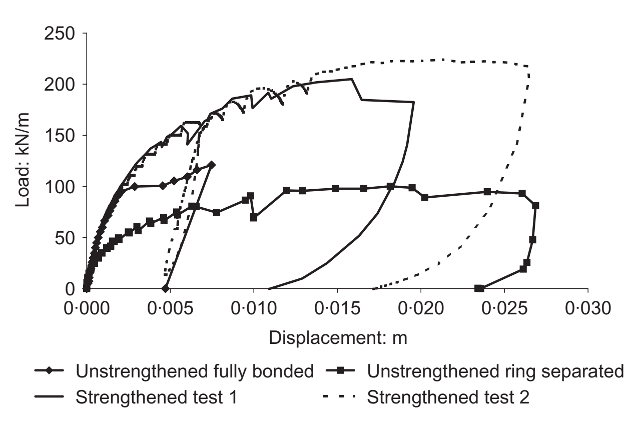



Figure 11. Strengthened and unstrengthened arch comparisons

### 6.3. Observations relating to serviceability

No clear definition of serviceability exists for masonry arches. Deflections and cracking behaviour is normally used to define a serviceability limit state. However, in arches these quantities are generally small and very difficult to detect under expected service loads and they cannot be calculated by conventional structural analysis. However, results from monotonic and cyclic load tests have been used to derive masonry stress limits in terms of a limiting factor of the ultimate capacity below which permanent damage does not occur from repeated loading.

Based on work done by TRRL in the 1980s, the Highways Agency assessment standards for arches are based on serviceability being maintained provided applied loads do not exceed half the ultimate capacity.

Cyclic loading on bridge piers has been investigated by British Rail Research (Clark, 1994) and some progress made in linking fatigue of brickwork with a serviceability limit state. It was concluded that, for dry brickwork, if applied loads do not exceed half the ultimate capacity an unlimited number of load cycles could be sustained. However, for saturated brickwork lower load levels are required.

Both observations of monotonic loading and cyclic loading have led to the recommendation of a 50% rule and are in effect stress limit based. The current strengthening design method, which uses load factors based on the UK Highways Agency standards, embraces the serviceability limit state implicitly within the load and material factors used at the ultimate limit state. Although this method is consistent with current practice, FDEM analysis used in the design also enables the behaviour of the arch under serviceability loading to be investigated.

Comparisons of results between unstrengthened and strengthened tests show that under identical loads, displacements are very similar. Corresponding structural analysis of the test arches predicts compressive stresses in strengthened arches to be lower than that of the unstrengthened arch under the same loading. For example, using the bridge proportions of the strengthened arch tests and UK highway 40/44 tonne vehicle axle loading, under the maximum service load the maximum compressive stress in the masonry barrel was reduced by approximately 15%. For this case Figure 12 compares maximum levels of compressive stress. The reduction in stress is due to the fact that the strengthening introduces bending capacity into the arch barrel, which can therefore resist the applied loading at the critical points more effectively. Hence, on the basis that serviceability can be defined by a stress limit, the reduction of stress levels in the masonry of strengthened bridges should have a beneficial effect on serviceability.

Other aspects of bridge serviceability might be concerned with specific deteriorated conditions in arch barrels, such as loose bricks and ring separation. The risk here is that debris falling from a bridge would represent an unacceptable hazard. An example of an arch barrel in a weakened condition that could develop loose bricks as a result of partial ring separation has been tested and used in comparison with strengthened barrel tests. Displacement results show that strengthening significantly increases the stiffness of the ring-separated barrel, restoring it to that of the fully bonded case (as-built condition); see Figure 11. The implication is that strains in the intrados have been reduced and the risk of bricks loosening is thereby also reduced. Provided an arch is maintained in reasonable condition the risk of bricks loosening should be reduced in comparison with an unstrengthened arch. There is also no reason to doubt that similar trends in behaviour will occur if the inner ring itself is in a deteriorated condition.

