Assessing Masonry Arch Bridges

from CS 454 to the forthcoming Eurocodes

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BSI Committees:

- Chair, B/525/-/3, Assessment and retrofitting of existing structures
- B/525 Structures
- B/525/2 Concrete Structures

Eurocode Committees:

- CEN/TC 250/WG 2 Assessment and retrofitting of existing structures
- CEN/TC 250/WG 2.T1 Project Team Assessment and retrofitting of existing structures
- CEN/TC 250/WG 2.T2 Project Team Assessment and retrofitting of existing structures
- CEN/TC 250/SC 2.T1 Project Team Design of concrete structures

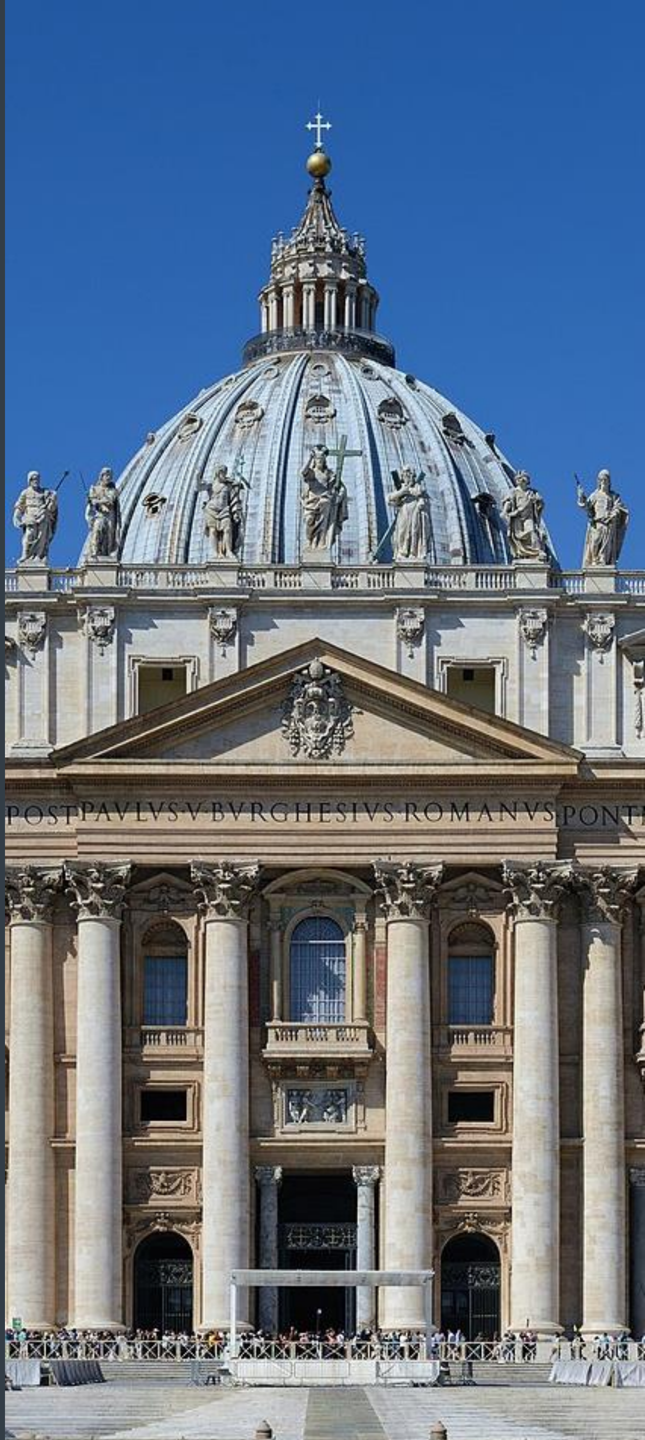
Relevant standards and guidance development:

- Co-authored content for prospective updates to EN1990, CEN TS 17440 and its UK National Annex
- Co-authored various assessment standards in the DMRB for National Highways - including CS 454
- Co-authored Concrete Society TR55 for Strengthening concrete structures with CFRP
- Steering group member for CIRIA C800 Guidance on the assessment of masonry arch bridges

Assessing Masonry Arch Bridges

Introduction

An early structural assessment



Introduction

Assessment of St Peter’s Basilica Dome, 1742

St Peter’s Basilica, Rome
Italy

Introduction

Assessment of St Peter's Basilica Dome, 1742

The report caused a furore. One comment at the time stated: 'If it were possible to design and build St Peter's dome without mathematics and especially without the new fangled mathematics of our time, it will also be possible to restore it without the aid of mathematicians and mathematics ... Michelangelo knew no mathematics and yet was able to build the dome ... Heaven forbid that the calculation is correct. For, in that case, not a minute would have passed before the entire structure would have collapsed.'

