International Institute for FRP in Construction
FRPRCS-14, Belfast - June 2019

Finite Element Analysis Modelling of bed scour in the FlexiArch^{TM} bridge at Queens University Belfast

Gyftaki, E.[1], Taylor, S.E.[2], Hamill, G[2], Rostagni, H.[3], Robinson, D.[2], McFarland, B.[4],

[1] *Atkins, Belfast, UK;* [2]*Civil Engineering, Queen's University Belfast, Northern Ireland;* [3]*University of Paris-Saclay* Paris, Saint-Aubin, France; [4] *McFarland Associates Ltd, Belfast, Northern Ireland.*

Abstract

Bed scour at bridges, and in particular scour at short spanned arch bridges, has recently come to the fore due to an increase in the number of structural failures associated with increased flood events and, in particular, masonry arch bridges. The incidence of failure in short to medium span bridges within the UK and globally due to scour accounts for 70% of bridge collapses. Additionally, the failure of short span masonry arch bridges, subjected to pressurised flow, has increased significantly over the past decade as a direct consequence of bridge-waterway scour and bridge abutment collapse. While the problem of bridge scour is well documented, the changes to the flow and subsequent scouring that take place due to increased flood levels has had scant attention. Previous research in this area has concentrated on either the structural behaviour of arch bridges or the hydrodynamic interaction of the flow within the river bed. It is, however, the consequential nature of the interaction between the bed scour and the structural response to this that causes collapse, and is an area that has not been fully investigated. This paper presents the simulation of the behaviour of the FlexiArch Bridge system under scour development. The non-linear finite element model of the FlexiArch Bridge that will be generated will have its stiffness modified and will be tested under different displacement loads in order to replicate the scour development.

Keywords: Masonry arch bridges, FlexiArch, Scour, Finite Element Analysis Modelling

Corresponding author's email: e.gyftaki01@qub.ac.uk

Introduction

Scour is the cause of failure for approximately 70% of short to medium span bridges in the UK and globally. The collapse of short span masonry arch bridges, subjected to pressurized flow, has increased significantly over the past decade as a consequence increased flood levels causing bridge abutment collapse and bridge waterway scour [1]. The three causes of scour at the bridge piers general, contraction and local are the most critical. Local scour is caused by the interference of the river flow with the structure and can lead to a sudden failure as there is little warning of distress to the structure [2]. Significant research has been carried out proposing monitoring technologies to measure the scour depth of the piers and foundations but there is little information on the predicted integrity of the bridge after flood events.

Background on masonry arch bridges and the FlexiArch Bridge System

One of the oldest architectural type of structures is masonry arch birdges. The vast majority of existing masonry arch bridges are now over 100 years old and some are substantially older. Over the past three centuries the structural response of masonry arch bridges has been studied extensively and its structural response still represents a topical issue in modern civil engineering research. There are various masonry arch bridges across the world constructed in many different styles, sizes and spans to carry railways, roads or even waterways over rivers, roads and railways [3]. In Europe, 40% of the railway bridges are masonry arch bridges with more than 60% being over 100 years old. In the UK , the interest in the behaviour of masonry arch bridges became prominent at the time of World War II with the development of a quick method of arch bridge assessment using a nomograph before military vehicles were allowed to cross [4]. Queen's University of Belfast and Macrete Limited developed the FlexiArch bridge under a Knowledge Transfer Partnership, it is an off - site, flat-pack, masonry concrete arch bridge with no corrodible reinforcement [5]. This bridge system is fabricated in the pre-cast yard, is transported on site in flat form and is lifted in place in the suitable position without the need for centring [6]. This flexible arch bridge is made from individual concrete voussoirs and on top of them a polymeric reinforcement is placed held in place via a top screed. The desired span and rise are enabled because of the tapered cross-section of the voussoirs. At the elevation of the bridge a spandrel wall is positioned to provide a permanent formwork for the backfill of the bridge. The FlexiArch uses a low grade polymeric reinforcement to connect the voussoirs and does not contain any mortar, so that deterioration is prevented as corrosion of reinforcement or loss of mortar are prevented.

