# Measured Live Loads on an Instrumented Sinusoidal Profile Helical Culvert

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## SYNOPSIS

The current design method of helical lock-seam culverts in accordance with AS 1761 and AS 1762 is based on hoop ring compression. A research program was initiated by the University of Queensland in association with Australian Standards committee CE/25 to investigate the adequacy of the design requirements and performance of helical culverts with low overburden fill.

This project includes instrumentation of four circular culverts with pressure transducers, displacement transducers and strain gauges. Depending on location, the strain gauges were configured to record strain on the centroid of the section or strain on the extreme fibres of the profile. This arrangement allowed the hoop force and bending effects to be determined.

This paper examines the response to a legally loaded vehicle travelling across a 3000 mm diameter sinusoidal profile culvert.

The test program has measured a significant bending effect in association with a hoop force on the culvert. This paper examines the distribution of the force and bending effects about the circumference of the culvert. There are major differences between the measured behaviour of the culvert from the assumed ring compression design methodology in the current Australian standard.

## 1 SCOPE

This paper reports on the response of a 3000 mm diameter sinusoidal profile culvert with 900mm of fill to the passage of a legally loaded truck. The measured strain distribution was decomposed into the hoop and bending components to develop an understanding of the response to the culvert.

The current design methods of AS 1761 and AS 1762 are based on the assumption of ring compression with zero bending moment. This methodology was derived principally from work carried out at Utah University by Watkins and Moser (1971) involving about 130 culverts with diameters between 600 mm and 1500 mm diameters tested in a load cell.

Abdel-Sayed, Bakht and Jaeger (1993) have reported a design method based on displacement and buckling of the crown of the culvert.

The test set-up reported in this paper examines the hypothesis that bending exists in the crown of the culvert, in particular in situations of low overburden fill.

## 2 TEST SITE

The test site was located at Bald Hills on the northern fringes of Brisbane, Queensland. This project was on the proposed Linkfield Road extension between the Gympie Arterial and South Pine Road across the South Pine River immediately west of Gympie Road.

## 3 INSTRUMENTATION

### 3.1 Test Culvert

The test culvert reported in this paper was a 3000mm diameter with 125 x 25 sinusoidal profile (Figure 1) with 900mm of overburden fill. The culvert had a wall thickness of 1.6mm.

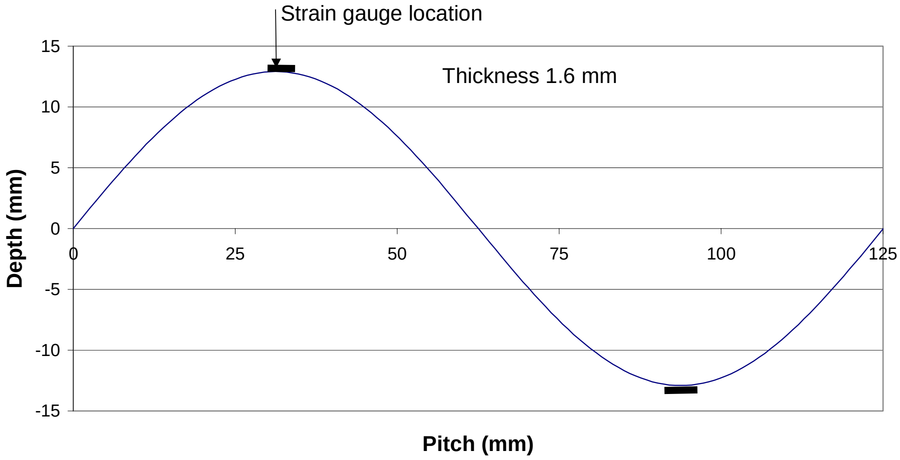


***Figure 1: Profile of 125 x25 Sinusoidal Culvert Showing Extreme Fibre Gauge Locations***

### 3.2 Location of Gauges

The test culvert was instrumented for strain in the steel, pressure in the soil and displacement of the culvert.

Pressure transducers and strain bridges were located at (Figure 2):

- Horizontal axis – left.
- 45 degrees above horizontal – left.
- 67.5 degrees above horizontal – left.
- Top. (crown)
- 45 degrees above horizontal – right.
- Horizontal axis – right.
- Bottom of culvert.

