EXPERIMENTAL TESTS OF MASONRY ARCHES

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Abstract

The paper reviews the experience from model test of masonry arches compares their results with several analytic solutions. The analytic methods range from simple semi-empiric formulas to sophisticated finite elements models.

Keywords: masonry, arch, experimental test, MEXE methods, program CTAP

1 Introduction

The project Masonry Arch Bridges compares the results of experimental test on masonry arches with several analytic solutions. The results from the comparison will serve as the input data for development of an analytical model for determination of the load bearing capacity of arches and vaults and for suggesting a methodology of assessment of load bearing capacity of arch structures, since there is no specific method of determination of load bearing capacity of arches and vaults. There are several methods of such determination in use these days in the Czech Republic and also abroad. Also, as for the assessment of the load bearing capacity at collapse, there are numerous methods which are essentially different

2 Experiment

In the experimental part of the project, three sets, where each set contained three arches were built. The shape of each arch was that of a circular arch band. The arch bands were made of full firebrick of the type P15 and cement-lime mortar, M2. The width of the arch bands was 29 cm, corresponding to the length of the firebrick. The thickness of the arch band was 14cm, corresponding to the width of the firebrick (Fig. 1). The span of the arch bands was 3 m with the height of 1.2 m, 1.0 m and 0.75 m. (Tab.1).

The static border conditions were secured with steel beams. The vertical displacement of arches was arrested by anchors attached to the floor. The horizontal displacements were arrested by a steel beams fix to the rear side of the foot of the arch. There beams were also anchored to the floor.

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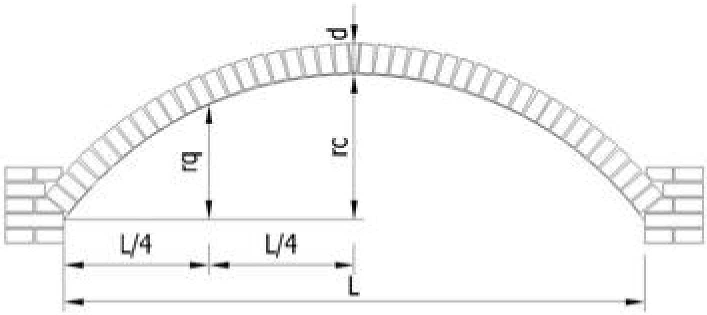

Fig. 1 The form of masonry arches

Height in a middle	rc [m]	1,2	1,0	0,75
Height in a quarter	rq [m]	1,002	0,817	0,594
Relationship of span and height	L/rc [m]	2,5	3	4
Relationship of height and span	rc/L [m]	1/2,5 (0,4)	1/3 (0,33)	1/4 (0,25)

Tab. 1 Geometry of masonry arches

2.1 Loading

The arch bands were loaded at a quarter of the span with a hydraulic press. The force acting at the arch band was transferred though a distributing device. The loading was continuous increased with a step of 0.1 kN, until the force reached the collapse force level – until the fourth hinge formed. Time interval between each loading step was 60 seconds.

2.2 Results

During the experiment, deformations of arches and stresses in the arches were monitored. The stresses, measured through the relative deformations, were recorded by strain gauges, the vertical and horizontal deformations were recorded by potentiometers and at the point where the load was applied deformations were recorded by an inductive sensor (Fig. 2). At one experiment, there were seven vertical deformations and two horizontals deformations recorded. The stresses are recorded at different six locations. For a better monitoring of crack formation the surface of arches was painted with gypsum grout.

