INCREASED LOAD CAPACITY OF ARCH BRIDGES USING SLAB REINFORCED CONCRETE

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Abstract. *This paper reports the results of a series of small-scale centrifuge model tests undertaken to investigate the service and ultimate load capacity of un-strengthened and repaired/strengthened masonry arch bridges. Un-strengthened two dimensional 1:12 scale models of a 6-m single span arch bridge were initially tested using appropriate service loads and were subsequently line loaded up to the observation of the first sign of failure. Two types of arch geometry were tested, one shallow arch with span/rise ratio of 4 and one deep semicircular arch. The ultimate strip load was applied over the whole width of the arch barrel on top of the backfill at the quarter point of the arch span for both arch geometries. Following the initial tests the arches were repaired/strengthened by laying a reinforced concrete slab on top of the backfill. The arches were subsequently re-tested, initially with a service loading, and then up to full failure. Deflection of the arches and the backfill/arch interface pressures were recorded during the application of all loads. The strengthened arch results are compared to both the un-strengthened results and to previous tests undertaken using a similar concrete slabs saddled immediately above the extrados and sprayed onto the intrados. The present results indicate a significant improvement in the ultimate load capacity of the repaired arch over the un-strengthened arch. The load at failure of the shallow strengthened model was 3.4 times of that of the un-strengthened model and 2.7 of average benchmark failure load with of the same shape. The results for the strengthened deep arch were, respectively, 3.7 and 3.2 times as strong as the un-strengthened arch. The application of the slab to the surface appears to be at least equivalent to application directly to the arch intrados and extrados.*

1 INTRODUCTION

Masonry arch bridges continue to be an important part of the transportation systems in many countries. Many of these structures were built over a hundred or more years ago and remain in constant, if not often increasing, use. As a result of increasing vehicle loads these structures are frequently loaded to many times the loads initially envisaged, therefore possibilities of strengthening these structures is of significant interest to many of their owners. In addition during their long service time some faults may have developed in these structures necessitating repair.

In recent years there has been significant development of experimental and numerical research techniques into modelling repair and strengthening measures for these structures. Some of these tests were carried out on full scale models [1, 2] and some using smaller scale models; work has also been undertaken looking at the performance of actual repairs undertaken on working full scale structures [3]. Arch stitching, arch reinforcement, concrete saddles, backfill strengthening and sprayed concrete to the intrados are the most common ways of strengthening currently used. Tests previously undertaken on small scale centrifuge models showed significant strength improvement in arch load capacity due to strengthening of arch by a layer of concrete laid immediately adjacent to the extrados or the intrados of the arch barrel. Both of these forms of strengthening have significant disruption difficulties associated with their construction. This problem is frequently exacerbated by the limited lane width available for construction and the fact that arch bridges are, in many situations, the only crossing point for an entire community. In addition the natural long term flexibility of the structures may be impaired by the presence of the un-jointed concrete.

2 TEST IDENTIFICATION AND MATERIAL PROPERTY

The arches tested as part of the study reported in this paper were 1:12 scale models of a three ring, 6 metre single arch span built with distorted scale bricks; 1:12 scale in the ring depth and 1:6 scale (including the joint) as viewed from beneath the intrados. The bricks used in the models were Staffordshire Blues (215mm x 103mm x 65mm) with a compressive strength of 96 N/mm2. UK mortar type v was used with a compressive strength of 1.7 N/mm2 (based on the compressive strength on 25 mm cube samples). The backfill material was composed of an approximate 1:6 scale granular limestone. This was suitable as the interaction with the brickwork is at the correct geometric scale and the scaled fill simulates prototype backfill properties in small scale centrifuge very well [4]. The backfill had a bulk density of 20.5 Kn/m^3 and the friction angle of 53^o. The un-strengthened tests had a crown backfill depth of 13mm to readily facilitate the placement of the concrete without overly disturbing the damaged arches. The overall depth of construction over the crown of the arch, including the 17 mm of concrete layer in the strengthened arches, was 30mm. In this sense the initial un-strengthened tests were different from the previous standard benchmarks which had an overall crown backfill depth of 30mm. The concrete itself was manufactured with 2.0mm aggregate as the coarse material, Chelford 95 silica sand as the fine aggregate and OPC, with mix proportion of 1:1.8:2.8:0.6 (cement: fine: coarse: water) by mass. Compressive strength tests on 25 mm concrete cube samples yielded 56 N/mm^2. The model concrete was nominally reinforced with a 20 mm mesh of type 304 manufactured of 0.8mm mild steel. The same materials had previously been used were used in other small scale centrifuge models [5].

