Ten stone masonry arch bridges and five different assessment approaches

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ABSTRACT: Internationally masonry arch bridges constitute a substantial portion of bridge stocks. An estimated 40% of railway bridges in Europe are of masonry arch construction while in China arch construction of various forms comprises 70% of all bridges.

In Ireland an estimated 80% of bridges are of masonry arch construction. Under the National Road Authority's (NRA) Eirspan Bridge Management Programme, the 877 masonry arch bridges on the national road network are being assessed. However there are a number of different assessment methods available with a corresponding number of different results for the load capacity of these structures. This has cost implications for both the bridge assessment itself and for the costs associated with load restrictions and strengthening measures. To address this issue, research is being carried out under the NRA's Research Fellowship Programme to develop a hierarchical assessment framework for the assessment of masonry arch bridges. This will aim to recommend different levels of assessment of increasing complexity, specifying limits of applicability for each and providing guidance on their use.

1 INTRODUCTION

Masonry arch bridges, most of which have far exceeded modern design lives have demonstrated themselves to be sustainable structures with low life-cycle costs (Sustainable Bridges 2007). However increasing loading requirements and material deterioration over time makes periodic re-assessment necessary. There is a multitude of assessment methods available for masonry arch bridges (Department of Transport 1997, Harvey 1988, Gilbert and Melbourne 1994, Fanning and Boothby 2003), yet there is no widely accepted framework for their application.

With the aim of developing a hierarchical assessment framework for masonry arch bridges a range of assessments has been carried out using potential first, second and third level methods including the MEXE method, a three hinge plastic method, a rigid block method, a 2D elastic method and a 3D elastic method. The assessed bridge set discussed in this paper comprises 10 bridges ranging in span from 2.4 – 15.2m representative of the vast majority of masonry arch bridges in Ireland. The relationship between the assessment methods, their complexity and the results depends on a number of varying factors and is discussed in detail in this paper.

2 ASSESSMENT METHODS

2.1 The modified MEXE method

The modified MEXE method is an empirical assessment method based on the work of Pippard and is now found in its current format in BA 16/97 The Assessment of Highway Bridges and Structures (Department of Transport 1997).

Pippard assumed a two pinned parabolic arch with a span to rise ratio of 4, loaded at mid-span. Pippard acknowledged that this was not the most onerous loading position for an arch, but argued that it allowed for the least amount of load distribution and therefore a greater concentration of load. Pippard also allowed for a small tensile capacity in the masonry and derived an equation for the safe axle load based on a limiting compressive strength.

The modified MEXE method in its present format centres around a nomogram relating the arch span and the total crown thickness to a provisional axle load. This is then modified by a number of factors intended to account for variations in bridge geometry and materials and also for defects and deterioration. However, there is a lack of full traceability between Pippard's referenced work and the modified MEXE method which does not promote confidence in its results. There are also a number of limitations to the modified MEXE method stated in BA 16/97 relating to the span length, span-to-rise ratios, multiple spans and the depth of fill. Questions over its conservativeness for short span bridges have also been raised in the literature (Melbourne et al. 2009).

2.2 Plastic methods

Two different plastic methods were used for assessment, a three hinge plastic method and a rigid block method. These are both based on the plastic analysis methods developed by Heyman. Heyman's plastic analysis is based on the formation of four hinges, causing failure of the arch. For a particular load the associated line of thrust for a unit width of arch barrel is determined from which a geometrical factor of safety is found, i.e. the ratio between the thickness of actual arch ring and the thickness of the arch ring that would be required to contain this line of thrust. For the purposes of developing a quick approximate method of analysis Heyman assumed that the worst case loading position was always exactly at the quarter span.

2.2.1 Three hinge plastic method

The three hinge plastic method developed by Harvey is available as the commercial software package Archie-M. Harvey's three hinge plastic method differs from Heyman's plastic analysis in that it determines the line of thrust associated with the formation of three hinges. The arch will remain stable as long as the fourth hinge is not formed. If the line of thrust for a particular load is within the boundaries of the arch ring the fourth hinge cannot form and the ring thickness is deemed to be sufficient to resist the load. If this line of thrust cannot be contained within the thickness of the arch ring the load is deemed to be unsafe. Harvey's method caters for any loading position thereby allowing the critical position to be identified, usually near to the quarter span.