Non linear Finite Element Analysis model

The collapse of short span masonry arch bridges, subjected to pressurized flow, has increased significantly over the past decade as a consequence of bridge abutment collapse and bridge waterway scour. The FlexiArch bridge system is a novel system providing an environmentally friendly alternative to the traditional arch bridges but there has been no testing of the system under pressurised flow. This paper reports a non-linear finite element análisis (NLFEA) of the FlexiArch bridge system to simulate the soil-structure interaction and assuming a settlement due to scour. This is the initial part of a research project with industry with longer term ambition of testing and modelling pressurised flow interaction with the FlexiArch bridge. The NLFEA model was created using the LUSAS software. The mesh applied to the model was quadratic plain strain (Figure 1) using a very fine mesh following a mesh sensitivity analysis. The Coulomb friction coefficient between the soil and the concrete parts of the structure was 0.6 and the contact slideline factor was set to 0.1 for the contact surfaces between soil and concrete and 1.0E-3 for the contact between the voussoirs. The backfill was modelled according to the Drucker Prager properties with a density of 20kN/m^3 E_{fil} = 40 MPa, v = 0.3, angle β = 42.66° and cohesion yield stress 0.0986 N/mm^2 (as tested in previous PhD research [7]. Boundary conditions were applied to the boundaries of the structure and the backfill was restrained against vertical displacement at the base of the fill and against horizontal displacement at the sides of the model.
The scour development below the bridge foundation was modelled as a displacement load below the left foundation of the model and the range that was applied to the model was between 10mm to 80mm. Figure 2 shows the displacement shape of the generated model and Figure 3 the deformed mesh of the model under the experimental load.

