Arch Bridges
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DYNAMIC EFFECTS IN ARCH BRIDGES – A FIELD STUDY

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Abstract. *There is no doubt that if sufficiently high loads are applied to arches, with sufficient frequency, they will begin to deteriorate long before the ultimate load is reached. Developing an understanding of this "fatigue" effect will be vital to protecting the vast number of arches, particularly on railway networks, throughout the world.*

The paper describes an investigation of one group of small arches. Deflections were measured simultaneously at many points on the arch soffit. The resulting deflections were post-processed to enable a video representation of the bridge deformation to be made. The resulting video provides a clear indication of how the bridge is behaving and introduces some ideas which are unlikely to have come to light in other ways.

The paper describes the basic problem, the equipment used, the processing required and the results obtained. Of the results, perhaps the most important is that bridges respond to moving loads in a directional way. That is to say, the effect cannot be considered quasi static at the speeds considered in these tests. Arches suffer load induced deterioration at loading levels substantially below ultimate capacity.

1 INTRODUCTION

Our understanding of the behaviour of arch bridges is severely limited. They are complex structures, with many potential load paths of closely similar stiffness. Modern analysis remains inadequate to give us a full understanding. When faced with difficult problems, testing can help an engineer to develop real understanding.

Over the past three years, the author has been involved with a series of difficult structures. As a result, he has progressively developed cheap quick and effective systems for measuring live load deflections. In most cases, the greatest level of economy is realized by using loads from normal traffic.

A particular bridge is considered in this paper, following which, a brief summary of recent developments is presented.

2 INITIAL STUDIES

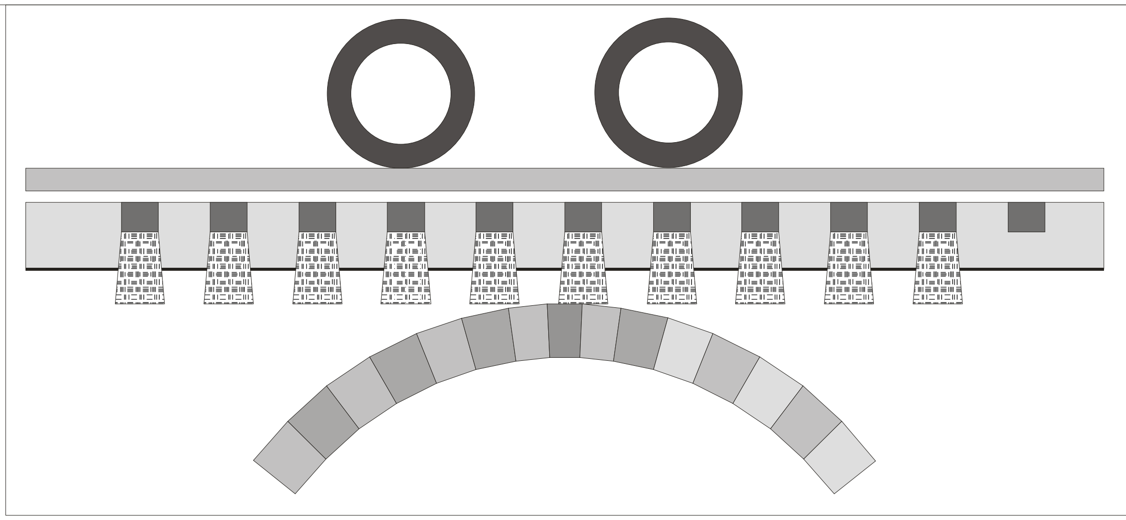

Figure 1 Cross section of arch loaded by two typical axles

2.1 General description

The bridge spaned 3.66m with 0.92m rise. By comparison it was wide, being over 10m from portal to portal. Construction was of good quality old red sandstone coursed in long sections. The voussoirs were markedly thicker near the springings, presenting 350mm courses reducing by steps to 225mm at the crown. The ring thickness expressed at the portal was 400mm. It seems likely that these unusually consistent but varying voussoirs were standard over a range of bridges allowing the stones to be cut in a mass production scheme, but without resorting to refined measurements. The faces were 14,13,12,11,10 and 9 inches with no decimal parts. The engineer was designing for economical production. The stones were typically 1m long and none were cracked.