From foreword to 1980 IStructE document "Appraisal of existing structures (First Edition)"

St Peter's Basilica, Rome
Italy

The challenges for masonry arch bridges

How to keep heritage structures in use?

How to understand the level of safety?

How to understand the critical limit states and corresponding load levels?

What data from the structure is needed?

How to understand the causes and consequences of cracking and distress?

How to combine information from the insitu structure and a theoretical analysis?

How to decide which type of analysis to use (simple or complex)?

What management recommendations do we make?

To answer these, we need standards and guidance.

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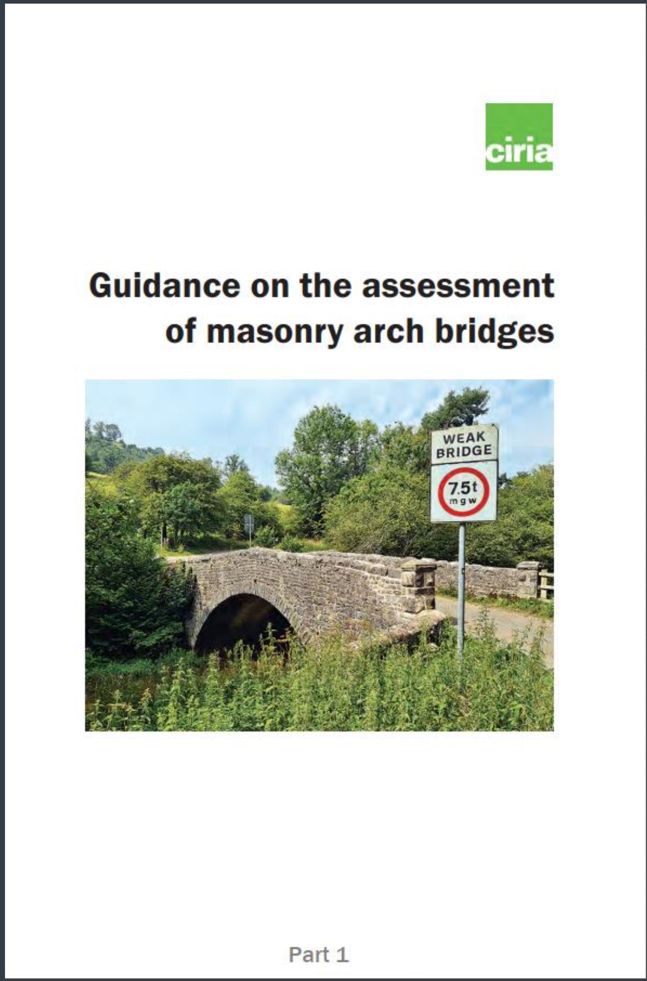
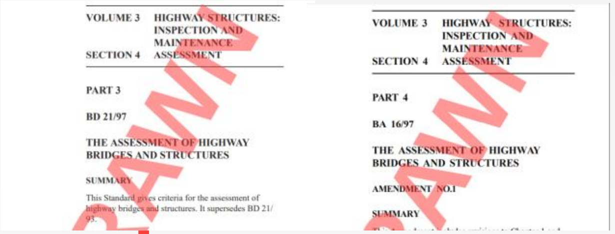
Recent developments in standards and guidance



Recent developments in standards and guidance



1997

Design Manual for Roads and Bridges BD 21/97 and BA 16/97

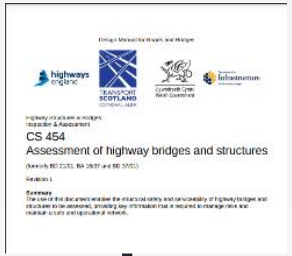
The assessment of highway bridges and structures