Bridge owners and experts in the field recognise the

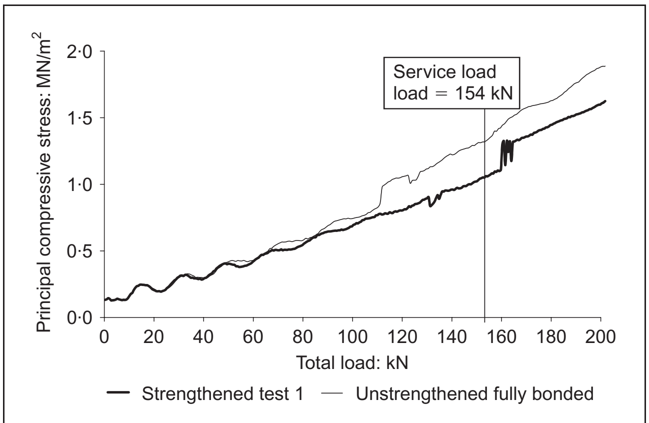



Figure 12. Comparison of maximum masonry compressive stresses

desirability of further research with respect to the serviceability limit state and phenomena likened to masonry fatigue. However, at the current time no specific guidance or criteria exist with respect to explicit evaluation of the serviceability state in arches.

To provide increased confidence that the serviceability of a bridge is being improved by strengthening designs, the following additional checks have been introduced into the design process.

(*a*) Either check that stresses under the required live loading do not exceed those in the unstrengthened bridge under existing live loading, or alternatively check that stresses in the strengthened bridge are below an agreed serviceability limit state value.
(*b*) To be sure that existing defects are not made worse, or for that matter introduced into arch barrels by strengthening, strains along the intrados under the required live loading are checked to ensure they do not exceed those in the unstrengthened bridge under existing live loading. Strains are calculated over a reasonable length so that an estimate of radial joint cracking, critical to loosening of bricks, is included.

These criteria are considered very conservative and have been introduced as a precautionary measure. It is likely that stresses and strains beyond these limits will be quite safe and have no adverse serviceability effects. However, further fundamental research is required to establish appropriate limiting criteria.

## 7. FIELD MONITORING

Several bridge monitoring programmes have been undertaken during the last decade to help verify FDEM arch simulations, and for strengthened bridges, to make before-and-after behaviour comparisons. The most recent of these was for the Massachusetts Highway Department with the first part of the programme, which involved live load testing of a four-span unstrengthened stone arch bridge carrying a two-lane highway, being completed in December 2009. Figure 13 shows the bridge, the FDEM model and sketches of the test vehicles.

As part of a rehabilitation programme Ames Street Bridge in Dedham, Massachusetts is to be over-spanned by a new reinforced concrete deck. The deck construction will firstly involve strengthening the existing arch bridge and protecting the masonry arch barrels from possibly damaging loads while in its weakened condition during construction. Although the efficacy of this over-spanning approach often used in North America is questionable, as many of the advantages of strength assessment and strengthening are not realised, the opportunity to provide some valuable test data was nonetheless available.

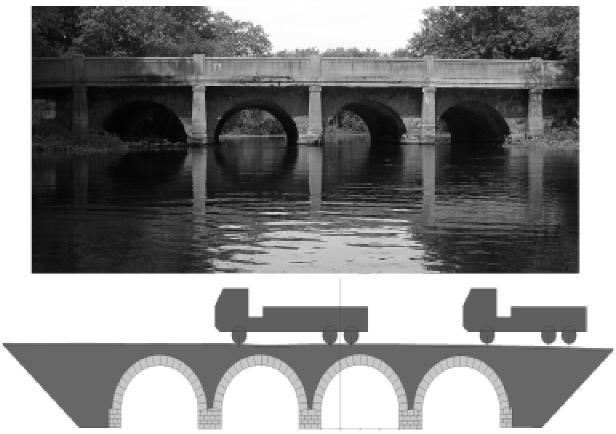


Figure 13. Ames Street bridge, photograph and FDEM representation

The programme of work included a series of tests and FDEM simulations to verify the strengthening process. A small sample of the findings of the first series of physical tests and accompanying simulations providing baseline information relating to the existing unstrengthened bridge is given here. Further work is planned during 2010 on the strengthened bridge before over-spanning work starts.

