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FATIGUE PERFORMANCE OF COMPOSITE AND RADIAL-PIN REINFORCEMENT ON MULTI-RING MASONRY ARCHES

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Abstract.

As a consequence of old age and changing loading régimes, many masonry arch bridges are being placed in repair/strengthening programmes. Current techniques involve the introduction of some form of reinforcement into or on the masonry arch barrel. All the currently reported work relates to static and low number cyclic loading.

The present work entails a series of 3m two-ring and 5m three-ring brickwork arches under long-term cyclic loading at various load levels until failure. Two methods of rehabilitation were tested. Firstly, Enforce Glass Fibre sheets were glued to the intrados of the brickwork arches and secondly radial pins were installed after failure of the FRP strengthened aches to check the efficacy of the technique to overcome ring separation.

1 BACKGROUND AND CONTEXT

As a consequence of old age and changing loading régimes, many masonry arch bridges are being placed in repair/strengthening programmes. Current techniques involve the introduction of some form of reinforcement into or on the masonry arch barrel. Performance of strengthening techniques has so far been tested mainly under static and short-term cyclic-loading. In the current research reported herein the behaviour of composite reinforced and radially pinned brickwork arches subjected to long-term (fatigue) cyclic loading is addressed and guidance offered.

2 MATERIAL PROPERTIES

Class "A" Engineering bricks (215 x 102.5 x 65mm) were used throughout the tests with an average compressive strength of 154N/mm^2 and density of 23.7 kN/m^3. 1:2:9 (cement:lime:sand) mortar was used with an average compressive strength of 1.7N/mm^2 and density of 15.5 kN/m^3. The average compressive strength of the brickwork was 25N/mm^2 and the density 20 kN/m^3. The composite material chosen for application was Enforce Glass Fibre Sheet (1 layer 340mm wide, 90/10 weave, tensile strength 53kN/m width).

2.1 Test series

A series of 3m and 5m span segmental arches were tested under static and long-term cyclic loading. For dimensions and loading conditions see Table 1.

Span (mm)	3000	5000
Rise (mm)	750	1250
Ring thickness (mm)	215	330
Arch width (mm)	445	375
Number of rings	2	3
Span : rise ratio	4:1	4:1
Dead load	2 x 10kN	2 x 22.5kN

Table 1 - Arch dimensions

2.2 Loading

In order to represent the weight of the fill on bridges (with fill height at the crown equivalent to the arch ring thickness and with density of 16kN/m^3) dead loads were applied at the ¼ and ¾ points of the arch either by steel weights or by hydraulic jacks (see Figure 1). Live load was applied at the ¼ point for static tests and alternatively at the ¼ and ¾ points for cyclic tests using hydraulic jacks.

Cyclic loading was applied at 2Hz frequency to represent the flow of traffic at ca. 30 miles/hours speed over the bridge. Cyclic loads were applied for at least 1,000,000 cycles at each load level, starting from a relatively small load. If after 1,000,000 cycles no damage or deterioration was observed the load was increased by 2kN and the process repeated until failure occurred. Formation of a mechanism, ring separation or slippage determined failure.

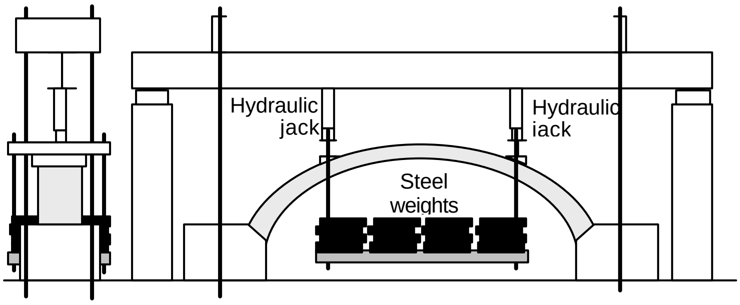


Figure 1 – Typical loading system

3 MASONRY ARCH STRENGTHENING

3.1 FRP

3.2 Composite reinforcement

The composite material chosen for application was one layer glass fibre sheet as the weakest form of FRP which was applied directly onto the good quality intrados surface (Figure 2).