2006

CIRIA C656

Masonry arch bridges: Condition appraisal and remedial treatment

2019



Design Manual for Roads and Bridges CS 454

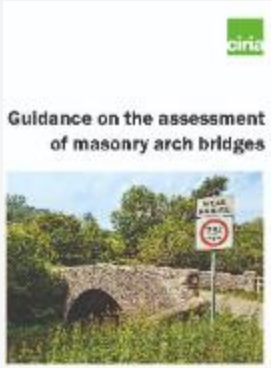
Assessment of highway bridges and structures

2020

PD CEN/TS 17440:2020

Assessment and retrofitting of existing structures (including UK National Annex)

2022



CIRIA C800

Guidance on the assessment of masonry arch bridges

Assessing Masonry Arch Bridges

DMRB content in CS 454

What is CS 454?

- Part of the Design Manual for Roads and Bridges
- Covers structural assessment of highway bridges in the UK
- Used by a range of authorities
- Replaced BD 21 and BA16 in 2019
- Significant technical updates
- Editorial updates and consistent style

What is CS 454?

- Sets out the principles for all bridge assessments
- Increasing levels of assessment, if needed to demonstrate sufficient resistance
- Includes the traffic load models for highway bridges
- Includes content on masonry arch assessment
- Revised in 2020 to include a reference to CIRIA C800

CS 454 Content

What is covered in CS 454?

- 1 Scope
- 2 Assessment processes
- 3 Basis of assessment
- 4 Properties of materials
- 5 Assessment actions
- 6 Structural analysis
- 7 Assessment of masonry arches
- 8 Assessment of cast iron
- Appendix A: Partial factors for actions
- Appendix B: Vehicle load models
- Appendix C: HB vehicle load models
- Appendix D: Models for wind and thermal actions
- Appendix E: Assessment of masonry arches using the modified MEXE method
- Appendix F: Partial factor and reliability-based methods of assessment

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Dedicated section devoted to arches

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Main sections used for masonry arch assessment

Sections that can also be used for masonry arch assessment

Dedicated section devoted to arches

Reductions in traffic loads

Application of partial factors

Verification of limit states

Structural analysis

Reductions in traffic loads

Wider notional traffic lanes

e.g. Carriageway widths <6m now need to carry just 1 lane of fast-moving traffic

Reductions in conservatism by considering beneficial effects of road surface quality and traffic flow

Reductions in traffic loads

ALL model 1

5.8 The ALL model 1 shall consist of vehicle loads, applied in the following situations, considered separately:

1) a single vehicle in each lane;
2) a convoy of vehicles in each lane.

NOTE *The convoy situation is applicable even when the loaded length can only accommodate a single vehicle.*

5.9 The characteristic loads for ALL model 1 shall be determined from the vehicle loads in Appendix B modified by the following factors:

1) an impact factor applied to the most critical axle, obtained from Table 5.9a;
2) a traffic flow factor from Table 5.9b;
3) a lane factor from Table 5.9c.

Table 5.9a Impact factors and lane widths

Load situation	Impact factor applied to critical axle[1,2]		Notional lane width	Minimum lateral spacing between wheel centres of adjacent vehicles
	Good road surface[3]	Poor road surface[3]		
Single vehicle in each lane	1.62	1.8	3m	1.2m
Convoy of vehicles in each lane	1.0		2.5m	0.7m

Note 1: For buried structures with >0.6m fill, the impact factor is applied in one lane only. For other structures the impact factor is applied in all lanes.
Note 2: CS 459 [Ref 4.N] includes further rules for buried structures, including a reduction of the impact factor to account for the damping effect of the depth of cover.
Note 3: The road surface category is defined in Section 2.

Table 5.9b Traffic flow factors

Traffic flow category[1]	Traffic flow factor
High	1.0
Medium	0.95
Low	0.9

Wider notional traffic lanes

e.g. Carriageway widths <6m now need to carry just 1 lane of fast-moving traffic

Reductions in conservatism by considering beneficial effects of road surface quality and traffic flow

Application of partial factors

BD21/01 had a very high partial factor on traffic when the structure was a masonry arch

(3.4 instead of 1.5)

- this included an allowance for the impact factor, and
- an implicit factor to avoid the load causing distress to the arch.

CS 454 now has the same partial factor for traffic for all structures

- enabling impact factor and distress to be considered separately - and less conservatively.