Physical testing involved monitoring the bridge whilst applying controlled vehicle loads with the bridge closed to normal traffic. Intrados circumferential strain and vertical displacement of the arch barrels were recorded at 36 positions on two adjacent spans. These measured bridge responses along six longitudinal and three transverse lines for each monitored span. Two ballasted three-axle dump trucks were used to traverse the bridge in several driving patterns at walking pace, with continuous recording of vehicle position as well as all displacement and strain results. FDEM simulations were used to mirror the tests.

Generally, predictions of bridge behaviour rely on a 2D plane strain analysis to model longitudinal behaviour, and hand calculations to determine the spread of the load effect in the transverse direction. Referred to as transverse load distribution, these hand calculations are developed along code of practice guidelines developed in the UK for the assessment of arch bridges (Highways Agency, 2001) and are known to be conservative. However, where comparisons are made with monitored bridges and it is not possible to load the full width of the bridge, it is often necessary to look at transverse load distribution more accurately to achieve good correlation. In the case of Ames Street bridge, an adjustment to allow for the combined effects of the live load transverse position and the transverse location of the instrumentation had to be made as full-width loading was not possible.

Figures 14 and 15 show comparisons between measured and predicted results for displacements, and intrados circumferential strains, respectively. Here one of the test vehicles traversed the bridge close to the edge of the arch barrels and the results shown correspond to a single quarter-span position. Although this is a small snapshot of the data collected, the good correlation that is shown is a reasonable representation of the broader range of comparisons that have been made.

## 8. CONCLUDING REMARKS

FDEM has been successfully applied for a decade in over 200 arch bridge assessments and strengthening projects, and the method is now recognised as a special assessment tool. During this period, verification of this technique has been carried out by making comparisons with the results of full-scale tests, with

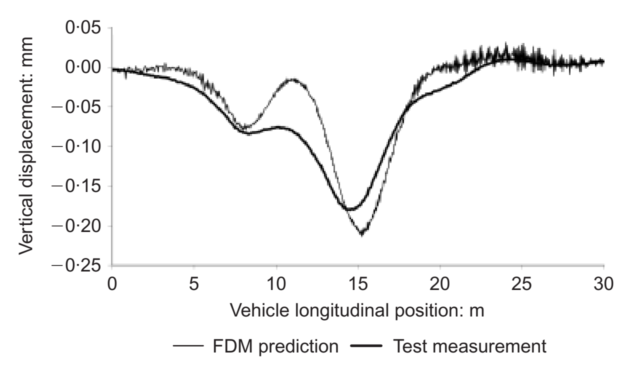



Figure 14. Comparison of measured and FDEM vertical displacement

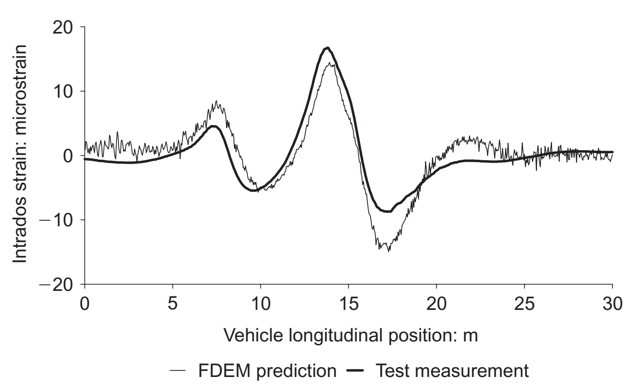



Figure 15. Comparison of measured and FDEM circumferential strain

data published by others on arch tests, with the results obtained by conventional arch bridge assessment methods and with the results obtained from monitoring programmes in the field. In all instances broadly good comparisons of strength and stiffness have been made.