At the top of the culvert and 67.5 degrees above horizontal – left, there were strain bridges at the extreme inside and outside fibre of the culvert. A single strain bridge was located at the centroid at all the other locations.

The deflection of the culverts was measured on the following axes (Figure 2): -

- Bottom left to top right, 45 degrees.
- Vertical.

- Bottom right to top left, 45 degrees.
- Bottom right to top left, 67.5 degrees above horizontal.
- Horizontal.

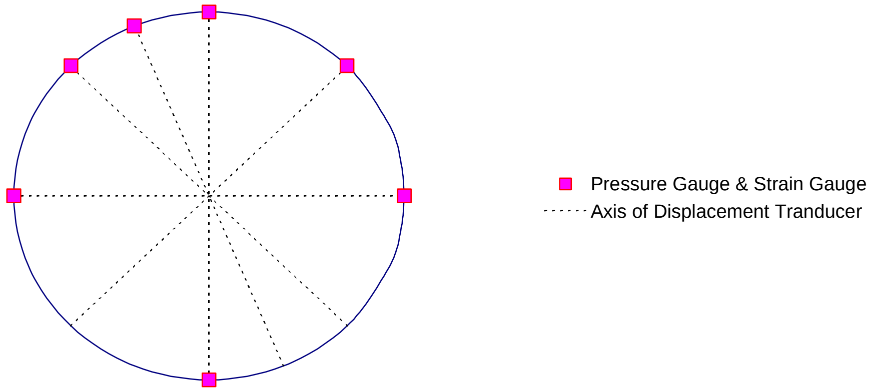


***Figure 2: Transducer Locations and Displacement Axes***

### 3.3 Displacement Transducer

Displacement was measured using PSI-Tronix Model DT-15-420 displacement transducers. These transducers had a maximum travel of 380 mm (15 inches).

A constant torque spring ensured a constant tension in the tracer wire. The deflections of the culvert caused the drum to rotate. Typical error was 0.15%.

### 3.4 Pressure Transducers

Pressure transducers consisted of a 170 mm diameter earth pressure cell and a pressure transmitter. The custom-made earth pressure cells were manufactured by Geotechnical Systems Australia. The sensing diaphragm had a diameter of 170 mm. The earth pressure cell was filled with a hydraulic fluid. A Druck PTX1400-2.5 bar pressure transmitter measured the hydraulic pressure directly by a micro-machined silicon pressure diaphragm.

The overall error of the pressure transducers was 0.5%.

### 3.5 Strain Gauges

Strain was measured using Micro-Measurements model CEA-06-125UN-350 precision strain gauges. The gauges had an active length of 3.175 mm (0.125 inches) and a nominal resistance of 350 Ohms.

The strain gauges were arranged into strain bridges. Each strain bridge consisted of four strain gauges in a Wheatstone bridge configuration. Each bridge consisted of two gauges measuring strain in the hoop direction and two gauges at 90 degrees measuring Poisson effects. The use of the bridge magnified the strain by a factor of 2.6 (true strain at each location plus 0.3 times the true strain for the Poisson effect). The Wheatstone bridge configuration also provided temperature compensation. The manufacturer had a stated error of the gauges of 3 percent, but experience based on other testing suggests the real error was closer to 1 percent.

### 3.6 Data Acquisition System

Data acquisition was logged on an IBM compatible PC with a DOS operating system. Keithley Matrabyts DAS1800 data acquisition boards were used. Signal conditioning and filtering were undertaken using Dataforth industry standard 5B signal conditioning modules. Signals with a frequency above 10 kHz were discarded for the purpose of noise reduction.

During the truck live load test run, the response to the individual gauges was sampled at a frequency of 200 Hz. Sampling between individual channels was at 100 kHz for each cycle of data acquisition.

### 3.7 Instrumentation Cable and Connections

Olex 2 twisted pair plus a shield instrumentation cable was used to connect the instruments to the data logger. The shielded cable was used to limit noise in the cable and improve the quality of the signal.