Verification of limit states

CS 454 now separates the verifications of limit states:

- ultimate limit state (i.e. collapse)
- risk that the loading causes distress to the arch

The default approach to verifying risk of distress is based on a simple minimum live load capacity factor C_{min} = 1.2 for normal traffic, 1.8 for abnormal traffic.

It is also possible to use the alternative approach in CIRIA C800 by verifying the Permissible Limit State.

Verification of limit states

7.2 The assessment of masonry arches shall confirm that the traffic loading does not reach levels that can cause further distress and reduce the life of the arch.

7.2.1 Equation 7.2.1, or another suitable approach, should be used to demonstrate that there is a sufficient live load capacity factor to avoid the traffic loading reaching levels that can cause further distress and reduce the life of the arch.

Equation 7.2.1 Required live load capacity factor to avoid further distress

$$C \geq C_{\min}$$

where:

C is the live load capacity factor, defined as the additional factor that can be applied to the assessment traffic actions (in addition to the partial factors as defined in Section 3) without causing the assessment action effects to exceed the assessment resistance at ULS.

$C_{\min}$ is the value of live load capacity factor that corresponds to the loads frequently reaching levels that could result in further distress and reduce the life of the arch, taken as $C_{\min} = 1.2$ for normal and restricted traffic or $C_{\min} = 1.8$ for abnormal traffic.

NOTE 1 The values for $C_{\min}$ have been derived based on the formulation $C_{\min} = \frac{\psi \gamma_{fL,SLS}}{K \gamma_{f3} \gamma_{fL,ULS}}$ where K is the proportion of the ULS resistance where further distress could occur, assumed here to be $K = 0.5$, and ψ is the proportion of the SLS traffic load that would be frequently experienced, taken as $\psi = 0.75$ for normal or restricted traffic. For abnormal traffic, ψ is taken as $\psi = 1.0$ to align with previous practice. The values of $\gamma_{fL,SLS}$ and $\gamma_{fL,ULS}$ are the partial factors for traffic loading given in Appendix A, and γ_{f3} is the value for masonry arches given in Section 3.

NOTE 2 In previous versions of this document $C_{\min}$ was included within the ULS partial factor for traffic on arches.

NOTE 3 CIRIA C800 [Ref 14.I], Guidance on the assessment of masonry arch bridges, describes an alternative approach to satisfy this clause.

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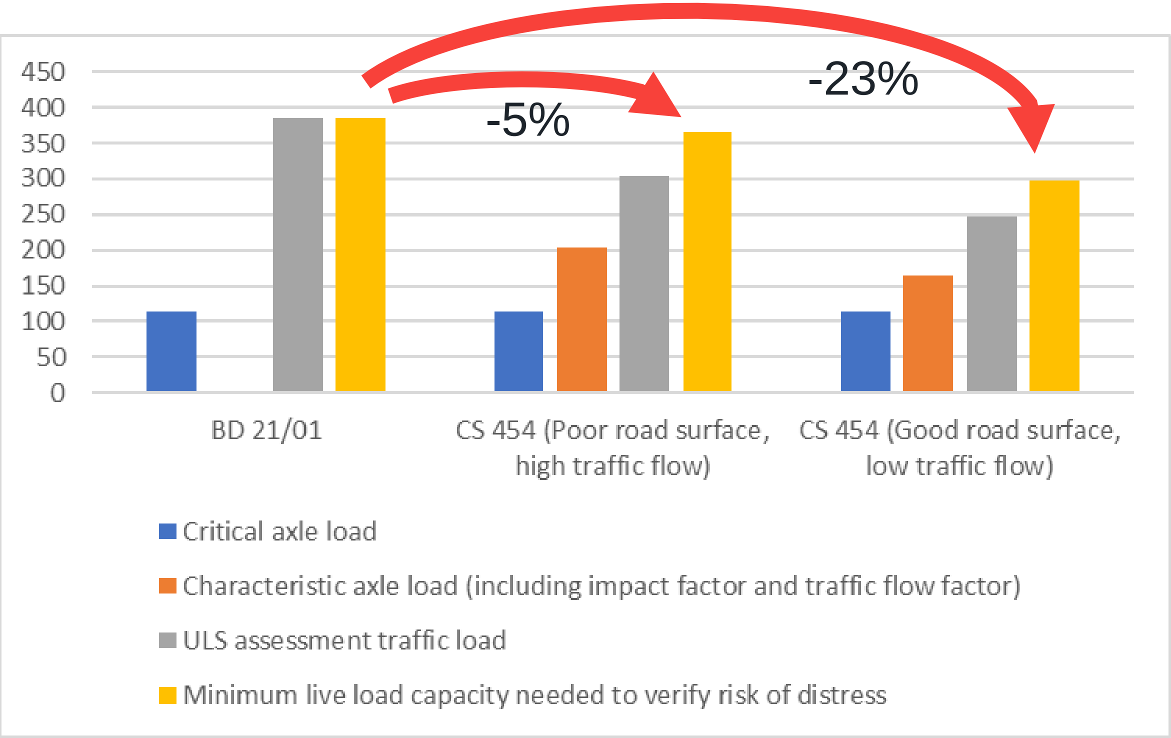
Comparison of old BD 21 and new CS 454 for masonry arches