2.2.2 Rigid block method

The rigid block method developed by Gilbert and Melbourne is available as the commercial software package Ring. This method is also based on Heyman's plastic analysis. Again, the line of thrust is determined for the critical loading position. However this method determines the plastic failure load, i.e. the load required for the formation of the fourth hinge to occur. This is expressed as a multiple of the applied load that has been specified and is called the failure load factor. The rigid block method models the arch ring as a series of rigid blocks with frictional interfaces and therefore can also allow for sliding failure between the blocks.

2.3 Elastic methods

2.3.1 Two dimensional elastic analysis

Two dimensional elastic analysis was carried out on a unit width plane frame model using the method proposed by Fanning and Boothby. The arch is divided into a number of segments running along the centreline of the arch ring and modelled as straight beam elements. A single modulus of elasticity is assumed for the masonry mortar continuum.

The support conditions were assumed to be fixed. This varies from the method set out by Fanning and Boothby where the supports are modelled as being fixed against rotation and vertical movement, with a spring stiffness defined in the horizontal direction. During service load testing reported by Fanning and Boothby the horizontal displacements at the abutments were generally less than 100μm for well founded abutments resulting in very high values of recommended spring stiffnesses. All of the abutments for the bridges presented in this paper were well founded with no evidence of yielding, and therefore for simplicity it was chosen to model the support conditions as fixed.

The live loads are assumed to be distributed over a 3m width and a corresponding unit width load is determined. In the longitudinal direction, the live loads are assumed to be applied over a 300mm wheel contact length and distributed longitudinally at a ratio of 1:2, horizontal to vertical. The fill is included in the model as a dead load and does not contribute to the strength or stiffness of the bridge.

The method set out by Fanning and Boothby assumes that the arch ring has a limited tensile capacity and derives an equation for the compressive strength required to resist the axial forces and bending moments based on the ratio of tensile to compressive strength and on the cross section of the arch barrel. Analysis of the elastic model gives the axial forces and bending moments throughout the arch barrel and the required compressive strengths to resist these forces are then compared with the compressive strength specified for the arch ring. The procedure is repeated iteratively using varying axle loads until the maximum axle load for the specified compressive strength is found.

2.3.2 Three dimensional elastic analysis

All of the assessments methods previously described are based on two dimensional unit width models, and do not directly take account of the transverse structural behaviour of the arch. By modelling the arch as a three dimensional shell the transverse structural behaviour of the arch is accounted for directly.

The arch barrel is modelled using shell elements. As with the 2D assessment, a single modulus of elasticity is assumed for the masonry mortar continuum, the support conditions are assumed to be fixed, the fill does not contribute to the strength or stiffness of the bridge and the live loads are assumed to be distributed laterally over a 3m width and in the longitudinal direction at a ratio of 1:2, horizontal to vertical. Again, it is assumed that the masonry arch has some tensile capacity.

3 DIFFERING ISSUES

3.1 Loads and load factors

A single axle and double axle bogie with a 1.8m spacing were applied for each of the assessments. The loads were factored in accordance with BD 21/01 which requires that a load factor of 1.9 is applied to all of the axles and a further impact factor of 1.8 is applied to the critical axle. For the modified MEXE method the allowable axle loads are determined directly and no factors of safety are applied.

The vertical road alignment for one of the bridges, Glanbehy Bridge, was humpbacked and therefore additional partial load factors were applied for axle lift-off for the double axle bogie. A load factor of 1.5 was applied to the critical axle and a load factor of 0.5 was applied to the other axle.

Table 1 : Partial Load Factors

	γ_{fL}	γ_{fL}
Single axle	3.4	
Double axle	3.4	1.9
Axle lift-off	5.1	0.95

3.2 Longitudinal load distribution

The MEXE method is based on the work of Pippard which assumes that the load is distributed at a ratio of 1:1. This might be considered rather generous for the type of fill typically found in masonry arch bridges. For the three hinge plastic method the loads are distributed at a ratio of 1:2, horizontal to vertical, in accordance with BD 21/01. For the rigid block method, the loads are distributed using a Boussinesq distribution. For the elastic methods the loads are distributed at an angle of 26.6°, equivalent to the 1:2 ratio specified in BD 21/01.

3.3 Transverse load distribution

BD 21/01 distributes the load in the transverse direction at a ratio of 1:2, horizontal to vertical. Based on the work of Davy and Chettoe and Henderson the effective width is then increased beyond the distributed width in an attempt to take account of the transverse structural action of the bridge.