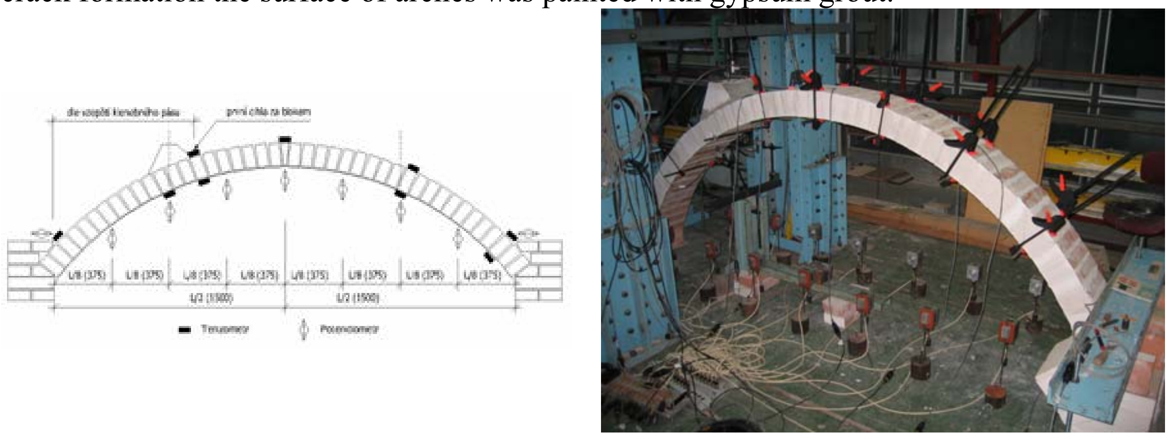

Fig. 2 Position of sensors

Deformation by collapse capacity, by generation of fourth joints (cracks), was same as a hypothetic. Cracks were as hypothetic i.e. in the quarters of arch and in the springers of arch (Fig 3). In the Tab.2 are the experimental values of arch capacity.

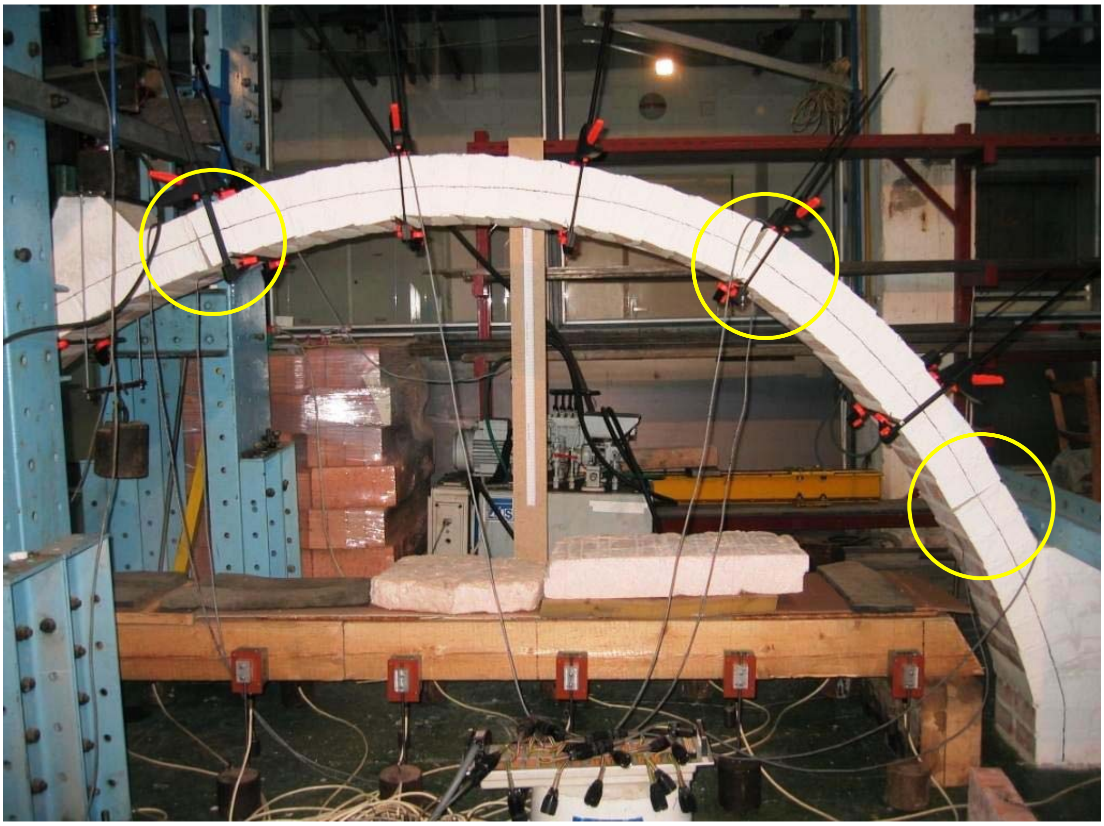

Fig. 3 The shape of arch by collapse capacity (in the yellow circle are the place of cracks)