Figure 2 Dropped stones near the inner face of the spandrel

The bridge was constructed with very low cover, the spandrel wall and parapet extending only 700mm above the ring so that formation probably gives a cover of only 300mm. Ballast has been built up over the decades and the parapets have been extended with brickwork so that the effective cover is now substantial. Inspection suggests that at least 700mm of ballast have been added to an initial depth of about 200mm below the sleeper.

Distribution of the tracks was symmetrical, so that the rails were approximately 2.5m and 4m from the portals on each side with approximately 2m clear at the centre. The track crosses the bridge on a modest curve, with the loaded trains travelling on the outside of the bend. Any centrifugal effect therefore puts the heaviest loads close to the spandrel wall.

There was evident damage to that half of the bridge carrying the loaded trains. There was rather less damage in the other half which was carrying lighter traffic. On a line roughly mid way between the inner face of the spandrel wall and the outer rail, alternate stones (shaded dark in Figure 1) had dropped and the perpend joint between their centres was obviously open and moving. The worst of the drops is shown in Figure 2. This stone now hangs 60mm below the general line of the arch and has been dressed back. The total drop is not quantifiable.

There was an open joint, but no dropped stones near the centre line of the bridge, between the two tracks. There were also some, apparently randomly distributed drops in the other half of the bridge. More will be said about these later.

2.2 Survey

With so many dropped stones, and some apparent distortion, it was necessary to conduct a detailed survey of the bridge. A total station was used, offering a laser pointer, which was invaluable in the confined space and with a near vertical view in places. The instrument measured angles and distances direct off the stonework so that it was possible to collect a large number of data points in a short time. Each corner of each stone was measured, thus giving a complete map of the arch and the drops. The data was reviewed in Excel and plotted to show cross (Figure 3) and long (Figure 4) sections.

It is clear from the result that there is an overall pattern of displacement as well as the dropped stones. From later measurements of other bridges, it seems that they may have been built with a fall towards the centre, but there is a superimposed deflection of perhaps 50-60mm under the heavily loaded track. Such a deflection represents a shortening of the ring of 50mm in 16 joints or 3mm per joint. This seems consistent with total loss of the mortar bedding in an area of the arch.

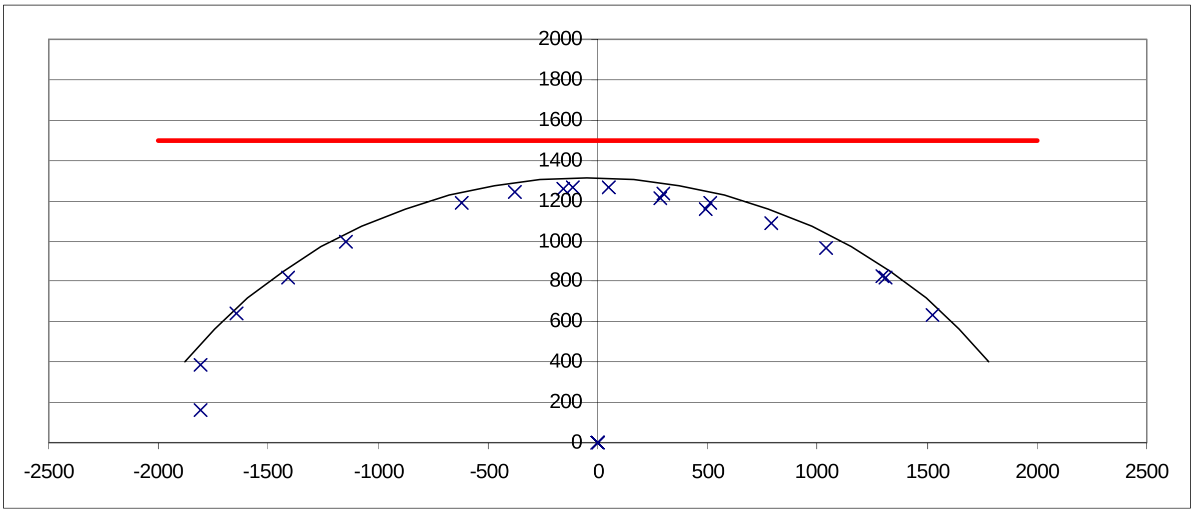

Figure 3 Survey points showing original profile (all dimensions mm)

