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Autor: Das, Parag C.

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Examination of Masonry Arch Assessment Methods

Examen des méthodes d'évaluation des ponts-arcs en maçonnerie

Vergleich von Bewertungsverfahren für Mauerwerksbrücken

Parag C. DAS
Princ. Civil Eng.
Dep. of Transport
United Kingdom

P.C. Das obtained his Doctorate in civil engineering in 1968 from Southampton Univ. He joined the Dep. of Transport as a bridge engineer. and has since been involved with research, design and technical approval of bridges. He is now a Principal Civil Eng. responsible for formulating standards.

SUMMARY

This paper gives brief descriptions of a number of masonry arch bridge assessment methods developed in the United Kingdom in recent years. It also describes the findings of an investigative study of the methods involving comparisons with collapse tests on full-scale bridges.

RÉSUMÉ

Cet article donne des renseignements sur quelques méthodes, récemment développées au Royaume-Uni, du calcul de la résistance restante des ponts-arcs en maçonnerie. Il présente les principes de ces méthodes sur la base de comparaisons avec des essais à la rupture sur des ponts prototypes.

ZUSAMMENFASSUNG

Dieser Beitrag beschreibt verschiedene Bewertungsverfahren für existierende Bogenbrücken aus Mauerwerk, die in letzter Zeit in Grossbritannien entwickelt wurden. Es liegen die Ergebnisse einer Studie vor, die diese Verfahren mittels Bruchversuchen an Originalbrücken untereinander vergleicht.

1. INTRODUCTION

1.1 Background

There are approximately 35,000 masonry arch highway bridges in the United Kingdom and a similar number on the country's railways. All of these are of considerable age and many are excellent reminders of the country's architectural heritage. It is important therefore not only to maintain these bridges in good condition but also, when necessary, to be able to estimate their load carrying capacity as accurately as possible so that the numbers needing replacement are kept to the minimum.

1.2 Masonry Arch Research In The UK

The UK Bridge Census and Sample Survey [1], published in 1987, indicated that almost 10 per cent of the masonry arch road bridges would be found to be sub-standard according to the commonly used assessment method given in the Department of Transport Advice Note BA 16/84 [2]. The Department therefore sponsored a coordinated programme of research aimed at improving on the method, known as the MEXE method, which was generally suspected to be conservative. This programme, which, in addition to the theoretical work, involved the collapse testing of 8 redundant bridges and 2 full-scale models [3], resulted in the development of three different computer-based analytical methods of assessment.

The ultimate load capacities of the test bridges calculated by using the three methods were compared with the test results. A further study was also undertaken to examine in greater detail the theoretical implications of the methods. This paper contains the results of the comparisons and the additional study.

2. ASSESSMENT METHODS

2.1 The Modified MEXE Method

This method is described in Advice Note BA 16/84. It is based on the earlier MEXE method which was originally developed for military purposes. It involves the use of a nomogram, or optionally, an equation which gives a provisional axle loading (PAL) for a given span and a given total thickness of the masonry plus fill at the crown. The PAL is then modified by a number of factors which deal with the specific geometry, materials and the condition of the bridge to give a modified allowable axle load. The allowable axle load can be converted into permissible gross vehicle weights with the help of a table.

2.2 The Modified Pippard Method

The precise theoretical basis of the MEXE method is not known. However, it was almost certainly based on the simple elastic method of Pippard [4], which involved the elastic analysis of a parabolic arch, shown in Fig.1, assuming its cross-sections to be able to take tension but using a permissible limit of compressive stresses. It has been confirmed by recent investigative work that if Pippard's arch were analysed by replacing the single axle with a two axle bogie, the original Pippard results would approximate to the modified MEXE values.

The Modified Pippard method, developed in the Department, involves the use of any frame analysis computer program to carry out the Pippard analysis, with two significant differences. Firstly, any arch, fill or loading configuration may be considered without the Pippard simplifications. Secondly, instead of using a permissible compressive stress limit,the compressive strength of the masonry is used to calculate the ultimate applied load. This is then reduced by the MEXE Condition and Joint Factors and a load factor of 3.0 to obtain the permissible axle or vehicle load.