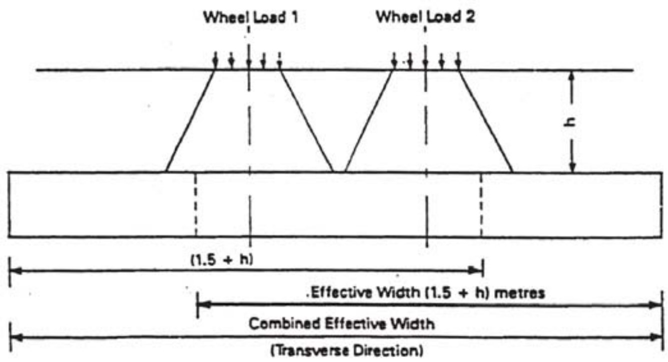

Figure 1 : Effective width reproduced from BD 21/01

For both of the plastic methods the effective widths are calculated based on the guidance set out above, as per BD 21/01, and a unit width load is determined. The effective width should be reduced if the axle loading is not along the centreline as would be the case for multilane bridges or where there is longitudinal cracking.

For the three hinge plastic method, the effective width that the loads are distributed over is calculated for each load position along the span and varies with the depth of fill. The maximum value for the effective width is automatically limited to the bridge width that is specified for the assessment. For the rigid block method there are two options for the effective width. Either the effective width may be automatically calculated for each load position or the effective width may be set at a fixed value for all load positions across the bridge. However, if the first option is selected it must be checked that the calculated effective width does not exceed the bridge width, as may be the case where there are large depths of fill.

For the 2D and 3D elastic methods the load is assumed to be distributed transversely over a 3.0m width. In addition to accounting for the transverse structural action of the barrel directly, an advantage of the 3D shell model is that the axle loads can be applied directly to the section of the arch barrel carrying the traffic lane. This makes it considerably simpler to deal with unsymmetrical restrictions to the transverse load distribution in situations with multiple traffic lanes or longitudinal cracking in the arch barrel.

The modified MEXE method does not account in any way for the bridge width.

3.4 Earth Pressures

Horizontal earth pressures generated in the fill material provide restraint to the arch barrel under load. The plastic methods allow for the inclusion of earth pressures, thereby increasing the assessed load capacity. However, both methods limit the proportion of passive pressure that can be applied as full passive pressure will only occur under large movements of the arch. Earth pressures are not included in the 2D or 3D elastic analyses, nor are they included in Pippard's work, the theory underlying the MEXE method.

3.5 THE BRIDGE SET

In Ireland it has been estimated that there are 16,000 masonry arch bridges comprising 80% of the total bridge stock (Molloy 1988). The National Roads Needs Study (NRA 1998) documented 646 masonry arch bridges on the national road network. The vast majority of these bridges, 97%, are less than 15m in span and 63% of these are single span structures.

The ten bridges selected for assessment are all single span structures of stone construction, ranging in span from 2.4m to 15.2m, and are therefore representative a large proportion of bridges on the Irish road network.

3.6 Bridge profiles and geometry

The profile of these bridges varied between segmental, semi-circular and three-centred arches. The condition and state of repair also varied considerably. The bridge profiles and geometries are presented in Table 2. The width refers to the width of the arch barrel being assessed and was dependant on the number and location of the traffic lanes. Backing was not included in any of the assessments.

Table 2 : Bridge geometries

Name	Shape	Span m	Rise m	Span/Rise	Width m	Ring thickness m	Depth fill m
Glanlough	Semi-circular	2.4	0.940	2.6	3.1	0.490	0.100
Temple	Segmental	3.0	0.680	4.4	6.525	0.380	0.050
Whistle	Segmental	6.21	1.306	4.8	3.65	0.435	0.475
Oghermong	Segmental	7.8	2.000	3.9	3.6	0.550	0.120
Owenmore	Segmental	8.6	2.280	3.8	3.82	0.440	0.320
Killeen	Three-centred	9.29	2.650	3.5	3.15	0.480	0.250
Griffith	Three-centred	9.46	2.710	3.5	3.92	0.446	0.126
Windy	Segmental	10.72	1.970	5.4	4.05	0.670	0.300
Glanbehy	Segmental	13.4	3.400	3.9	6.4	0.625	0.150
Anglesea	Segmental	15.2	1.525	10.0	3.117	0.800	0.300

3.7 Material properties

The material properties were determined on the basis of visual inspections and are presented in Table 3. The values for the density of masonry were based on BS 648:1964 Schedule of Weights of Building Materials. The compressive strengths were taken from BD 21/01 Fig.4.3 Characteristic Strength of Normal Stone Masonry. The values for tensile strength, Young's modulus and Poisson's ratio were based on the guidance provided in Fanning and Boothby, with the tensile strength assumed to be equal to 5% of the compressive strength.

