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The effect of skew angle on the mechanical behaviour of masonry arches

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ABSTRACT

This paper presents the development of a three dimensional computational model, based on the Discrete Element Method (DEM), which was used to investigate the effect of the angle of skew on the load carrying capacity of twenty-eight different in geometry single span stone masonry arches. Each stone of the arch was represented as a distinct block. Mortar joints were modelled as zero thickness interfaces which can open and close depending on the magnitude and direction of the stresses applied to them. The variables investigated were the arch span, the span: rise ratio and the skew angle. At each arch, a full width vertical line load was applied incrementally to the extrados at quarter span until collapse. At each load increment, the crack development and vertical deflection profile was recorded. The results compared with similar "square" (or regular) arches. From the results analysis, it was found that an increase in the angle of skew will increase the twisting behaviour of the arch and will eventually cause failure to occur at a lower load. Also, the effect of the angle of skew on the ultimate load that the masonry arch can carry is more significant for segmental arches than circular one.

1. Introduction

A skew arch is a method of construction that enables masonry arch bridges to span obstacles at an angle (Fig. 1). Bridges with a small amount of skew (i.e., less than 30°) can be constructed using bedding planes parallel to the abutments (Melbourne and Hodgson, 1995). However, bridges with large amount of skew present significant construction difficulties. Fig. 2 shows three well-known methods of construction for an arch spanning at 45 degree skew (Page, 1993). Fig. 2a shows the simplest form of construction where units are laid parallel to abutments. Fig. 2b shows the English (or helicoidal) method which is constructed such that the bed at the crown is perpendicular to the longitudinal axis of the bridge. For geometrical reasons and for the beds to remain parallel, the orientation of the block units causes the beds to "roll over" and thus rest on the springings at an angle (Fig. 1b). This is a cheap method of construction since every voussoir is cut similar to each other. Fig. 2c shows the French (or orthogonal) method which keeps the bed orthogonal with the local edge of the arch. This is the most expensive method of construction since it requires varying sized masonry blocks and availability of high skilled masons, since almost every block in the arch barrel to be of unique shape. The procedure used for the construction of such bridges and their mathematical curves are described in full detail by Rankine (1862).

There are many thousands of stone masonry arch bridges in Europe, many of which have spans with a varying amount of skew (Brencich & Morbiducci, 2007). Most of these bridges are well over 100 years old and are supporting traffic loads many times above those originally envisaged. Different materials and methods of construction used in these bridges will influence their strength and stiffness. There is an increasing demand for a better understanding of the life expectancy of such bridges in order to inform maintenance, repair and strengthening strategies. Although a great deal of work has been carried out to assess the strength of square span masonry arch bridges using mainly two dimensional methods of analysis (Heyman, 1966; Gilbert, 1993; Page, 1993; Melbourne and Hodgson, 1995), comparatively little work has been undertaken to understand the three dimensional behaviour of skew arches (Hodgson, 1996; Wang, 2004). The analysis of skew arch bridges has many difficulties and there is no universally accepted method of analysis yet. Today, in many countries, including UK, skew arches are routinely assessed on the basis that the skew span is straight

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(a) (b)

Fig. 1. Typical skew masonry arch constructed using the English method: (a) front view and (b) detail of the intrados.

(e.g., DB 21/01; DB16/17). However, experience from previous studies has clearly shown that depending on the method of construction and geometry, the stiffness and strength of skew arches might be quite different (Hodgson, 1996). In addition, such method is not suitable for non-standard geometries or for arches which suffered damage and deterioration.