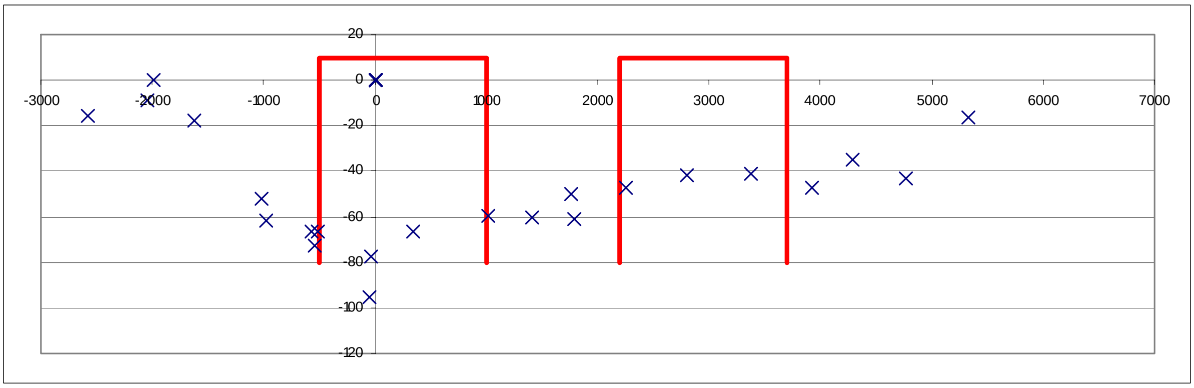

Figure 4 Transverse profile showing drop under loaded track (all dimensions mm)

2.3 Analysis

The arch had originally been assessed using MEXE. With a sound condition factor this yielded a capacity for 40 tonne axles. The actual traffic was 22.5 tonne axles.

Analysis using a thrust line based program[i], on the other hand, showed the arch to be fully utilised without any allowance for impact Figure 5.

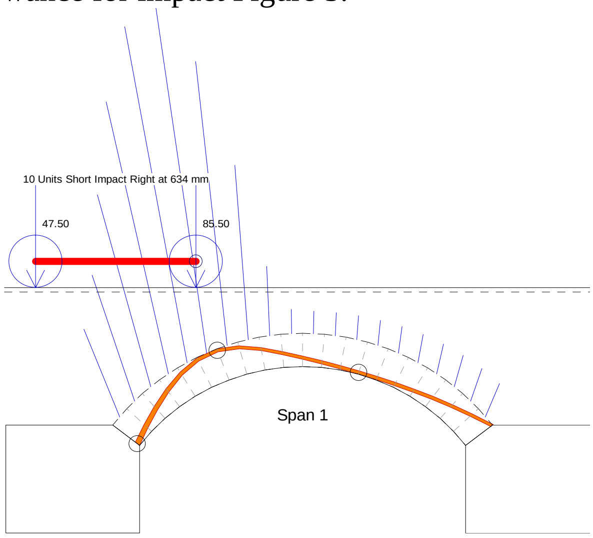

Figure 5 Thrust line analysis from Archie-M

2.4 Deflection measurements

A simple deflection pole was constructed using aluminium tent poles and a potentiometer with a parallel port “oscilloscope”. This was used to measure crown deflection and span change under a train with the results shown in Figure 6 and Figure 7.