Reduced conservatism – improved assessment results of between 5% and 23%

Further improvements of up to 40% possible for carriageway widths between 5m and 6m

Structural analysis

Methodology selected and defined in the Approval in Principle document.

Condition defects are included:

- directly through the analysis model, or
- indirectly through condition factors.

May comprise one or more of:

- Mechanism analyses
- Equilibrium-based analyses
- Non-linear FE analyses
- Modified MEXE method

Enables more explicit analysis of arch behaviour and failure mechanisms as now possible using up-to–date software

Structural analysis

There is clearer guidance on the principles of the analysis.

More consistent with software packages in common usage.

Aim to continue to allow simple analyses - where they can be used safely, and also enable more sophisticated analyses to be used.

Principles enable innovation and development of analyses based on failure mechanisms or on load paths, with potential for both to consider 3D behaviours if needed.

The section on analysis is no longer based on modified MEXE as the “default” method.

There are new restrictions on modified MEXE.

The modified MEXE method

7.12 Where the modified MEXE method is used for arch assessment, the resistance shall be determined using Appendix E.

7.13 The modified MEXE method shall not be used for any of the following:

1) multi-span arches;
2) multi-ring arches where ring separation is likely to limit the capacity of the structure;
3) arches with deformed profiles;
4) arches with span lengths less than 5m;
5) arches with span lengths greater than 18m;
6) arches with a depth of the fill at the crown that exceeds the thickness of the arch barrel;
7) flat arches and arches with a span/rise ratio that exceeds 8;
8) arches with a skew angle that exceeds 35 degrees.

New restrictions based on: UIC Code 778-3 R. 2011 and CIRIA 656

Keeping the DMRB up to date

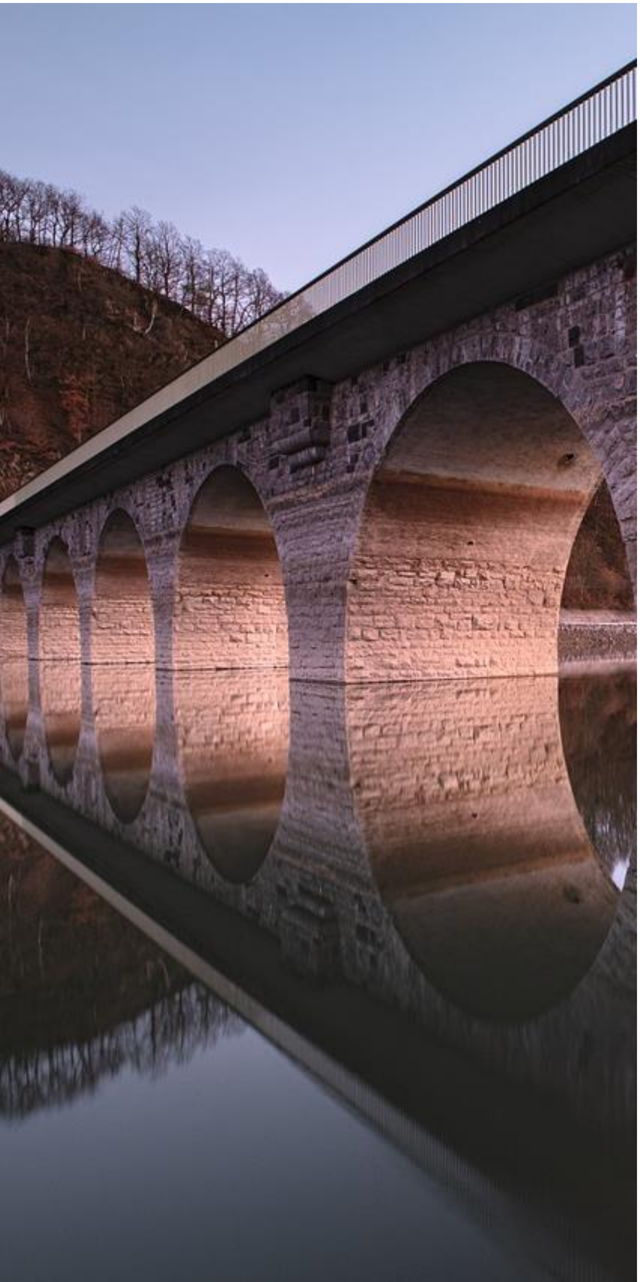
The DMRB refresh in 2020 was accompanied by new processes to gather feedback on the standards more effectively and governance processes to implement minor updates more efficiently.