Figure 2 – Application of glass fibre sheet and mode of failure

Performance of FRP reinforcement was tested under both static and cyclic loading. A series of complementary arch tests without FRP reinforcement had also been undertaken. It has been found that under static loading the load capacity of reinforced 3m (2 ring) arches was reduced by up to 30% compared to arches without reinforcement and significantly increased for the 5m arch. Under cyclic loading FRP reinforcement improved the load capacity of the 3m arches by around 20% (see Table 2).

		Unreinforced				FRP reinforced			
Span	Load	Arch	Max load (kN)	Number of cycles	Failure mode	Arch	Max load (kN)	Number of cycles	Failure mode
3m	Static	A	29	1	Four-hinge	H	25	1	Ring separation
		G	28	1	Four-hinge	I	20	1	Ring separation
	Cyclic	C	14	23,500	Ring separation	J	26	174,500	Ring separation
		E	12	25,000	Ring separation	K	18	145,000	Ring separation
						L	18	500,000	Ring separation
5m	Static	M	30	1	Ring separation	N	72	1	Ring separation
	Cyclic	O	18	333,000	Ring separation	O	ONGOING		
3m	Cyclic					KPin	28	1000	Slippage
						JPin	ONGOING		

Table 2 – Static and cyclic test results

The surprisingly low static load capacity of the 3m reinforced arches was the consequence of the change in failure mechanism due to the presence of reinforcement. While unreinforced arches under static loading generally failed as four-hinge mechanisms, the glass fibre-sheet prevented the formation of hinges at the extrados and thus caused higher shear stresses between the rings (see Figure 2).

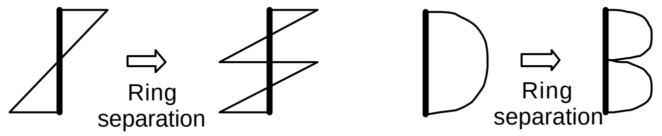
Flexural strengthening of arches using composites enhances the stiffness of the arch but also increases brittleness. For reinforced arches the initial cracks in the critical (high tensile stress) region occur at higher loads compared to unreinforced arches because of the ability of the bond between the glass fibre and masonry to transfer tensile stresses. Once the bond strength has been reached an initial crack occurs and the glass fibre acts as bridging over the crack and transfers tensile stresses through the bond back into the stiffer (masonry) part. This can happen as long as there is sufficient bond between the glass fibre and masonry. Once the bond between the FRP and masonry is broken down in the cracked region, cracks will similarly occur at other locations. Although in the experiments no cracks have been observed prior to final failure, acoustic emission recordings did clearly indicate cracking in the brickwork during load application. Cracks were however held together by the glass fibre sheet and were prevented from developing hinges. All reinforced arches failed by ring separation. A limited extent of delamination over a few individual bricks under the points of load application was observed which however did not propagate and was not responsible for failure. There was no (tensile) failure of the reinforcement itself.

The lower than expected static load capacity of the 3m arches has highlighted the pronounced danger of FRP strengthening if it is used when its consequences are not well understood. Although the presence of composite strip reinforcement can prevent the development of hinges it can also change the mode of failure without necessarily improving the performance of the structure. On the contrary to the 3m arch, reinforcement did enhance the static load capacity of the 5m arch beyond an expected degree. The fatigue performance of 3m arches was improved with composite reinforcement although it became more varied and less predictable. Although relatively small amount of reinforcement was applied onto the arch intrados, it did change the behaviour of the structure, load capacity and mode of failure and made the load capacity less predictable.

3.3 Radial stitching

Radial stitching on two arches has been included in the present test series. Both arches have been reinforced by FRP and subjected to cyclic loading up to failure (radial pins were introduced using 10mm diameter bars in pairs at 130mm centres longitudinally) and cyclic loading continued. Radial pinning stopped further separation of the rings and reinstated the original load capacity. The arch eventually failed by slippage (radial shear). The test indicated that radial pinning may improve the load capacity in one respect but it can also change the mode of failure for which alternative assessment procedures need to be carried out.