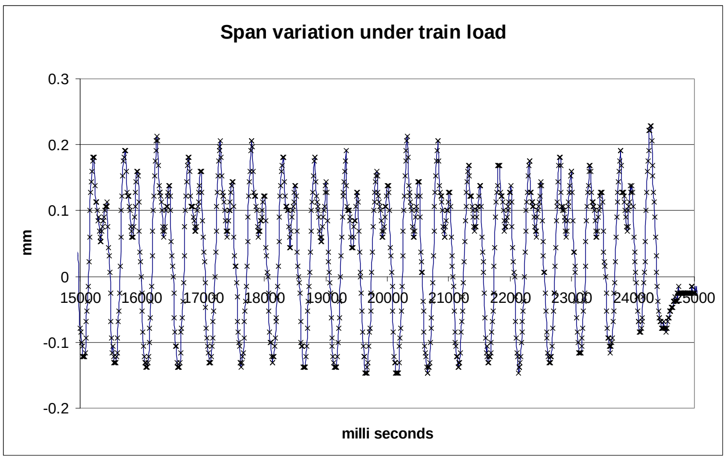

Figure 6 Change in span with load showing rear of train only

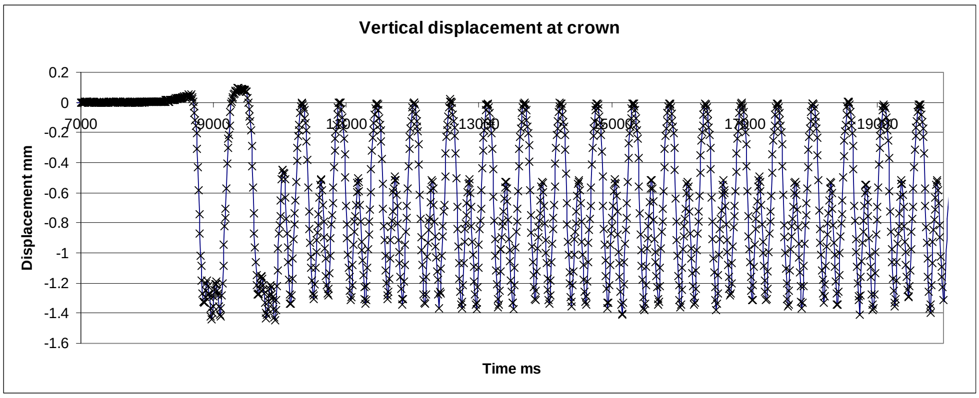

Figure 7 Vertical displacement

3 DYNAMIC MEASUREMENTS

3.1 Equipment

The intention was to consider displacement relative to the springings of the arch. Measuring vertical springing movement was not considered important in light of the response in simple tests. Three aluminium frames were constructed in the form of two A-frames, braced together 1m apart. This placed a firm structure within reasonable reach of the arch. Short struts were used to support the gauges off these frames.

The gauges themselves were linear potentiometers with 20mm travel and a basic resistance of 2kOhm. Thirty gauges were used wired in parallel and supplied with a controlled 5Volt supply.

The output voltage was measured using a DataTaker DT800 high speed data logger running in burst mode. This gave a maximum of 64k readings at up to 100kHz. In order to get a full pattern of deflections the burst was set to take 2000 on each gauge, running at 2kHz, thus delivering 333samples per second on each gauge.

Measurement was triggered using a single switch. The burst being triggered manually to start about 2 seconds before the load entered the bridge. At the end of the cycle, the DataTaker processed the results and downloaded them to a memory card over a period of about 5 minutes. Thereafter, the card could be swapped and the equipment ready for another run.

3.2 Measuring and processing

The interesting traffic on the bridge comprised coal trains which travelled full in one direction and empty in the other. The idea of measuring so many deflections was to construct a dynamic map of deformation of the whole arch barrel. It was expected that this would highlight important aspects of behaviour.

The 60k data points delivered presented a complex handling problem. The measurements were taken sequentially through a binary number of points, thus 30 measurements were taken followed by two blank cycles before starting again. In order to map the progressive changes in shape, it was necessary to phase shit the readings to get a simultaneous measurement over all 30 gauges. It also proved necessary to remove some ambient noise from the signal. Both these processes were accomplished with a MathCad program set up by Houghton. The measurements were then plotted as a surface with 6 sets of 5 deflections each carrying a fixed point at each end. The surface thus comprised 42 data points. It was then a simple process to animate the data to produce a video of deflection.

3.3 Constraints

A number of constraints were placed on the measurements. Timing was difficult because trains were run as soon as possible after they were filled. There were identified pathways but no guarantee that a train would run on each occasion. The aim was to achieve three or four good sets of readings in each direction during a visit.

4 RESULTS

4.1 Consistency

An obvious concern when using un-calibrated loads and testing a bridge for which little detail was known, was the level of consistency of the results. It seems reasonable to suppose that the locomotive weight varies little, though they do carry a substantial load of fuel, it remains small in relation to the mass of the vehicle. The coal wagons proved to be of remarkably consistent effect, though it cannot be proved that this demonstrates consistent loads.