An initial appraisal of the likely effects of the concrete was required to ensure that adequate consideration was given to the instrumentation adopted. Locating the concrete at the road surface, as opposed to its traditional position adjacent to the arch ring, is likely to contribute in a different way to the arch strengthening. In considering the differing effects it is appropriate to consider the effects of a line loading at the quarter span at ultimate load. A concrete saddle provides additional compressive strength at the extrados of the arch beneath the applied load but more importantly the reinforcement provides significant additional tensile strength at the side remote from the applied load. For the arch strengthened with sprayed concrete to the intrados the reverse is true, here the reinforcement provides addition tensile strength beneath the applied load but there is little contribution to the side remote from the load unless there is a significant thickening. For the surface concrete there is a significant load distribution effect and the reinforcement has a potential larger lever arm effect at the side remote form the load assuming that some composite action is possible between the masonry, fill and slab. Important issues are therefore soil pressures overall stiffness and, of course, strength.

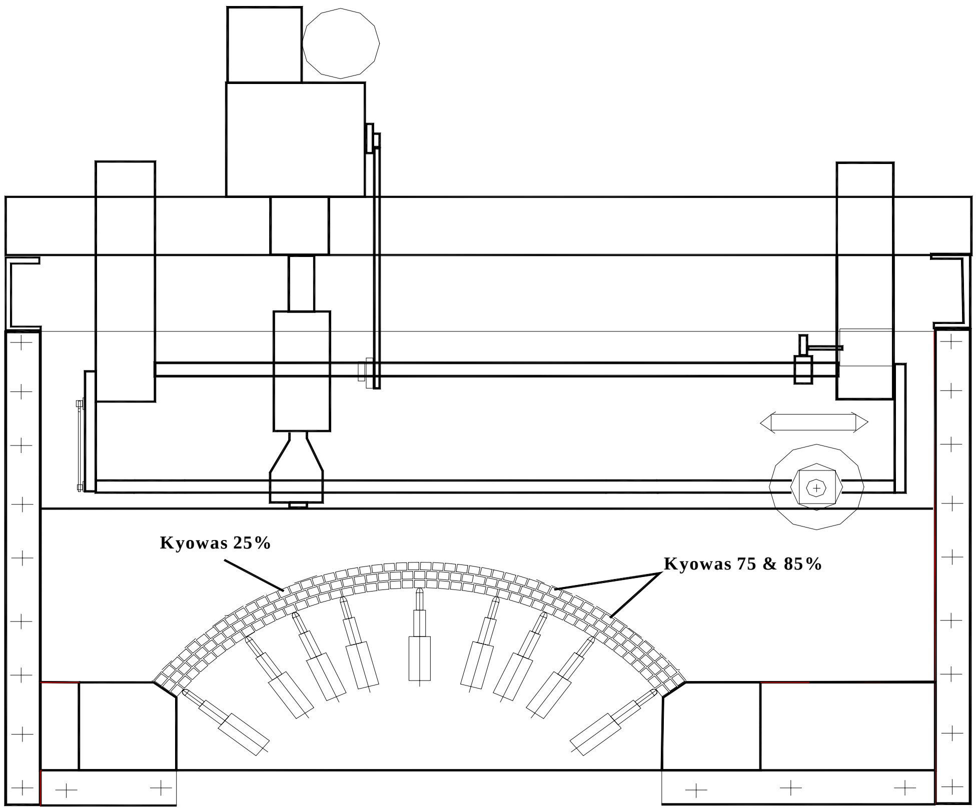

Figure 1: General view of the scale model test arrangement

3 LOAD SYSTEM AND MEASURMENTS

3.1 Service load system

Three in-line steel annuli rollers (equivalent to 10 tonnes on a 2.5m axle) simulated the service load during the tests. These rollers were rolled on the top of the fill from a point above one abutment to the other. Fourteen pass of the roller were carried out in each test and the position of the roller was recorded and referenced to the other monitoring equipment.