For example, after publication of CIRIA C800 for assessment of masonry arches, CS 454 was revised to include a reference enabling the approaches in C800 to be used.

If you have further feedback on CS 454 or other DMRB document, this can be done via the website https://www.standardsforhighways.co.uk/feedback

Assessing Masonry Arch Bridges

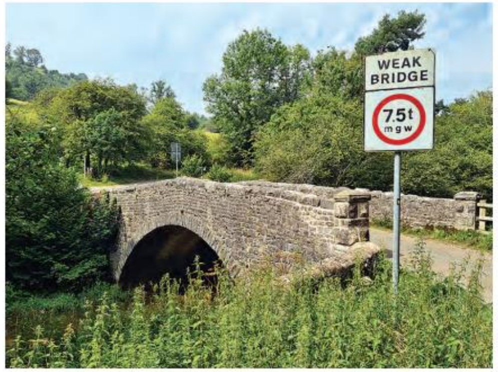
CIRIA C800



CIRIA C800

ciria

Guidance on the assessment of masonry arch bridges



Part 1

ciria

Guidance on the assessment of masonry arch bridges

Part 2

Contents

Case studies

The focus for DMRB standards is on stating the requirements – there is limited guidance in CS 454 on how to carry out an assessment.

Complementary guidance documents like CIRIA C800 are very useful.

The quality of the advice provided to clients in assessments is dependent on the appropriateness of the methods used.

CIRIA C800 provides a comprehensive amount of guidance on all aspects of masonry arch behaviour and analysis to help engineers understand how arches work and how to assess them.

As well as providing guidance which helps understanding of the assessment, the publication of C800 has also introduced a new approach of assessing arches for the limit state can reduce the life of the structure.

In C800 this is called the Permissible Limit State (PLS).

Using the PLS approach is an alternative to the simple rule of thumb-based criterion in CS 454.