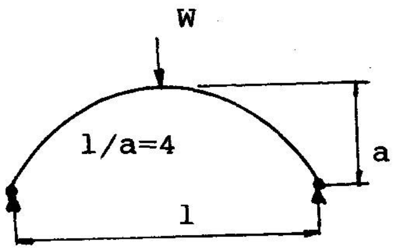


Fig.1 Pippard arch

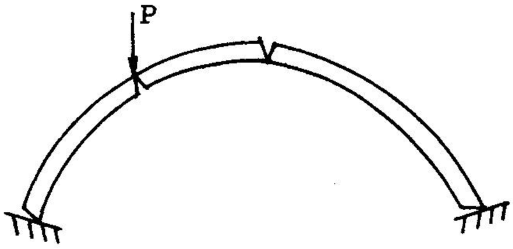


Fig.2 Failure mechanism

2.3 The Dundee Mechanism Method

The Mechanism Method, developed by Heyman [5], envisages that the arch shown in Fig.2 will, under increasing load, ultimately fail by forming the four hinges as shown. The method states that the line of thrust, i.e the line through the resultants of the compressive stresses in successive cross-sections of the arch, approaches the extrados and the intrados at the four potential hinge positions as the applied load increases. At the point of collapse, the thrust line touches the extrados and the intrados at the four points as shown in Fig.2. Since at these points moments are zero, it is possible to obtain the applied load which will cause the arch to collapse by taking moments of the reactions and forces about the hinge points, the system being statically determinate. The Heyman method assumes that the deformations are negligible and that the masonry has infinite compressive strength. The method also assumes that the surrounding fill only acts as vertical dead weight on the arch.

The Heyman method has been modified in a computer program by Harvey [6] of Dundee University to incorporate horizontal fill resistance. Since the method does not involve any elastic analysis, the fill resistance is applied as fixed fractions of the ultimate passive pressure of the soil.

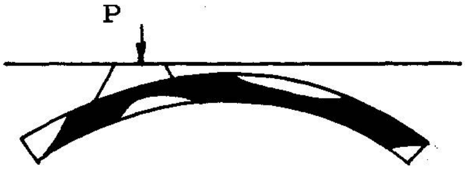
2.4 The Cardiff Elastic Method

The Cardiff elastic method [7] is based on the Castigliano [8] method and involves an elastic analysis of the linear arch, the cross-section of which is successively reduced in order to eliminate the areas with tensile stresses. The Cardiff method employs a computer programme to carry out the necessary iterations at increasing levels of the applied live load. At the end of the iterations, at any load level, the resultant cross-section becomes as shown in Fig.3. The centre-line of the solid (uncracked) cross-section is also modified at each load level to take account of the deformations occurring up to that load. As the applied live load increases the deformations increase more rapidly as shown in Fig.4 until failure occurs.The Cardiff method assumes that the ultimate compressive strength of the masonry does not influence the analysis. The method represents fill resistance by a series of horizontal springs.

3. COMPARISONS WITH TEST RESULTS

3.1 The Full Scale Tests

Ten full-scale tests to collapse have been carried out under the supervision of the Transport Research Laboratory in order to provide a datum for comparing the merits of different assessment methods. These tests, involving carefully selected typical road bridges and two models, have been fully described by Page [3]. The more significant details of the ten bridges are given in Table 1. The arches were loaded with a line load across widths at quarter span positions as indicated in Fig. 3.