Table 3 : Material properties

Name	Density of masonry kN/m³	Compressive Strength Masonry MPa	Tensile Strength Masonry MPa	Masonry Young's Modulus GPa	Poisson's ratio	Density of fill kN/m³
Glanlough	22	7.6	0.38	4	0.3	18
Temple	22	4.5	0.23	3	0.3	18
Whistle	22	14.2	0.71	13	0.3	18
Oghermong	22	4.5	0.23	3	0.3	18
Owenmore	22	7	0.35	4	0.3	18
Killeen	22	15	0.75	10	0.3	17
Griffith	22	15	0.75	10	0.3	17
Windy	22	10.5	0.53	5	0.3	18
Glanbehy	22	7	0.35	4	0.3	18
Anglesea	22	14.2	0.71	13	0.3	18

For the elastic methods all of the material properties listed below are required. For the plastic methods the density of the masonry, the compressive strength of the masonry and the density of the fill are required. The MEXE method is an empirical method and while modifying factors based on the bridge materials are used, specific material properties are not required.

4 RESULTS AND DISCUSSION

4.1 Allowable axle loads

The allowable axle loads for the double axle bogie are presented in Table 4. For the 3D elastic method the axle load capacities in both the longitudinal and transverse direction are presented separately, with the allowable axle load for the arch being the lesser of the two values.

BD 21/01 states that where the depth of fill at the crown is greater than the ring thickness of the arch the MEXE results may be unconservative. This was the case for Whistle Bridge. The MEXE method is also unsuitable for bridges that have a span/rise ratio greater than 8, as was the case with Anglesea Bridge.

Table 4 : Allowable Axle Load (tonnes) per axle for a 1.8m double axle

Name	MEXE	Three hinge plastic	Rigid block	2-D elastic	3-D elastic longitudinal	3-D elastic transverse
Glanlough	43.5	25.1	37	65	62	65
Temple	18.5	23.3	28.5	22	23.5	24
Whistle	27*	22.5	28.9	37	51	52
Oghermong	13.5	16.2	21.5	16	19	19
Owenmore	16.5	10.3	23.2	13.5	16.5	18.5
Killeen	7.5	3.9	7.3	5.5	9	20
Griffith	7.5	5.2	8.3	9	12	32
Windy	18	35.7	43.4	25	40.5	54
Glanbehy	8.5	13.9	13.3	11	19	15
Anglesea	–	50	77.6	19	21	60

*MEXE result may be unconservative

4.2 *Comparison of results*

The allowable axle loads have been normalized with respect to the 3D elastic analysis and then ranked according to the highest assessment results in Table 5 and Table 6 respectively.

For this bridge set the highest results were achieved using either the rigid block method or the 3D elastic method, with the exception of Glanlough Bridge for which the 2D method gave a 5% increase in capacity over the 3D method. The rigid block method, based on determining the line of thrust, favoured bridges with profile characteristics which reflected the line of thrust at the critical location near to the quarter span. Whereas the 3D elastic method gave higher values for bridge profiles which deviated from the line of thrust profile, for example bridges with three-centred arch profiles or semi-circular profiles.

Generally, it can be seen that the rigid block method can be expected to give higher results than the three hinge plastic method and that the 3D method can be expected to give higher results than the 2D elastic method. This is consistent with underlying structural analysis theory.

The MEXE results are interesting. The MEXE method is an empirical method and attracts criticism based on its underlying principles and lack of traceability back to its initial development. However it is very easy to use and for this particular bridge set was always conservative as there was always another assessment method that gave higher results. However, the degree of conservatism of the MEXE method is highly variable as it does not account for a number of factors which the other assessment methods account for such as the width of the bridge and variations in ring thickness as a proportion of the total crown thickness.

As mentioned previously, earth pressures are included in the plastic methods and are not included in the 2D or 3D elastic methods. Further work is required to determine the effect on the rankings of the assessment methods by including the earth pressures for the elastic methods.