Height in a middle	rc [m]	1,2	1,0	0,75
Relationship of span and height	rc/L [m]	1/2,5 (0,4)	1/3 (0,33)	1/4 (0,25)
Experiment 1		1,230*	2,130	1,970
Experiment 2		1,590	1,690	2,250
Experiment 3	F [kN]	1,423	1,553	2,120
Experiment 4		1,533	-	-
Average		1,515*	1,791	2,113

Tab. 2 Experimental value of arch capacity
(*average without Experiment 1 – Experiment 1 was unsuccessful)

3 Computations

3.1 MEXE method

The method was developed by the British Army's Engineering Experimental base (MEXE) [1, 2]. The MEXE is a simple empiric method for estimation of load bearing capacity of masonry circular arches for army purposes. The method allows for consideration geometric properties of circle arches. The method is also used for civilian purposes.

The method uses a monogram, or equations, e.g. $PAL = \frac{740(d+h)^2}{L^{1,3}}$, for preliminary determination of permissible axle loading (PAL), which depends on the span, the axial length of an arch and the height of a mound. The PAL value can be modified by various coefficients regarding the geometric and other condition of an arch. The MEXE method is limited by the arch span of 18 m.

Height in a middle	rc [m]	**1,20**	**1,00**	**0,75**
Height in a quarter	rq [m]	1,002	0,817	0,594
Width of mound	h[m]	0	0	0
Width of arch	d [m]	0,150	0,150	0,150
Span of arch	L [m]	3,0	3,0	3,0
PAL $PAL = 740(d+h)^2 / L^{1,3}$	**PAL [t/m]**	**3,992**	**3,992**	**3,992**
Relationship of span and height ratio	**Fsr**	1,0	1,0	1,0
	L/rc	2,5	3	4
Arch shape ratio	**Fp**	0,780	0,830	0,897
$Fp = 2,3*((rc-rq)/rc)^{0,6}$				
Material ratio	**Fm**	1,0	1,0	1,0
Fm = (Fb*d + Ff*h) / (d+h)				
Ratio of arch material	Fb	1,0	1,0	1,0
Ratio of mound material	Ff	0	0	0
Gap between band element ratio	**Fj**	0,720	0,720	0,720
Fj = Fw * Fmo * Fd				
Ratio of width gap	Fw	0,8	0,8	0,8
Ratio of mortar in gap	Fmo	1,0	1,0	1,0
Ratio of gap design form	Fd	0,9	0,9	0,9
Construction quality ratio	**Fc**	1,0	1,0	1,0
PAL * Fsr * Fp * Fm * Fj * Fc	**MAL [t/m]**	**2,242**	**2,386**	**2,577**
	KN/band	**6,727**	**7,158**	**7,730**

Tab. 3 Capacity by MEXE method

3.2 Program CTAP

The second program CTAP [3] was used as one of the analytical methods for calculation of the load bearing capacity at collapse. This program was developed at the University of Wales, Cardiff, Great Britain. The computations of collapse capacity were performed on an arch with a width of 1 m and subsequently the computed results were reduced for arches with the width of 0.29 cm.

Height in a middle	rc [m]	1.2	1.0	0.75
Position of collapse capacity	L [m]	0.97	0.63	0.59
Collapse capacity	[kN/mb]	14.2	17.2	20.0
	[kN/band]	4.26	5.16	6.02
Elastic capacity	[kN/mb]	miscalculated	2.35	1.18
	[kN/band]	miscalculated	0.705	0.544

Tab. 4 Value and position of collapse capacity

3.3 KSM program

The program developed at the Department of Structural Mechanics of CTU (DSM) represents the third analytical method used in this project. The method is based on the model which is described in [4]. The plane strain condition is assumed. The circle is modelled as a layered beam with five layers. The material of the layers is considered elasto-plastic with Rankin's condition and with linear softening. Constant are: E=3000MPa; ν=0,15; f'_c=3MPa; f'_t=0,08MPa; ρ=2,0t/m3; G_f=10N/m; l_{char}=0,15cm; ε_{lim}=0,0017. The fracture energy G_f valid for mortar was estimated with the assumption that the crack occurs in mortar.