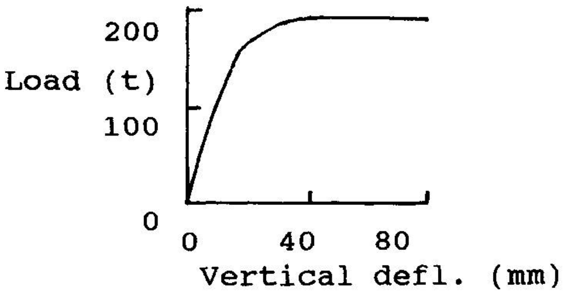


Fig.3 Section after thinning Fig.4 Cardiff load deflection

Bridge	Span (m)	Rise (m)	Ring Th.(m)	Width (m)	Failure Loads (tonnes) Test	Castigliano	Mechanism	MEXE/Pippard
Bridgemill	18.30	2.85	.711	8.30	310	183	278	245
Bargower	10.36	5.18	.558	8.68	560	601	336	350
Preston	5.18	1.64	.360	8.70	210	184	130	181
Prestwood	6.55	1,43	.220	3.60	22	0	2	7
Torksey	4.90	1.15	.343	7.80	108	103	91	124
Shinafoot	6.16	1.19	.542	7.03	250	268	204	296
Strath'ie	9.42	2.99	.600	5.81	132	118	142	112
Barlae	9.86	1.69	.450	9.80	290	232	216	320
Dundee	4.00	2.00	.250	6.00	104	90	23	123
Bolton	6.00	1.00	.220	6.00	117	41	39	124

Table 1 Comparisons with test results

3.2 Comparisons

The three methods were used to calculate the collapse loads for the ten bridges which are given in Table 1. The methods took account of the different conditions and defects of the arches as far as these could be accommodated. It should be noted that the calculations were carried out with the knowledge of the test results. Some of the parameters required by the methods, for example some of the compressive strengths of the masonry, were not recorded for all the bridges. Such missing items had to be assumed for the calculations.

It can be seen that all three methods give generally safe results. However, regarding the two more advanced methods, the following features have been observed. Compared to the test results, the Cardiff method gives generally low capacities for the flatter arches. Many of the Dundee results are very low. Obviously no theoretical method can be expected to provide uniformly accurate collapse loads for bridges in different degrees of deterioration, some of which also contained special features such as internal spandrel walls. Nevertheless, the results of these two methods for the two laboratory controlled model bridges and the Bridgemill bridge, all of which were in very good condition, are disappointing. The Pippard method gives both higher and lower results in equal numbers, the 'error' being mostly within +/- 20%, which is a desirable characteristic of an assessment method.

4. THEORETICAL INVESTIGATION

4.1 Failure Modes

In the first stage of the theoretical investigation a general frame analysis computer program MINIPONT, modified to carry out the Castigliano type elimination of the tensile part of the cross-section, was used to analyse the arch shown in Fig.5, the three loads P, W and R approximately representing the applied live load, the fill dead weight and the passive soil resistance respectively. At a typical longitudinal position (say X) the stress condition, derived from the bending moment and axial force present at that position, would be as shown in Fig.6, which also shows the position of the resultant thrust line in terms of its eccentricity 'e'from the intrados. The following three cases were analysed :-

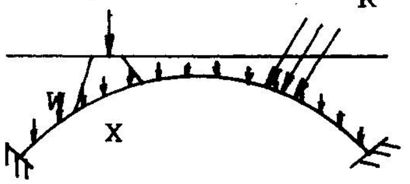


Fig.5 Analysis loads

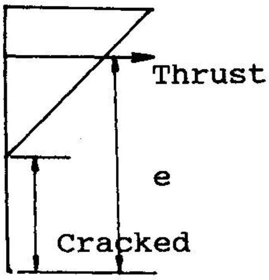


Fig.6 Stress at X

Case A : P increasing, W constant, R=0
Case B : P and R increasing in constant proportion, W=0
Case C : R increasing more slowly than P, W=0

The load deflection curves for the three cases are shown in Fig.7a and the changes of the thrust line eccentricity e is shown in Fig.7b.

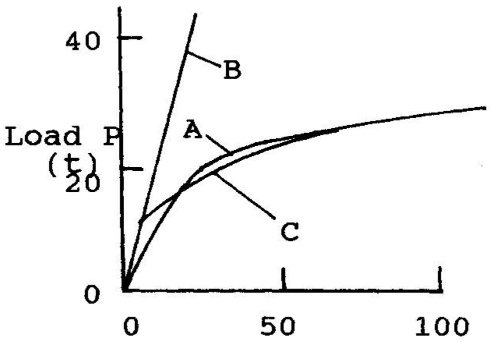


Fig.7a Load v deflection

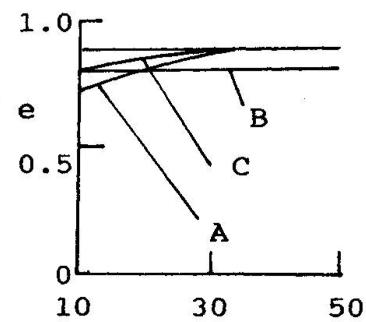


Fig.7b Load v ecc.