Table 5 : Results normalized with respect to 3-D elastic method

Name	MEXE	Three hinge plastic	Rigid block	2-D elastic	3-D elastic
Glanlough	0.70	0.40	0.60	1.05	1
Temple	0.79	0.99	1.21	0.94	1
Whistle	0.53*	0.44	0.57	0.73	1
Oghermong	0.71	0.85	1.13	0.84	1
Owenmore	1.00	0.62	1.41	0.82	1
Killeen	0.83	0.43	0.81	0.61	1
Griffith	0.63	0.43	0.69	0.75	1
Windy	0.44	0.88	1.07	0.62	1
Glanbehy	0.57	0.93	0.89	0.73	1
Anglesea	–	2.38	3.70	0.90	1

*MEXE result may be unconservative

Table 6 : Ranking of assessment results

Name	MEXE	Three hinge plastic	Rigid block	2-D elastic	3-D elastic
Glanlough	3	5	4	1	2
Temple	5	3	1	4	2
Whistle	4*	5	3	2	1
Oghermong	5	3	1	4	2
Owenmore	2	4	1	3	2
Killeen	2	5	3	4	1
Griffith	4	5	3	2	1
Windy	5	3	1	4	2
Glanbehy	5	2	3	4	1
Anglesea	–	2	1	4	3

*MEXE result may be unconservative

4.3 Transverse load distribution

The transverse load distribution requires further study. The plastic methods and the 2D elastic method do not account completely for different lane locations across the width of the bridge. This has an effect on the resulting assessed capacity. For example for Temple Bridge using the rigid block assessment, the automatically calculated effective width at the critical load position was 3.6m and the allowable double axle load was 28.5 tonnes. However, when the effective width was restricted to 3.0m due to an adjacent traffic lane the double axle load was reduced to 23.9 tonnes.

For the 2D elastic method the load is assumed to be distributed over a 3m effective width. For this bridge set, this was found to be conservative by comparison with the automatically calculated effective widths for the plastic methods.

4.4 Shallow arches

The bridge for which there was the greatest disparity in the results was Anglesea Bridge. Anglesea Bridge has a span of 15.2m and is very shallow in profile with a span-to-rise ratio of 10. This span-to-rise ratio puts it outside the range for a MEXE assessment which is not suitable for flatter arches. However, the span and thickness at the crown gave a provisional axle load of 26 tonnes. The results for the three hinge plastic method and the rigid block method, 50 and 77.6 tonnes respectively, were considerably higher than the results for the 2D and 3D elastic assessments, 19 and 21 tonnes respectively, which indicated that the bridge would fail by compressive failure at the abutments. This may indicate that the methods based on line of thrust analysis may give excessively large capacities for shallow arches.

4.5 Failure mechanisms and validation

The MEXE method provides no information on the likely failure mechanism of a bridge or any diagnostic information for the purpose of remedial works. The plastic methods illustrate where hinges leading to a collapse are most likely to occur. The rigid block method can also account for sliding failure between the masonry units. The elastic methods identify the location of compressive failure under a given load. The 3D elastic method can account for failure of the arch barrel in both the longitudinal and transverse direction.

The plastic methods predict the collapse mechanism and therefore can only be validated at the ultimate limit state; whereas the elastic methods can predict the deflections under given loading conditions and therefore can be validated against service load testing.

5 CONCLUSIONS

The results for this bridge set clearly demonstrate that there are a number of challenges to developing a hierarchical assessment framework.

For this bridge set, where a MEXE assessment was carried out the MEXE method was shown to be conservative. However, alternatives to the MEXE method are required for a number of reasons. There are circumstances where it is not applicable. Furthermore, where a bridge fails the MEXE assessment another assessment method may yield higher results avoiding unnecessary load restrictions or strengthening measures. The MEXE method also does not provide any information as to where a bridge is deficient.

The transverse load distribution requires further attention. For all of the two dimensional unit width methods, it is important to accurately account for the lane location as this will affect the effective width and therefore the unit width that is applied. The ability to account for transverse structural action is a clear advantage of the 3D elastic method, particularly for bridges where the traffic lane is not centrally located on the section of arch being considered.

The rigid block method consistently gave higher results than the three hinge plastic method and the 3D elastic method can be expected to give higher results than the 2D elastic method. For this bridge set, the highest results were achieved using either the rigid block method or the 3D elastic method.

The effect of including the earth pressures in the 2D and 3D elastic methods on the rankings of the assessment methods requires further investigation.

6 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the National Roads Authority of Ireland for funding this research under the National Roads Authority Research Fellowship Programme 2008.

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