Recognising that arch bridge displacement, strain and damage can also be predicted, and that these factors are important to bridge serviceability, further work has been carried out to investigate in-service bridge behaviour. However, until limiting criteria are developed, whether strain, stress, crack or fatigue based, and until the serviceability behaviour of masonry arch bridges is better understood, a method has been developed that ensures that stress and strain conditions when strengthening for larger loads do not exceed those in existing arch barrels under existing loading.

By representing the constituents of masonry arch bridges in a natural and non-homogenised way, FDEM can provide realistic simulation of structural behaviour for use in both special assessment and strengthening design.

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## Appendix C – The assessment and strengthening of masonry arch bridges

The assessment and strengthening of masonry arch bridges

Ramboll are internationally recognised experts in assessing, strengthening and managing ageing infrastructure. We are renowned for our non-standard assessment approaches which have avoided costly strengthening or replacement of structures, saving our clients millions of pounds. We provide World class expertise in areas such as post-tensioning, the realistic assessment of structures, failure mode effect and criticality analysis, the application of advanced engineering simulation, and 3D computational design. These skills, coupled with our experience of specialist design and construction techniques enable us to safely maximise the capacity of existing structures and, where unavoidable, define strengthening schemes within significant operational constraints.

Amongst the advanced methods of engineering simulation that Ramboll have applied to the assessment of bridges is the Finite Discrete Element method (FDEM). Ramboll were the first in the World to recognise the power of this technique and to apply it industrially to the problem of assessing masonry bridges. This has included single span bridges, multi-span viaducts, bridges with masonry piers and abutments, 3D vaults and jack arch bridge decks. The FDEM assessment process was first developed to strengthen masonry arch bridges in response to European requirements to increase vehicle loading to 40/44 tonnes. Subsequently, it has been used to undertake special strength assessments for highway authorities and the railways including Network Rail and Indian Railways.

The development and application of FDEM arch bridge assessments was possible because of the close collaboration of Ramboll and Rockfield Software, a technology outlet for Swansea University. Important additional partnering with contractor Cintec International extended the process from strength assessment, when a weak bridge is identified, to bridge strengthening. Strengthening is based on a low impact installation and highly sustainable process of precisely positioned retrofitting reinforcement. There have been many instances where this form of strengthening avoided more costly and disruptive alternatives such as concrete saddling, arch barrel lining and even bridge replacement.

In most cases FDEM assessments follow bridge strength assessments based on traditional techniques which for Network Rail would generally follow Level 1 assessment work, and for highways where under-strength bridges were first identified as part of the 40/44 tonne assessment programme. Often the bridges that are assessed are beyond the scope of assessment guidelines, for example spans exceed 20m, the structures are multi-span or perhaps have been propped or damaged. Over 350 bridges have now been assessed and many strengthened, ranging from small rural bridges in the UK to massive structures used by Indian Railways. Significant economic and environmental benefits have been gained through their continued use. For instance, as part of a bridge health monitoring programme for Eastern Railways in India FDEM simulations were used to not only complete strength assessments but also to predict behaviour under operational conditions and heavy freight loads. This work included comparing measurements of displacement and strain by field monitoring under test trains and live traffic. The work allowed Eastern Railways to increase freight loading on broad gauge tracks to 100 tonne wagons and with no other intervention.

FDEM arch bridge simulation has been applied and verified during a development phase between 1998 and 2002 and included a programme of full-scale laboratory tests, supplementary load tests on bridges in the field, and several monitoring programmes. Many awards have been gained including a prestigious Queens Award for Innovation:Enterprise, and several awards for strengthening historic bridges and including one that avoided strengthening despite a strengthening contract being awarded.

Masonry is a non-homogenised material, can be regarded as a discontinuum and as such is ideally suited to FDEM. Simply, a masonry arch bridge is a special form of masonry structure, which is an important consideration when faced with complex bridge arrangements. The approach that has been developed for arch bridges uses smeared masonry compressive properties and explicit mortar shear and tensile properties. Each brick or block unit is modelled with a separate Finite Element mesh and each unit becomes a single discrete element. Bridges are then assembled using blocky arrangements in hundreds, possibly thousands of discrete elements. FDEM arch bridge simulations develop failure mechanisms consistent with limit analysis results if these are critical as well as providing displacements, stresses and strains consistent with those predicted using solid mechanics and non-linear Finite Element analysis.