4.2 Basic Patterns

The basic pattern of behaviour was consistent with that achieved from the simplest gauges. The approaching train shortened the span by increasing the soil pressure behind the abutment. As the axles came on to the bridge, the effect was overcome by a wave of deflection under each axle. Recovery was not complete between the axles of a bogie on the locomotive, but the length of the loco was such that it briefly straddled the bridge, loading each abutment and producing the maximum rise in the span.

Each coal wagon had two axles, with a spacing over buffers of about 2m and between axles of about 6m. There was thus the opportunity for the bridge to recover briefly between each pair of axles. These patterns can be seen clearly on individual deflection plots. And compare well with the individual deflections measured earlier.

4.3 Overall movement

Of much more interest is the overall movement of the structure. Deflection under an axle at the first quarter point of the span was noticeably greater than under the same axle at the third quarter. What became more obvious from an animated simulation of the deflections was that the effect was correspondingly narrower on the first quarter and broader on the second (Figure 8 and Figure 9. This prompted closer examination of the structure and revealed some interesting behaviours.

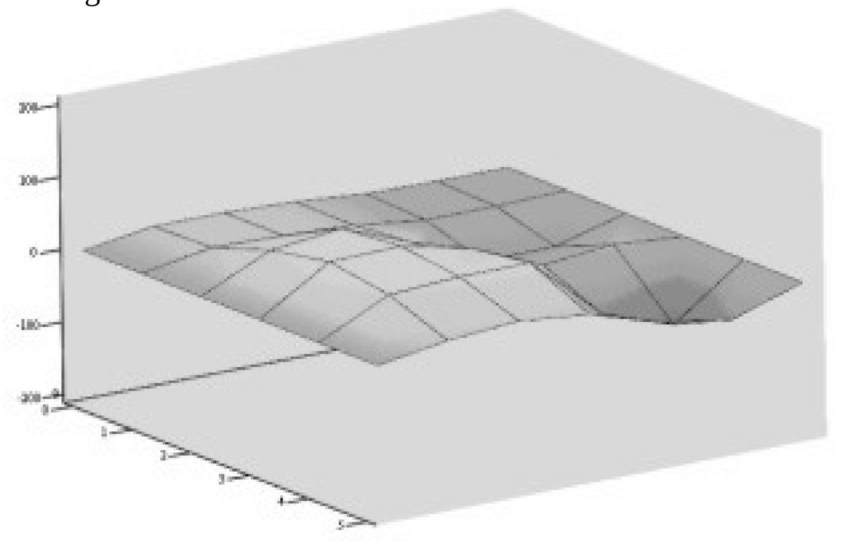

Figure 8 Concentrated displacement as load enters the bridge (travelling L-R)

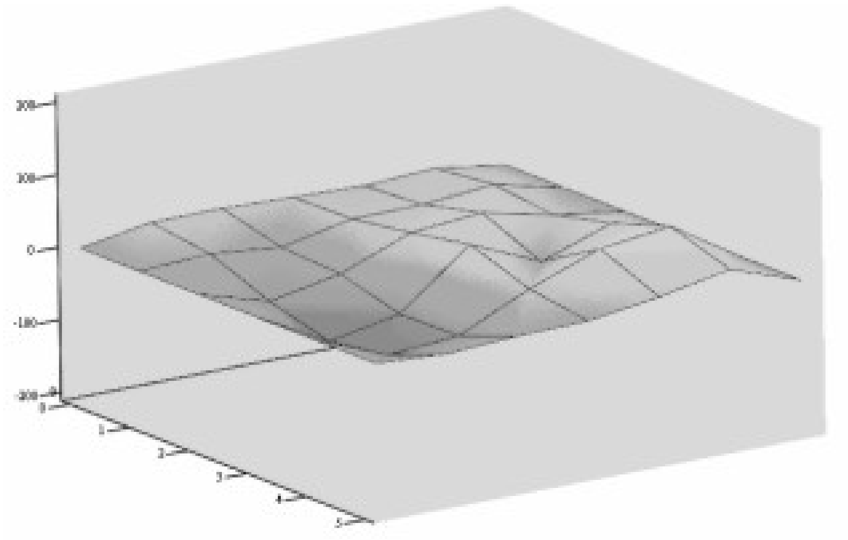

Figure 9 Distributed deflection on exit

5 FURTHER INSPECTION

On further inspection of the bridge, the reason for the distribution of open joints and dropped stones became clearer. The arch wants to sway away from the load as it enters. To do this, it has to break the connection to the spandrel wall and to the remaining stable section of the arch. At the spandrel, this is achieved by destroying the mortar and rattling a row of stones to allow movement. On the centre line, the same action works on the approach half, but beyond the crown, the weakest line is on a diagonal through consecutive perpend and bed joints. These open, allowing at least one stone behind the open joint to drop. This detail is set out in Figure 10.