Ring separation may occur in multi-ring arches because of loss of inter-ring mortar due to deterioration or wash-out or due to longitudinal shear stress overload. Either way there will be a loss of mechanical integrity with the resulting reduction in mechanical performance. Figure 3 illustrates the consequence of ring separation on the flexural and shear stress distribution for a two-ring arch.



a) Flexural stress distribution

b) Longitudinal stress distribution

Figure 3 – Effects of ring separation on stress distribution

Previous work had established the flexural stress redistribution due to ring separation but the effects on the longitudinal shear stresses had not been considered before. If there is no mechanical connection between the rings (i.e. no radial pins etc.) then the barrel will rely entirely upon the bond between the mortar and the bricks to transfer the longitudinal shear stress. In which case, there will be slip strain between rings. (Slip strain is the rate of change of slip along the beam - this is not actual slip but is the same as strain is the rate of change of displacement). For full interaction a very stiff connection is required. Radial pins may be introduced to provide the necessary shear connection between the rings and these can fail in a number of ways as illustrated in Figure 1 separately or in combination.

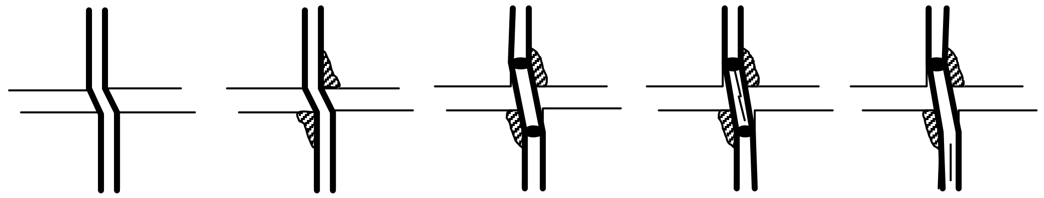


Figure 4 – Failure mechanisms in pin

Each mechanism may be considered in turn and quantified in the context of an idealised model. Table 3 indicates the maximum longitudinal shear stress for the inter-ring mortar for steel pins of various centres and is based upon a number of assumptions and idealisations. Firstly, the bearing stress for the brickwork is $2f_K$ (where f_K is the brickwork compressive strength). The confined nature of the pin bearing enhances the failure stress to between 4.3 and 5.5 f_K for static loading and approximately half this figure for fatigue loading i.e. $2f_K$). This gives a range of bearing stresses for brickwork f_K = 5 N/mm^2 to 20N/mm^2 of 10 N/mm^2 to 40 N/mm^2 respectively. This allows, for various pin diameters, the bearing and shear capacities of the pins to be calculated and compared.

In the case where bearing capacity is exceeded, the shear transfer is reliant upon the pin capacity in conjunction with the bearing capacity. An idealised free-body diagram indicates that for a weak brickwork an embedment length of at least 50mm would be necessary for a 25mm diameter bar. Additionally, the shearing action will also induce tensile stresses in the pin. Alternatively shear stress will also induce alternating movements (and local crushing) which affects the long-term performance. In the case of longitudinal 'slip' of 1mm and 10mm diameter bar this could result in tensile yielding of the pin.

The test arch which had pairs of 10mm diameter steel pins (shear strength 250 N/mm^2) at 130mm centres. Using the chart, assume the pins at 200mm centres and the masonry strength of 0.50N/mm^2. Modifying the figure for the closer centres gives a pro-rata figure of 0.69 N/mm^2. It can be shown that the maximum applied load of 28kN produced a maximum radial shear force of 18kN which, on a full cross-section, would induce a maximum longitudinal shear of 0.30 N/mm^2. This would explain why failure occurred by another mechanism i.e. radial slippage.

It is interesting to note that flexural cracks can also propagate as shown in Figure 5. The consequence of a crack at that plane is to change the longitudinal shear stress at the inter-ring mortar level. Figure 5 shows how the longitudinal shear stress changes from 0.30 N/mm^2 to a maximum of 0.35 N/mm^2 where x=60mm as the intrados crack propagates radially. It is worth noting that this phenomenon is equally true for perished radial joint mortar.