In recent years, sophisticated methods of analysis like Finite Element Method (FEM) have been applied to understand the three dimensional behaviour of arches (Choo and Gong, 1995). A nice overview of the different arch models performed in the 1990s can be found in Boothby (2001). However, in such models, the description of the discontinuity is limited since they tend to focus on the continuity of the arch. Sophisticated FEM approaches (e.g., contact element techniques) are able to reflect the discrete nature of masonry. Examples of such models have been undertaken by Fanning and Boothby (2001), Gago et al. (2002), Ford et al. (2003) and Drosopoulos et al. (2006). The disadvantages of these methods are mainly associated with: (a) high computational cost; (b) crack development cannot be obtained and (c) convergence difficulties if blocks fall or slide excessively. An alternative and appealing approach is represented by the Distinct Element Method (DEM), where the discrete nature of the masonry arch is truly incorporated. The advantage of the DEM is that considers the arch as a collection of separate voussoirs able to move and rotate to each other. The DEM was initially developed by Cundall (1971) to model blocky-rock systems and sliding along rock mass. The approach was later used to model masonry structures including arches (Lemos, 1995, 2007; Mirabella and Calvetti, 1998; Toth et al., 2009; Sarhosis and Sheng, 2014), where failure occurs along mortar joints. These studies demonstrated that DEM is a suitable method to perform analysis of masonry arches and to describe realistically the ultimate load and failure mechanism. However, the above studies were mainly focused on the two dimensional behaviour of arches.

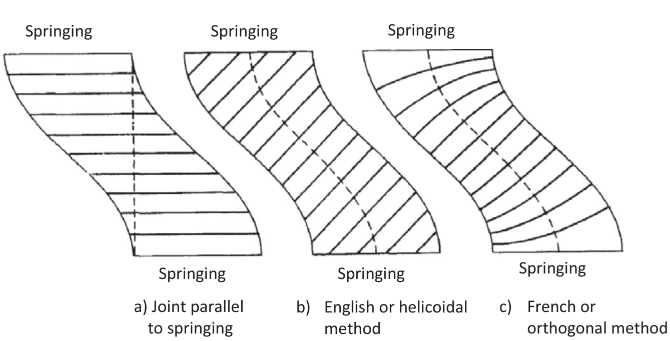

Fig. 2. Intrados of an arch spanning at 45 degree skew (Page, 1993).

The aim of this paper is to study the three dimensional behaviour of single span skew masonry arches and provide useful guidance for the design engineer. Using the three dimensional DEM software 3DEC (Itasca, 2004), computational models were developed to predict the serviceability and ultimate state behaviour of twenty-eight stone masonry arches with different geometries and skew angles. DEM is well suited for collapse analysis of stone masonry structures since: (a) large displacements and rotations between blocks, including their complete detachment, can be simulated; (b) contacts between blocks are automatically detected and updated as block motion occurs; (c) progressive failure associated with crack propagation can be simulated and (d) interlocking can be overcome by rounding the corners.

At this study, arches were constructed with joints parallel to abutments (Fig. 2a). Since the intention of the authors was to investigate the effect of the arch ring geometry, the effect of fill has not been included at this stage. The variables investigated were the arch span, the span: rise ratio and the skew angle. Results are compared against the load to cause first cracking, the magnitude of collapse load, the mode of failure and the area of joints opened. The suitability of the DEM to model the three dimensional behaviour of skew arches is also outlined. It is anticipated that results of this study will provide insight into the structural performance of skew masonry arches as well as will provide useful guidance for the design engineers.

2. Overview of 3DEC for modelling masonry

3DEC is an advanced numerical modelling code based on DEM for discontinuous modelling and can simulate the response of discontinuous media, such as masonry, subjected to either static or dynamic loading. When used to model masonry, the units (i.e., stones) are represented as an assemblage of rigid or deformable blocks which may take any arbitrary geometry. Typically, rigid blocks are adequate for structures with stiff, strong units, in which deformational behaviour takes place at the joints. For explicit dynamic analysis, rigid block models run significantly faster. For static problems, this computational advantage is less important, so deformable blocks are preferable, as they provide a more elaborate representation of structural behaviour. Deformable blocks, with an internal tetrahedral FE mesh, were used in the analyses reported herein. Joints are represented as interfaces between blocks. These interfaces can be viewed as interactions between the blocks and are governed by appropriate stress-displacement constitutive laws. These interactions can be linear (e.g., spring stiffness) or non-linear functions. Interaction between blocks is represented by set of point contacts, of either vertex to face or edge to edge type (Fig. 3). In 3DEC, finite displacements and rotations of the discrete bodies are allowed. These include complete detachment between blocks and