3.2 Knife load system

In each model after the service load was applied the centrifuge was stopped and the rolling load was replaced by a 20mm knife edge loading system across the full width of the arch. The load was applied on the top of the backfill at the quarter span point of the arch for both geometries of models until the observation of the first sign of failure in model. The model was then subsequently repaired by adding the 17 mm reinforced concrete slab. The applied load was measured by a suitable load cell during the tests (10 Kn. load cell in the benchmark and un-strengthened tests and 100 Kn. in strengthened models). Figure 1 details a general view of arch model and shows (concurrently) both the rolling and knife edge loading systems.

3.3 Soil/ Masonry interaction arch deflection measurements

The pressures between the arch barrel and the backfill were measured using 6mm diameter diaphragm (Kyowa) pressure cells installed within special brick units in the outer (extrados) layer of arch barrel. Two cells were located across the arch at a number of sections as shown in Figure 1.

The arch deflections were measured using two rows of displacement transducers (LVDTs). One LVDT row was installed along the centerline of the arch the other row parallel to the first but close to the edge (spandrel) face. The LVDTs were installed normal to the arch barrel to measure the radial deflections of the arches.

4 TEST RESULTS

4.1 Soil/Masonry interaction

The at-rest soil pressures at different locations along the arch barrel under dead load (at a stable stage of acceleration of 12g) are detailed in Figure 2 (Prefix B and R represent the benchmark/un-strengthened and repaired/strengthened results respectively, and E the elastic theory). Given the natural vagaries in the determination of at-rest pressures the results are generally considered to be appropriate and in reasonable agreement with those obtained from simple half space elastic theory. There is little obvious apparent effect of the additional weight of the concrete. The effect of the reinforced concrete slab on top of the fill on the soil/arch interface pressures generated by the rolling load are detailed Figure 3 for the shallow arch and in Figure 4 for the deep arch. Both figures show the variation of the pressures at the three quarter point (75%) of the span for different positions of the rollers. These figures are