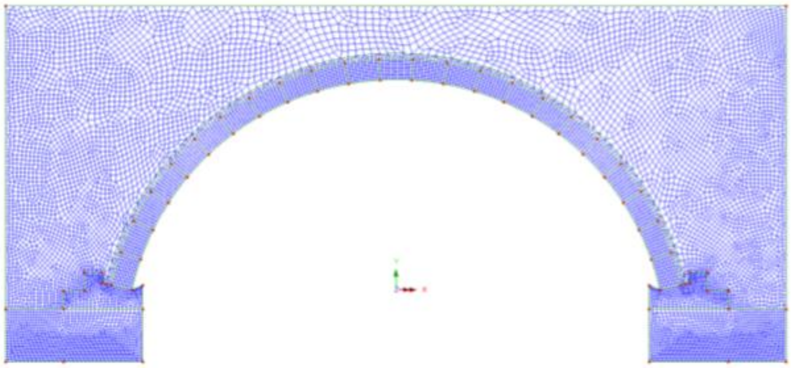

Figure 1: PLain Strain Mesh

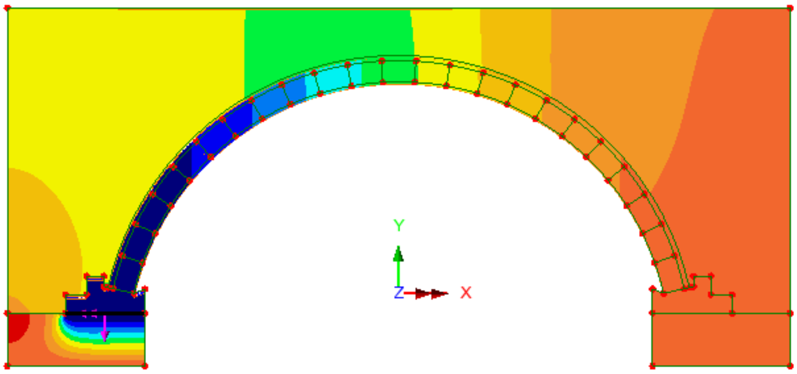

Figure 2: NLFEA output with 400mm Displacement at LH

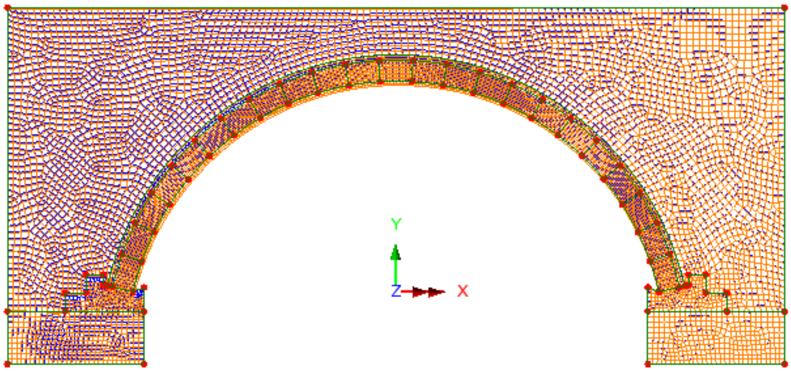

Figure 3: Deformed Mesh

Discussion of NLFEA results and further research

The results indicate that hinge formation was limited under the range of settlements investigated. The polymeric reinforcement, although designed for the purposes of construction, does provide resistance to the development of hinges when the settlement was applied. The ongoing experimental research should provide corroboration of these initial findings. It is intended to use vision monitoring techniques both above and below the water levels to measure the response of the FlexiArch bridge in flood conditions.

Conclusion

Masonry arch bridges are one of the oldest type of bridges worldwide. The collapse of short span masonry arch bridges, subjected to pressurized flow, has increased significantly over the past decade as a consequence of bridge abutment collapse and bridge waterway scour. Research has been held in the area of masonry arch bridges in the past that is concentrated on either the structural behaviour of arch bridges or the hydrodynamic interaction of the flow within the river bed. It is however, the consequential nature of the interaction between the bed scour and the structural response to this that causes collapse that should be further investigated in the future. The NLFEA study suggests that the FlexiArch bridge has some resistance to induced settlement at the supports. Further research with testing under flood conditions should corroborate these findings.

Acknowledgements

The authors would like to thank the UK Research Council (EPSRC) and McFarland Associates for funding this Doctoral Training Partnership.

References

[1] Richardson, E.V. and Davis, S.R. (2001) Evaluating Scour at Bridges, Fourth edition., US Department of Transportation, Federal Highway Administration.

[2] Kirby, A.M., Roca, M., Kitchen, A., Escarameia, M. and Chesterton, O.J. (2015) Manual on scour at bridges and other hydraulic structures, second edition, 2nd edn., London, UK: Ciria.

[3] MEXE (1952) 'Classification of masonry arch bridges', MEXE, Christchurch, UK.

[4] Page, J. (1993) 'State of the Art Review - Masonry Arch Bridges', First edn, HMSO, London, UK.

[5] Taylor, S.E., Long, A.E., Robinson, D., Rankin, B., Gupta, A., Kirkpatrick, J. & Hogg, I. (2006) 'Development of a flexible concrete arch', 11th International Conference on Structural Faults and Repairs, ed. M.C. Forde, Edinburgh, UK, 13th-15th June 2006.

[6] Taylor, S.E., Robinson, D., Grattan, S., Bourke, J., Long, A.E., Gupta, A. & Kirkpatrick, J. (2009) 'Monitoring of Tievenameena *Flexi*Arch bridge', 4th International Conference on Advanced Composites in Construction 2009, ACIC 2009, September 1, 2009 - September 3NetComposites Limited, Edinburgh, UK, 2009, pp. 135.

[7] McNulty, P (2014), 'Behaviour and analysis of a novel skew flexible concrete arch bridge', PhD thesis, Queen's University Belfast