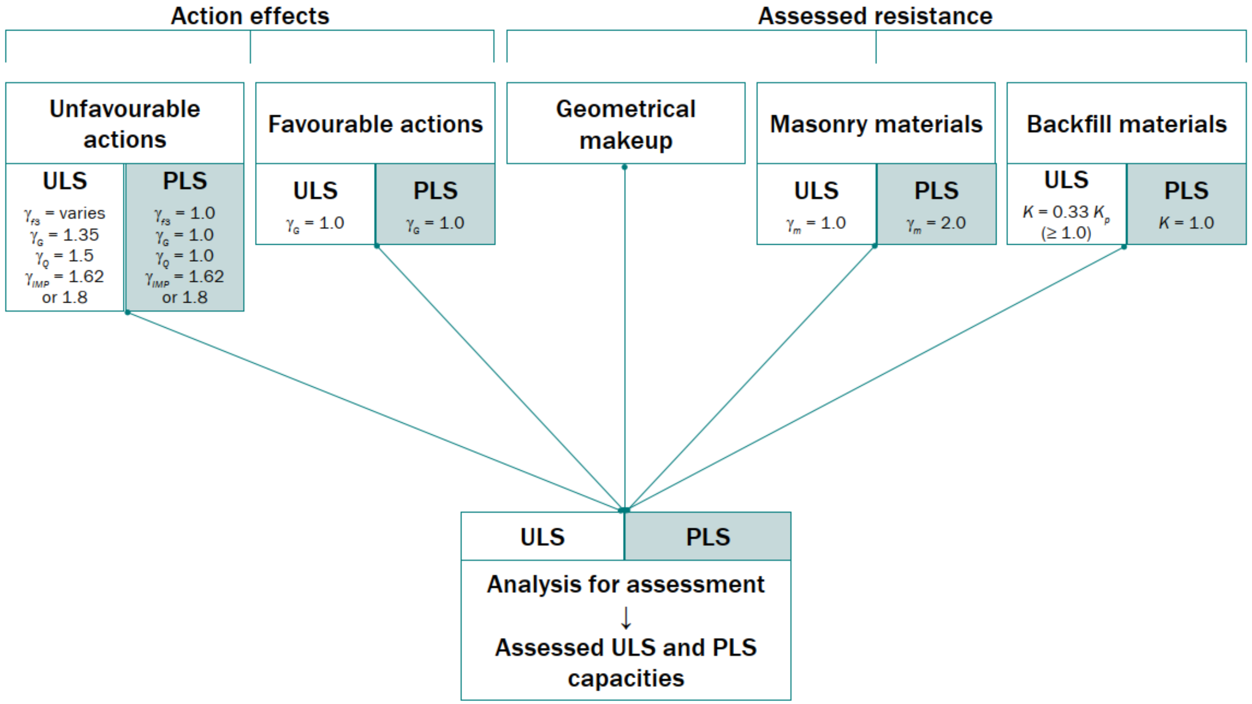


Figure 7.5 Key inputs to ULS and PLS (Level 1/2) analysis for assessment calculations

Table 7.5 Actions: partial factor values

Description		ULS	PLS
Load effects factor (γ_{f3})[1]	Level 1	1.2	1.0
	Level 2	1.1	
	Level 3	1.0	
Permanent unfavourable action, γ_G		1.35[2]	1.0
Permanent favourable action, γ_G		1.0	
Variable unfavourable action, γ_Q		1.5[3]	1.0

Notes

1 If 2D analysis model used to analyse bridge with skew angle >30 degrees then γ_{f3} (Level 1) = 1.3 and γ_{f3} (Level 2) = 1.2.

2 Alternatively material-specific factors described in DMRB CS 454 and NR/GN/CIV/025 (which principally lie in the range of 1.15 to 1.75) can be employed.

3 For abnormal highway loads a different factor is applicable (see DMRB CS 458 [Highways England, 2020e]).

Assessing Masonry Arch Bridges

Eurocodes for assessment?