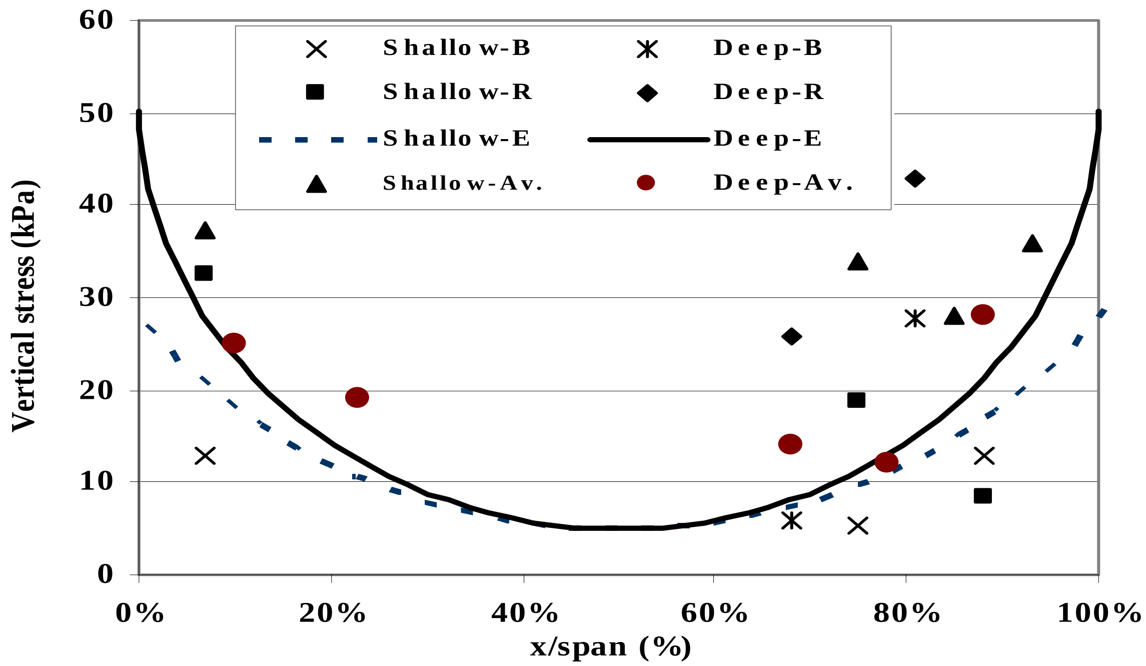

Figure 2: Comparison between calculated and measured pressure

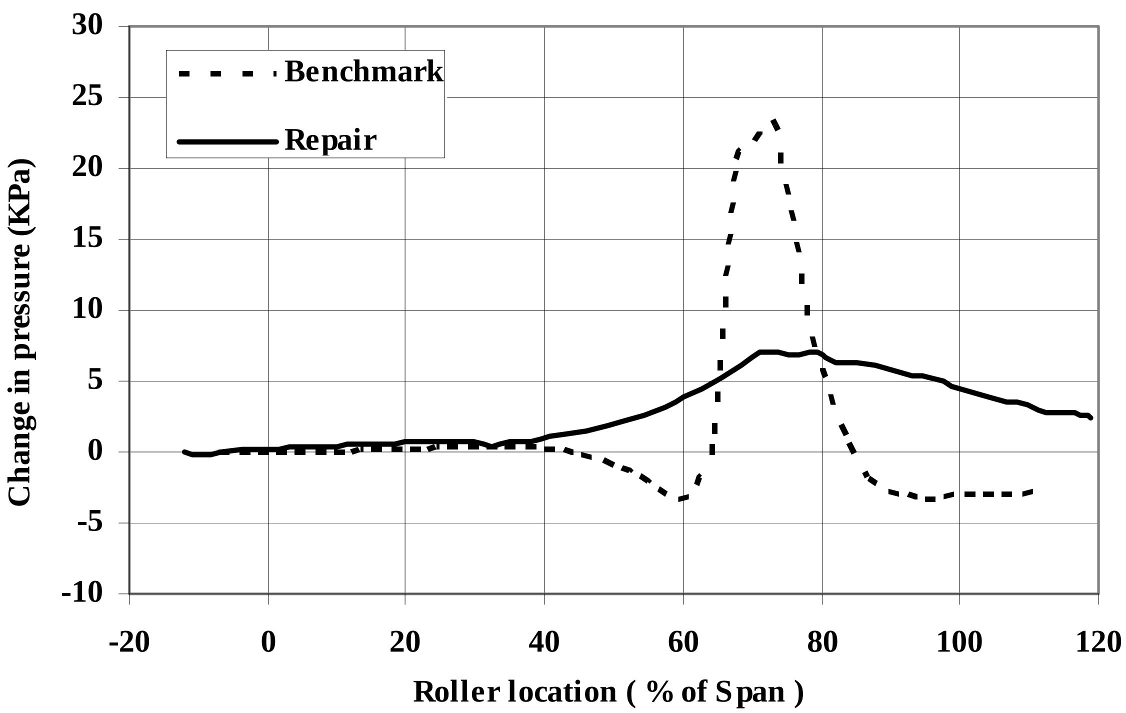

Figure 3: Shallow arch pressure at ¾ point on arch barrel for the final pass of the roller

for the rollers moving from left to right. Figure 3 shows that for the shallow arch the applied load was significantly redistributed by slab when the load was located above the sensor. The reduction in pressure associated with the load positioned on the crown did not happen this occurs on the benchmark tests as the load pushes the arch away from the fill reducing the pressure. For the slab test the load is much more distributed and therefore this trough is not present.