Ramboll's expertise in masonry arch bridge assessment was also called upon in the development of the Level 0 masonry arch bridge assessment tool for Network Rail. The Office of Rail Regulation require that Network Rail demonstrate the safety of their bridge assets. With so many bridges a method of quickly assessing strength was required and Network Rail responded by undertaking a series of research and development programmes to create tools to quickly evaluate risk. These tools provide so called Level 0 assessments. Working with Mott MacDonald, Ramboll developed a simple-to-use tool for Network Rail to use to assess its masonry arch bridge stock. This formidable exercise would require the assessment of approximately 30,000 masonry arch bridges and viaducts across the network. The use of conventional methods was simply not feasible given the budget and required timeframe.  To tackle the many different arch bridge arrangements, Ramboll developed an innovative approach to automatically carry out thousands of bridge assessments.

The Level 0 project comprised the strength assessment of arch barrels and piers, and that of spandrel walls.  Each required carefully designed automation to carry out many thousands of assessments. Spandrel wall assessment is particularly challenging, as their behaviour is not yet fully understood. Some 16,000 typical bridge arrangements were automatically generated and assessed numerically, to predict the load rating of each one.  Without the level of automation achieved, the extremely demanding programme set by the Office of Rail Regulation would have been impossible to achieve.

Further work to expand the assessment tool to multi-span bridges involved creating 234 FDEM analyses, determining the failure load and relating the multi-span load capacity to the single span load capacity and other key parameters. Relatively simple formulas were then generated, using genetic algorithm software, to approximate the results of all these numerical assessments closely enough. The actual assessment tool is a smart-looking spreadsheet containing these formulas.

The innovative approach to analysis, incorporating parametric analyses, automated processes and genetic algorithm generation, allowed an enormous set of analyses to be undertaken, resulting in the provision of a system for quickly assessing masonry arch bridges and vastly improving knowledge of multi-span arch bridge capacities. Without this Level 0 tool, along with others developed for different types of bridge, it would have been impossible to assess Network Rail's bridge assets within a realistic budget and timeframe. The process has now allowed weak structures to be identified so that the Network Rail territories where necessary can target more detailed investigations, assessments and strengthening.

Ramboll have over 20 years of experience in the assessment and strengthening of masonry arch bridges using FDEM for performance predictions as well as using more conventional arch assessment tools based on Limit Analysis techniques. FDEM bridge assessment is now described in CIRIA C656 and UIC code 778-3.

Ramboll's established expertise in the advance analysis and simulation of masonry arch bridges, including the pioneering work using FDEM, the track record of detailed bridge assessments and the work involved in developing the engine for Network Rail's Level 0 masonry arch bridge assessment tool led to the Network rail LNE & EM territory selecting Ramboll to help assess LEN/229 Hawthorn Viaduct.

LEN3/229 Hawthorne Viaduct

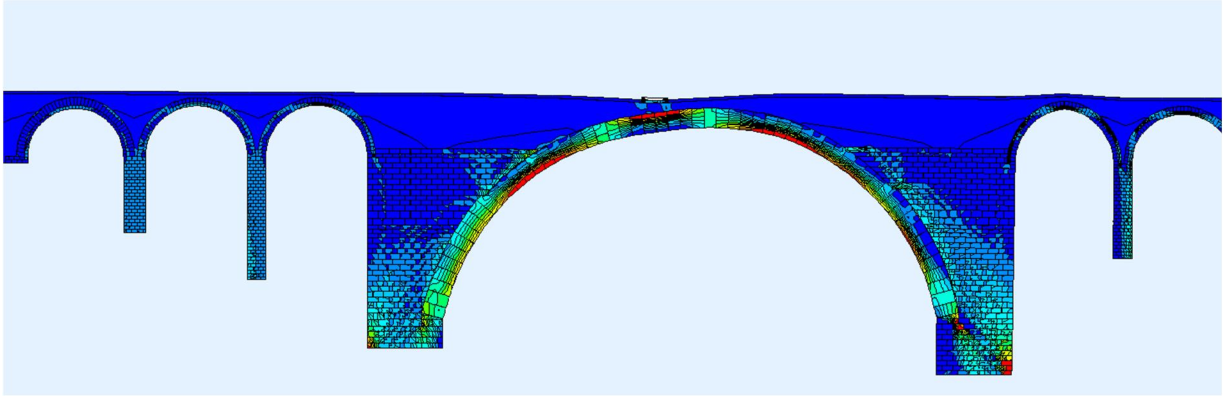
Ramboll collaboration with Arup, Amey and Network Rail to deliver a pilot strength assessment project. Using advanced methods of analysis to simulate bridge behaviour the project sets the scene for future Level 2 and 3 assessments of masonry arch bridges where traditional assessments cannot be reliably used.