In Case A, only one unknown load parameter is involved and any single position of the thrust line corresponds to a unique value of the applied load. The Mechanism method and the Cardiff method can both model this situation. In this analysis it has been assumed that the masonry has infinite crushing strength and the deflections have been assumed to be negligible.

In Case B, which represents a very rigid soil condition, the thrust line does not move as the loading increases and the failure can only be initiated by the compressive stresses reaching a limit at successive parts of the longitudinal section. Since in such cases a single position of the thrust line can correspond to any magnitude of the applied loading, the Mechanism method is not strictly applicable. The Cardiff method is also not suitable because it does not consider (i.e. model) material crushing. However, more recently, finite element methods using line elements have been developed [9] for arch analysis which incorporate material crushing. Such a method would be suitable for this type of failure. The behaviour of the arch being linear, at least between successive hinge formations, the Modified Pippard method may also be appropriate for such cases, provided the compressive stresses developed in a cracked arch could be reasonably predicted by the non-thinning Pippard analysis, and the arches can be assumed to be pinned at the supports, which is probably quite realistic. It has been found in the above finite element analysis that the arch fails shortly after the the masonry crushes at the third hinge position, which is the limiting condition of the Modified Pippard method.

Case C represents a failing soil condition and the Cardiff method would be the only appropriate method in such cases. Although the failure is by forming a mechanism, more than one unknown load parameter is involved, which makes the Mechanism method unsuitable.

In the discussions above, deflections are assumed not to influence the arch behaviour. However, in theory at least, deflections added to the analysis as the load increases can speed up the collapse. However, for arch bridges of realistic dimensions, when the analysis was repeated in this manner this effect was found to be negligible. This is not to say that, for arches of more slender proportions, and especially for those without backfill, a deflection-aided failure can be precluded.

4.2 Finite Element Plane Stress Analysis

In order to examine which of the failure modes described above are likely to be relevant for typical highway arch bridges, a two-dimensional plane-stress finite element computer program SAFE [10] was used to analyse the ten test bridges with increasing applied load. All ten test bridges were idealised, as shown typically in Fig.8, and analysed for increasing load levels, approximately up to the test collapse loads. At each load level, iterations were performed to eliminate the areas with tension. In essence this analysis was identical to the Cardiff type

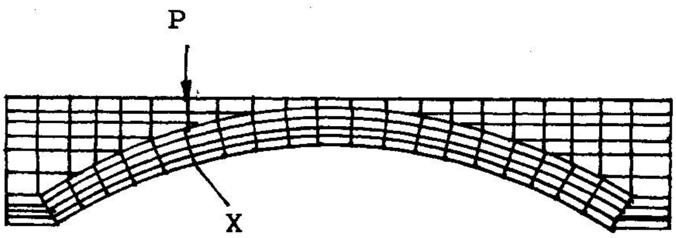


Fig.8 Finite element plane stress idealisation

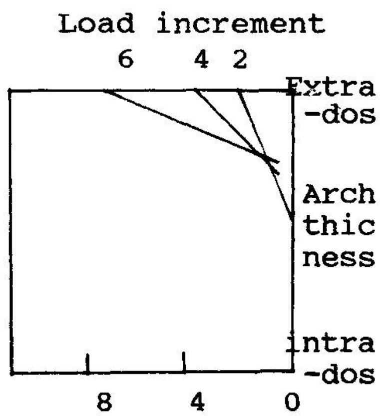


Fig.9 Stresses at X

analysis except that no simple linear stress distribution through the thickness of the arch was assumed (i.e plane sections remaining plane). The soil model used in the analysis was capable of yield in accordance with the Mohr Coulomb criterion.No crushing strength limit was used. Deflection correction was also not used.Stress distributions across the thickness at different load levels for one of the bridges are shown in Fig.9. These indicate that the stress blocks are basically triangular in shape and the extreme fibre compressive stresses are somewhat proportional to the load increments. The thrust lines appear to move at the early stages of the loading but then become stationary.