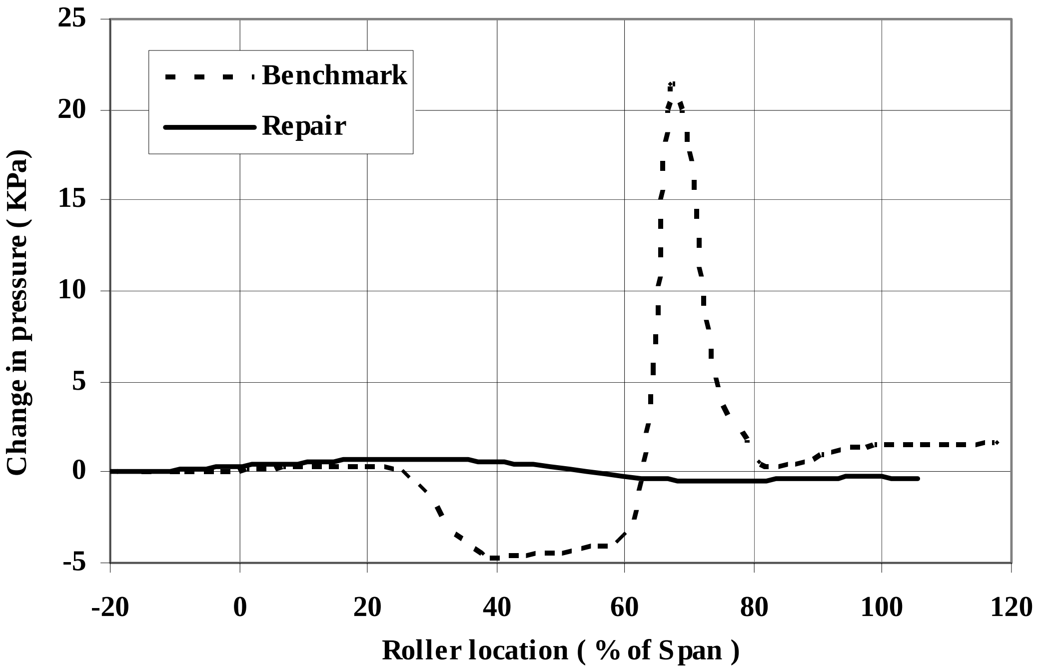

Figure 4: Deep arch pressure at ¾ point on arch barrel for the final pass of the roller

The pressures when the load is at the quarter point remote from the sensors are similar in both the benchmark and the strengthened test, suggesting a similar sway extent; this is not considered unrealistic.
For the deep arch (Figure 4) there was little evidence of the passing of the load at all, but there is some indication, when the load is at the quarter point remote from the sensor, of the presence of pressures developing as the arch sways into the fill.

4.2 Arch deflection

The deflections of the arches under service loads when the rollers were located at mid span are presented in Figure 5. The test results show, as expected, that the maximum radial deflection occurs at mid span of the arch when the rollers are directly located above. The slightly non symmetric nature of the deflections is to do with the direction of movement of the roller. The results of both the shallow and deep benchmark arches are similar. The figure shows a significant decrease in the deflection resulting from the application of the surface reinforced concrete slab. The deflections of both the deep and shallow arch are decreased to about 10% of their previous values.