It is interesting that, even over a long period, and after considerable break-up of the bond in the bridge, back-sway forces from exiting loads have less effect than forward sway from entering loads. This suggests that there is a dynamic element, perhaps in the form of an advancing wave of horizontal pressure in front of the load which pushes the arch much more firmly on approach than on exit. This is clearly worthy of further research.

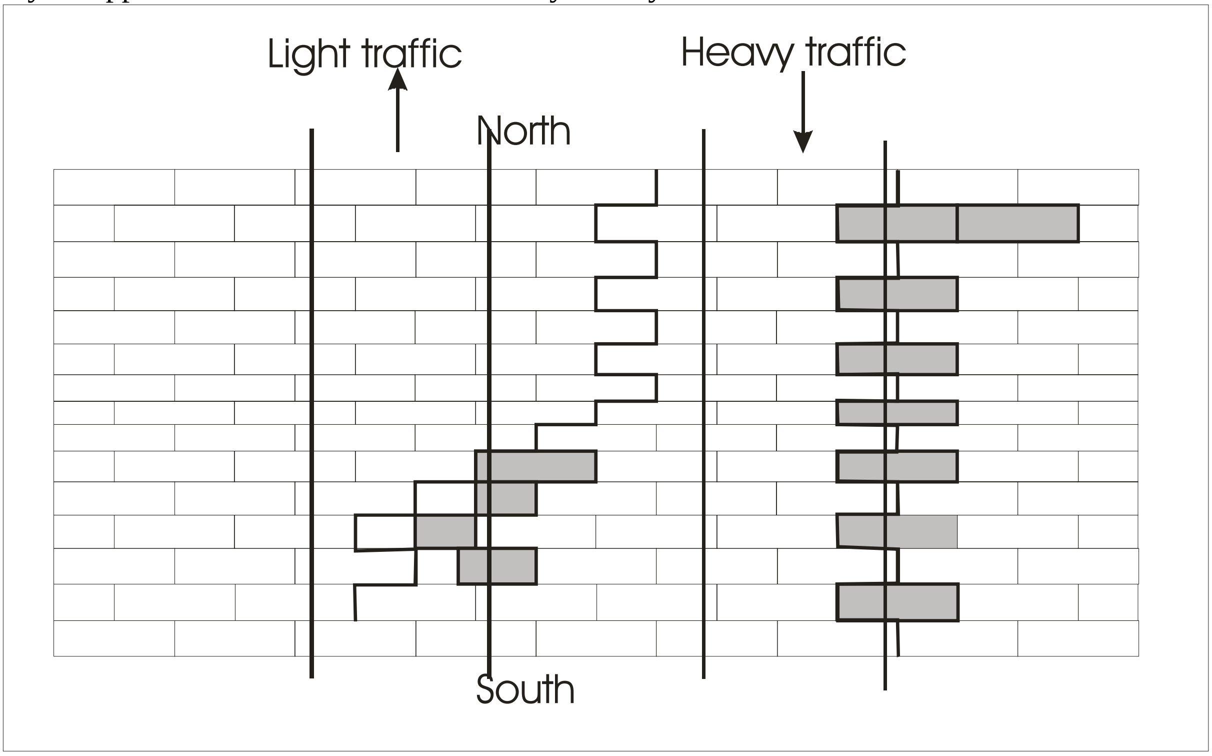

Figure 10 Plan showing voussoirs, cracks and dropped stones

6 CONCLUSIONS

There is a clear direction element to the response of arches to moving loads.

It seems likely that speed has an effect.

MEXE "analysis" cannot take that into account.
High speed deflection measurements are useful and economical.
Interpretation of the behaviour may be difficult.
Animation of deflection measurements gives better visualisation.
Research is needed to identify real serviceability limits for arches.

[i] Archie-M, OBVIS Ltd, www.obvis.com