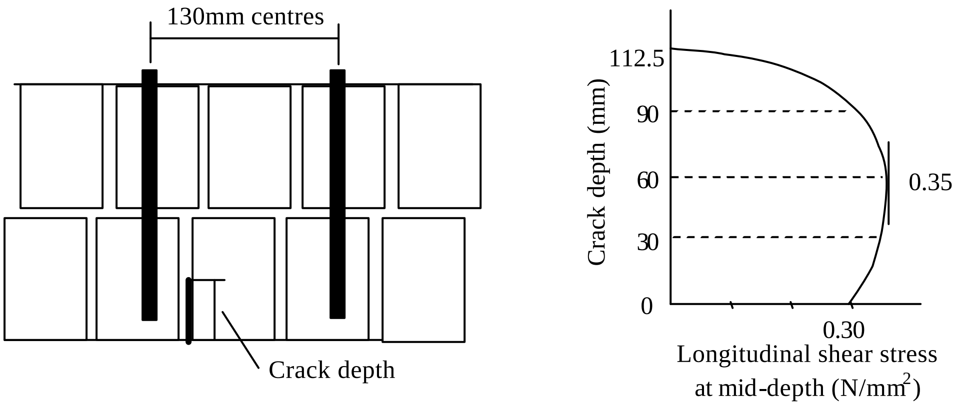


Figure 5 – Crack depth vs Shear stress

4 CONCLUSIONS

- Glass fibre composite reinforcement can reduce the load capacity of multi-ring masonry arches by changing their mode of failure.
- Composite reinforcement seemed to improve the fatigue performance of multi-ring arches
- Radial pinning together with composite strengthening seems to reinstate and improve the original load capacity of the arch (without reinforcement).
- Possible forms of failure mechanisms for pin reinforcement are presented.
- Practical guide for quantifying the number of required radial pins for inter-ring joint shear stress is presented.

5 ACKNOWLEDGEMENTS

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Shear strength (σ_v)	c/s	200mm			250mm			300mm			350mm			400mm		
	Masonry strength (σ_m) / Diameter (mm)	5	10	20	5	10	20	5	10	20	5	10	20	5	10	20
125	8															
	10	0.20	0.25	0.25	0.13	0.16	0.16	0.09	0.11	0.11	0.07	0.08	0.08	0.05	0.06	0.06
	12	0.26	0.35	0.35	0.17	0.23	0.23	0.12	0.16	0.16	0.09	0.12	0.12	0.07	0.09	0.09
	16	0.31	0.63	0.63	0.20	0.40	0.40	0.14	0.28	0.28	0.10	0.21	0.21	0.08	0.16	0.16
	25	0.50	1.00	1.53	0.32	0.65	0.98	0.22	0.45	0.68	0.16	0.32	0.50	0.12	0.24	0.38
250	8															
	10	0.20	0.40	0.50	0.13	0.26	0.32	0.09	0.18	0.22	0.07	0.14	0.16	0.05	0.10	0.12
	12	0.26	0.52	0.70	0.16	0.32	0.46	0.12	0.24	0.32	0.09	0.18	0.24	0.07	0.14	0.18
	16	0.31	0.62	1.26	0.20	0.40	0.80	0.14	0.28	0.56	0.10	0.21	0.42	0.08	0.16	0.32
	25	0.50	1.00	2.00	0.32	0.64	1.28	0.22	0.45	0.88	0.16	0.32	0.65	0.12	0.24	0.49
375	8															
	10	0.20	0.40	0.75	0.13	0.26	0.48	0.09	0.18	0.33	0.07	0.13	0.24	0.05	0.10	0.18
	12	0.26	0.52	1.04	0.17	0.34	0.62	0.12	0.24	0.47	0.09	0.18	0.35	0.07	0.14	0.27
	16	0.31	0.62	1.26	0.20	0.40	0.80	0.14	0.28	0.56	0.10	0.20	0.40	0.08	0.16	0.32
	25	0.50	1.00	2.00	0.32	0.64	1.28	0.22	0.44	0.89	0.16	0.32	0.64	0.12	0.12	0.50

Bearing critical
Shear critical

All values in N/mm^2
Further check is required with regard to mechanisms of failure

Table 3 – Ultimate longitudinal shear stress (N/mm^2)