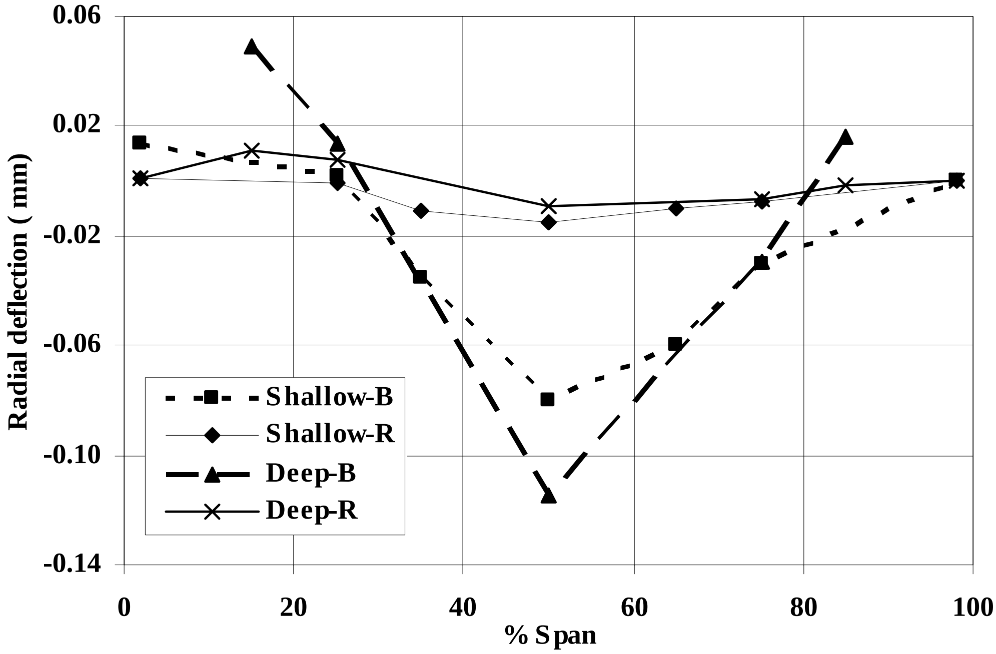

Figure 5: Deep and shallow arch crown deflections under service loads

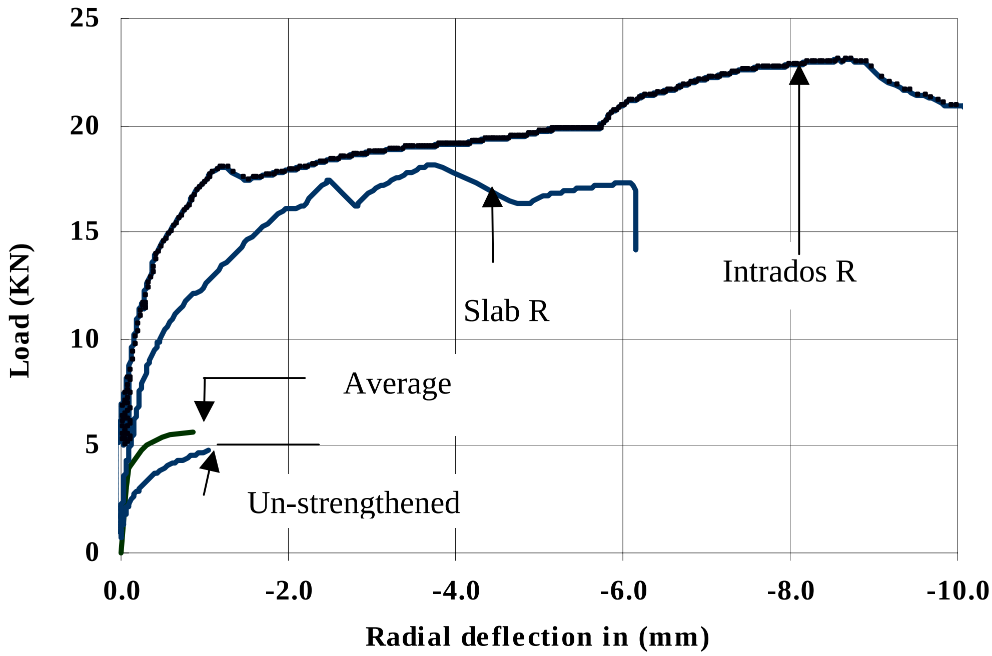

Figure 6: Load deflection curve for deep arch geometry

4.3 Ultimate load capacity

Following the service loading the ultimate knife edge loading was applied at the quarter span location in each test. The resulting load deflection responses are presented in Figure 6 and Figure 7 for the deep and shallow arches, respectively. Included in Figure 6, for comparison, are the previous results obtained using a similarly constructed concrete slab applied to the arch intrados, as well as the average benchmark and un-strengthened test results. There is no significant difference between the average benchmark and the un-strengthened test showing the arch (to be strengthened) was of average construction. Both strengthening results show a significant strength enhancement over the average un-strengthened (benchmark) and specific un-strengthened results.

The two repair/strengthening technique results show very similar responses with both providing a significant increase in both strength and ductility. The failure load of the shallow strengthened model was 3.7 times of that un-strengthened model and 3.2 of the average benchmark failure. Although the results for the intrados concrete show a slight enhancement over the surface slab in a real situation this would be associated with a reduction in headroom and an effective shortening on the span.