LEN3/229 Hawthorne viaduct

A recent example of Ramboll using the advanced FDEM assessment techniques for strength assessment was the Level 2 assessment of structure LEN3/229, Hawthorn Viaduct, within Network Rail LNE & EM territory. This grade II Listed six-span masonry arch underbridge carrying two mainline tracks over Hawthorn Dene, Easington, County Durham had been partly assessed previously but it was recognised that the large main span was out of the scope of current assessment guides. Ramboll were commissioned to independently check the Level 2 strength assessment undertaken by Arup and worked collaboratively with Arup, Amey and Network Rail to successfully complete this pilot project to better understand the feasibility of assessing the strength of massive masonry structures. Ramboll used the advanced non-linear FDEM technique and the principal focus of the work was Span 4, the main span. With a span of 37m there were concerns with non-linear snap-through behaviour which can be critical for large slender masonry arch spans but something conventional arch assessment techniques such as Limit Analysis cannot allow for. Further complexity existed with the interaction of the main span with the five smaller approach spans, which would be expected for a multi-span structure, so that the entire viaduct had to be considered.

Given the nature of this pilot project Level 2 strength assessment and the extensive experience Ramboll have of this type of work Ramboll work closely with Arup to jointly develop the Form AA – Approval in principle for assessment.

Arup's Advanced Technology and Research Group working with their Bridge Engineers used non-linear Finite Element analysis, a technique known as dynamic relaxation and the computer software LS-DYNA to predict the bridge strength under series of static RA, wagon and test load cases. As an agreed alternative, Ramboll used the FDEM technique to check Arup's findings, and were also able to consider moving loads to more comprehensively envelop the bridge response and importantly consider the influence of multi-ring arch barrel behaviour on strength, something which Arup could not easily incorporate in their assessment.



LEN3/229 Hawthorne viaduct FDEM model used for Level 2 assessment

By using a FDEM model Ramboll could predict both strength and stiffness of the structure and the true performance of the viaduct simulated. It is the prediction of strain and displacement that is an important addition to the Level 1 work so that buckling and snap-through behaviour can also be represented. It is these behaviours that were identified during the earlier Level 1 work for further assessment and required more sophisticated analysis and refined predictions of structural performance.

The assessment of Hawthorn Viaduct was carried out for strength at ULS but also under operational conditions with freight loads and SLS load factors. The strength of the main span was shown to be more than RA10, exceeding the published route availability of RA8, indicating that costly intervention and possibly strengthening would not be required. However, the smaller side spans were shown to be far weaker. With this knowledge Network Rail can now focus improvement on the critical parts of the structure and targeting monitoring in the most vulnerable areas, knowing that the main span which is very difficult to access is no longer the priority.

Ramboll worked with Arup to develop overall conclusions and recommendations although as checkers Ramboll had already considered some of these, for example the assessment of the approach spans and multi-ring behaviour in the arch barrels.

Recommendations included 3D laser scanning and comparing measurements with a similar survey undertaken in 2012. Comparing data sets, using cloud compare technology, would indicate whether known defects were active or not. Ramboll have considerable experience of point cloud data-processing and have written Apps to help with this process and to visualise results.