3.4 Program ADINA

The ADINA [5] program is the fourth and last method. The program works with the Drucken-Prager condition with an additional limitation surface in tension and with tensile softening. The nine-point isoperimetric elements are used in five layers in combination with the Newton-Raphson and the arc-length methods for solving the nonlinear equation system.

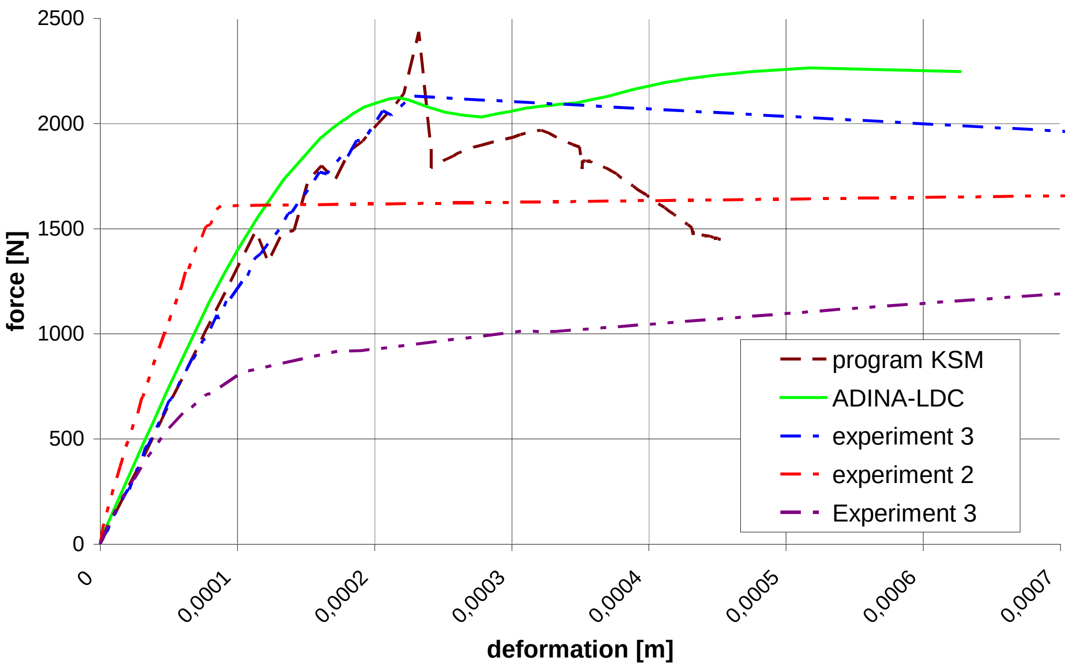

Fig. 4 Experimental and computation arch capacity (arch with height 1.0m).

4 Conclusions

In the next part of the project, the experimental tests will be finished and further comparative calculation of the load bearing capacity at collapse will be performed. The conformity of the analytical solutions and the experimental results was not acceptable. However, the considered analytical methods (DSM, ADINA) have some free parameters. The calibration of these free parameters is one of the next goals of the project. Further, development of an analytical model for determination of the load bearing capacity of arches will be pursued with subsequent verification of the developed 2D model, or preferably 3D model, with the experimental test results.

Acknowledgements

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References

[1] BA 21/97 The Assessment of Highway Bridges and Structures (Incorporating Amendment No. 1 dated August 1997)
[2] BA 16/97 The Assessment of Highway Bridges and Structures (Incorporating Amendment No. 1 dated November 1997)
[3] CTAP Masonry arch assessment package, University of Wales, Cardiff, UK
[4] Řeřicha, P. Statistic and Dynamic Limit Loads of Reinforced Concrete Structures. Praha: CTU Report Praha, 2000. 107 s. ISBN 80-01-02247-1
[5] ADINA program manual, ADINA R&P, Inc., 71 Elton Avenue, Watertown, MA 02172 USA