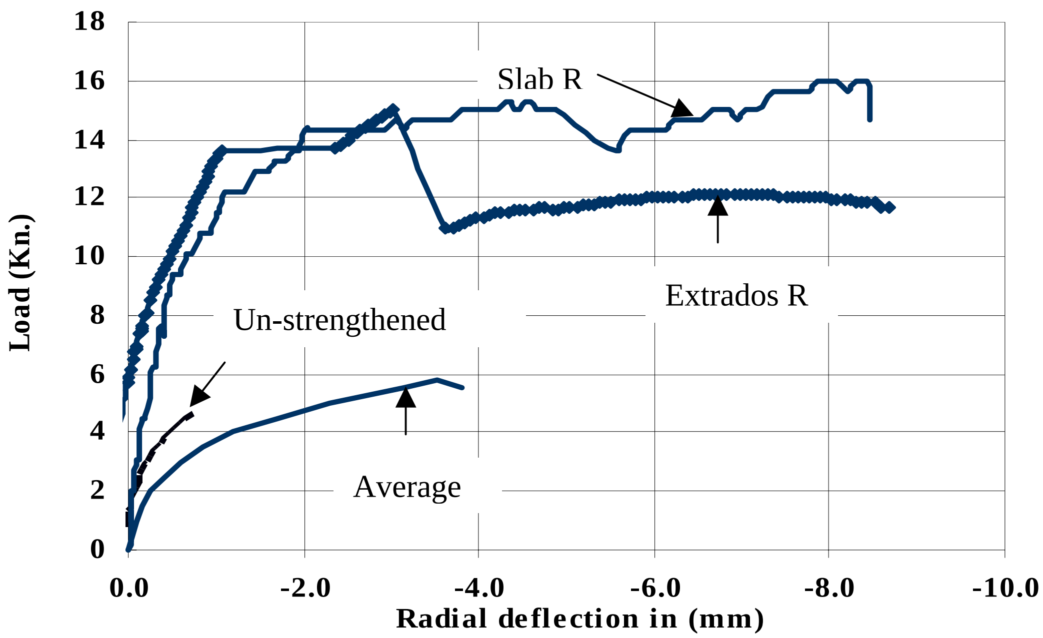

Figure 7: Load deflection curve for shallow arch geometry

Included in Figure 7 for the shallow arch are the previous results obtained with a concrete saddle applied to the arch extrados as well as the average benchmark and un-strengthened test results. The shallow un-strengthened result shows significantly reduced ductility and an accompanying slight loss of strength when compared to the average benchmark; the less fill the depth is then, proportionally, it is likely to have a larger effect on the shallow arch than it did on the deep arch. Both strengthening techniques provided a similar increase in both ductility and strength. The failure load of the shallow strengthened model was 3.4 times of that un-strengthened model and 2.7 of the average benchmark failure. The results of full scale tests at the TRL, on a similarly proportioned full scale arch, indicated that a layer of 150 mm spread concrete and a concrete saddle increased the ultimate capacity by factors of 3.72 and 2.90 respectively [1, 6] and this has shown good agreement with the result was achieved from the small scale centrifuge tests.

Overall the results show a significant improvement in arch behaviour obtained from the application of a surface slab concrete for both the arch geometries considered. This is perhaps somewhat surprising since the compacted backfill that it replaced is in itself quite a competent material, full details of which are available elsewhere [4]. The results from the application of concrete slab to the road surface compare very favourably to previous test results where the slab has been cast against both the extrados and the intrados of the arch barrel.

5 CONCLUSIONS

There are a number of conclusions that can be drawn directly from the current work and also a number of resulting observations on suitability of the proposed strengthening technique.

- The placement of a reinforced concrete slab as a road surface on top of the fill achieves similar ultimate load and ductility characteristics as an equivalent slab placed as a saddle on the extrados or as a soffit slab beneath the extrados.

- There are likely to be significant construction benefits associated with laying the concrete as a road surface, specifically the limited extent of the excavation as compared to a saddle, especially for deep arches represents a significant saving. There is also no loss of headroom beneath the structure. Difficulties associated with access to services, associated with the flat slab, need to be considered.

- The improvement in the distribution of load to the arch barrel suggests that there may be significant serviceability advantages associated with the surface slab. This coupled with the maintenance of the arch ring as a flexible jointed structure may provide additional resilience to any long term movements of the foundations.

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