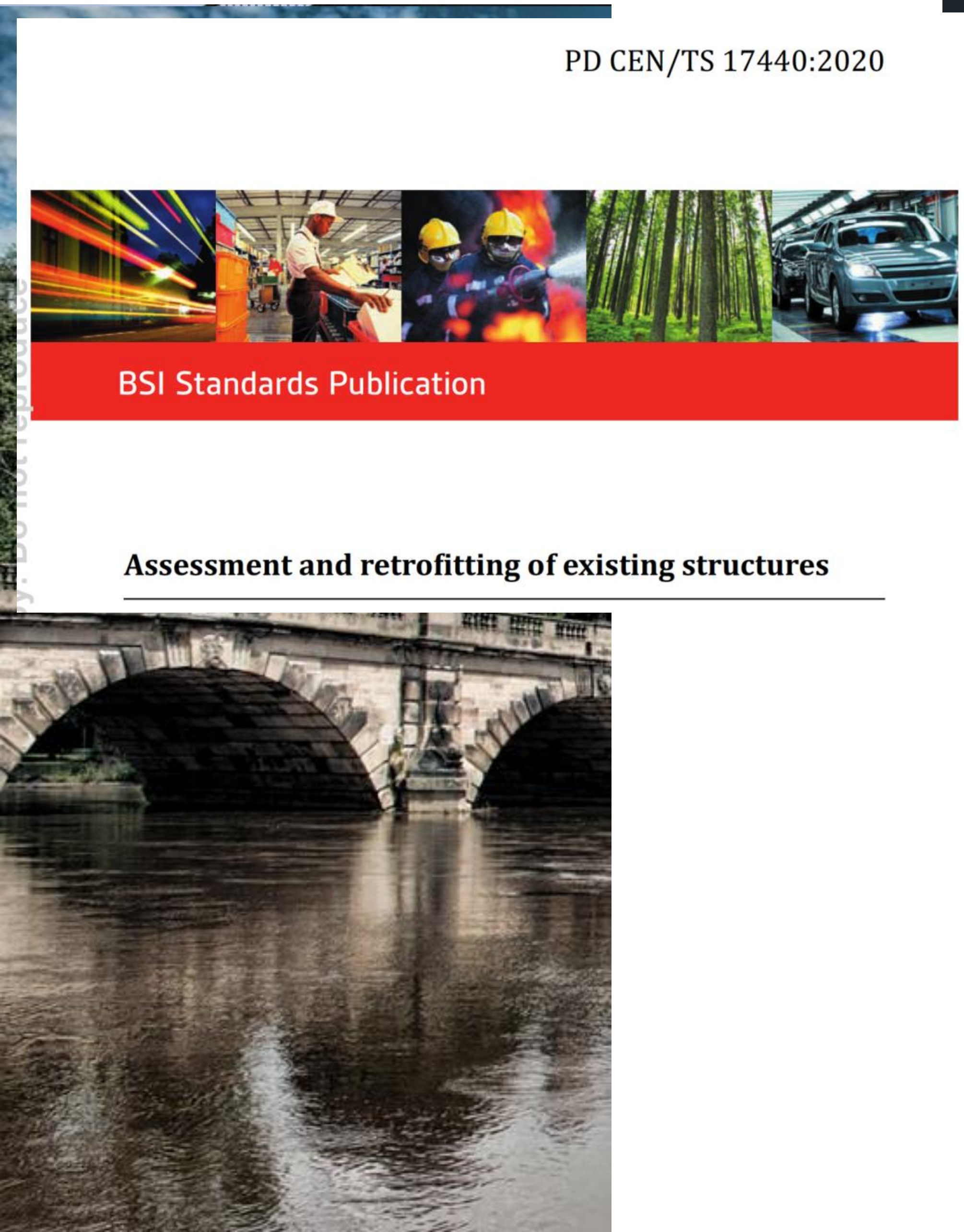
Eurocodes for assessment

The first generation of Eurocodes replaced many British Standards for design of new structures in 2010.

They do not include very much content on assessment of existing structures.

We have continued to use the existing approaches for assessment – including use of CS 454 and other DMRB documents.

However, Eurocodes are being updated to a second generation suite of documents, and this will include content on assessment and retrofitting of existing structures.



PD CEN/TS 17440:2020

A voluntary pre-normative Technical Specification was produced by CEN and published in the UK by BSI together with a UK National Annex in 2020.

The focus is on how the principles of EN 1990 for Basis of design can be applied to existing structures.

It does not contain specific guidance for different materials or structure types – so nothing about how to assess masonry arches – but it gives a framework for how the basic variables could be treated in existing structures.

This content has been developed into a future Part 2 of EN1990 that will be in the second generation of the Eurocodes.

Over the coming 5 years we will start to see some of the new Eurocodes. Some of these (EN1990 Basis of Design, EN1992 for concrete) will include content for assessment.

However, most of the material parts will not yet have content for assessment, and this could follow in a 3rd generation.

For UK masonry arch structures, it is expected that CS 454 and CIRIA C800 will remain the key documents for assessment.

Assessing Masonry Arch Bridges

Conclusion: Successful assessments

Structural assessments can be difficult!

- We need to be on the safe side, to avoid collapses...
- We also need to avoid unnecessary conservatism, to keep our heritage structures in use...
- We can't always rely on design standards that are intended for new materials and construction
- Even the "simplest" structures can involve a complex analysis if the failure mechanism is 3D.

Standards only set out the "requirements" – they don't tell you how each structure should be analysed.

For masonry arch assessment an understanding of how arches behave at the relevant limit states can be essential.

Assessing Masonry Arch Bridges

from CS 454 to the forthcoming Eurocodes

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05/09/2023

Thank you

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