Comparisons of extreme fibre compressive stresses at the critical third hinge position (X) between the plane stress finite element analysis and the modified Pippard analysis are shown in Fig.10. This shows that in general there seems to be a constant relationship between the two sets of stresses. It should be noted that a lower Pippard stress could result in a potentially unsafe ultimate load estimate since in the Modified Pippard method the ultimate capacity is almost inversely proportional to the extreme fibre compressive stress. As the Modified Pippard stresses are in general about 25% lower, this possibility could be eliminated if a consistently conservative estimate of the masonry crushing strength is used in the calculations.

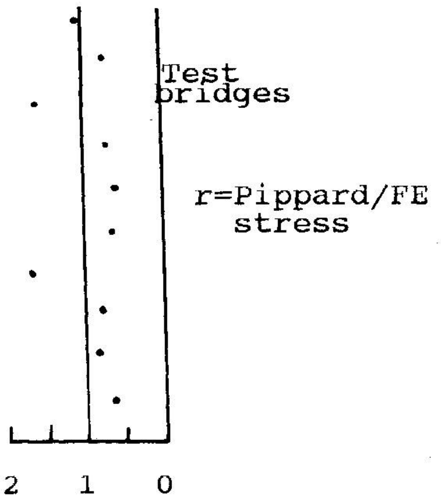


Fig.10 Stress comparison

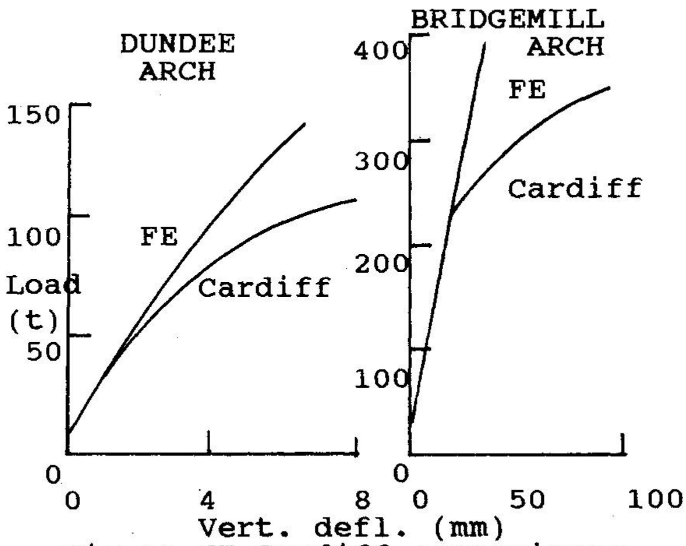


Fig.11 FE-Cardiff comparisons

The finite element plane stress results show that, without a crushing strength limit, and despite local passive yield of the fill, the load/deflection behaviour remains almost linear. This is shown in Fig.11 for two of the bridges. This figure also shows the load/deflection curves obtained from the Cardiff analyses without deflection correction. It should be remembered that the results from the Cardiff analysis without deflection correction should be comparable to the finite element plane stress analysis.

5. CONCLUSIONS

The finite element plane stress analysis results strongly indicate that fill resistance increases proportionately with applied live loading and the behaviour of a typical highway arch bridge is likely to be similar to that of Case B in 4.1. As discussed earlier, both the Mechanism method and the Cardiff method are not strictly applicable for the assessment of such situations although the simple bending theory implicit in the Cardiff method seems to be confirmed by the triangular stress distributions through the arch thickness given by the finite element plane stress analysis. A thinning method which eliminates the tensile areas of the cross-section and also able to model crushing failure, would however be suitable. Furthermore, as shown in Fig.11, the Cardiff method produces failures in the arches without masonry crushing (the method does not consider this) which, according to the plane stress analysis, it should not. A possible reason for this may be that the horizontal soil spring idealisation used by the method does not adequately represent overall soil resistance. It has been observed from tests [11] that on the passive side of the arch, the vertical soil pressure also increases with load. The Cardiff method assumes this to be constant i.e, equal to the dead weight of the fill above per unit horizontal area. This could be the reason why the method gave poorer correlation for the flatter arches where vertical soil pressure might have greater influence.

The Modified Pippard method seems to predict realistic compressive stresses at the critical third hinge point, and hence may be used as a refinement of the empirical MEXE method.

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