Gold plated contacts were used for connection of the instrumentation to the data logger.

### 3.8 Power Supply

Normal mains 240V 50Hz power supply was used in this project.

The use of portable generators was discarded because the noise in the supply would have had a detrimental effect on the quality of the data measured.

## 4 TEST VEHICLE

The test vehicle was a legally loaded six-axle semi trailer (Figure 3). The axle loads were:-

- Single steer axle 5.77 tonnes
- Dual drive axles 16.55 tonnes
- Tri-axle trailer 16.51 tonnes

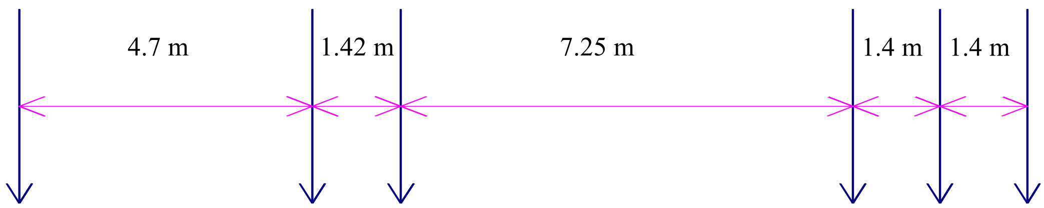


***Figure 3: Spacing of Truck Axles***

## 5 DESCRIPTION OF LIVE LOAD TEST

### 5.1 Details of Test Run

The test truck travelled at 20 km/h from left to right with an offset of 50 mm from the centreline of the gauges.

## 5.2 Pressure

Figure 4 shows the distribution of pressure at the various pressure transducers for the passage of the test vehicle.

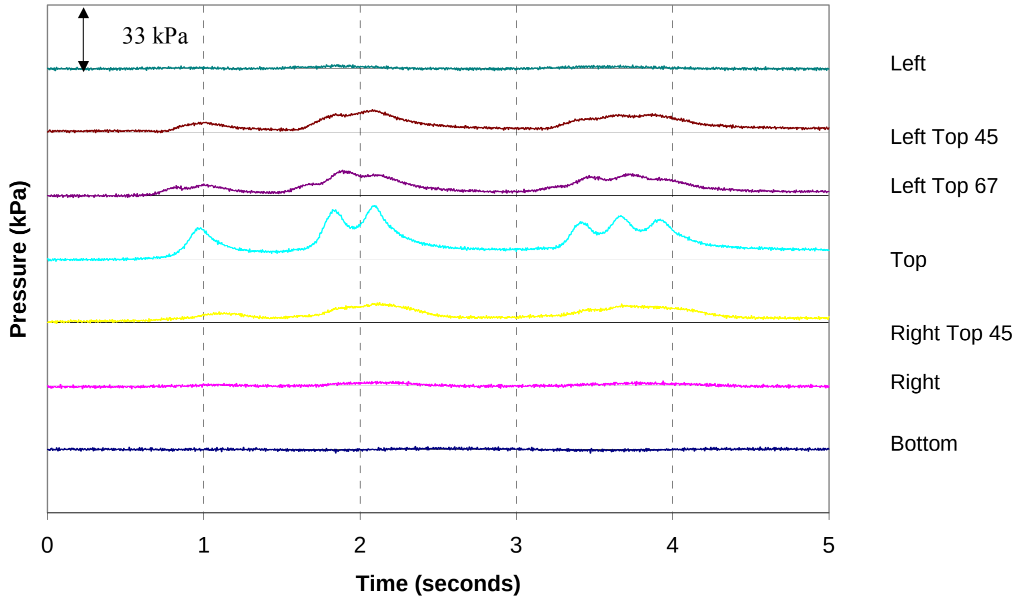


***Figure 4: Pressure Plot for Passage of Test Vehicle***

The key features of the plot are:

- The pressure at the top of the culvert has distinctive peaks for each of the axles when they pass over the gauge.
- The other gauges show an increase in pressure in response to the axle group rather than to individual axles.
- The largest pressure for a gauge was measured when the load was closest to the pressure transducer. This explains why all gauges record their peak load at slightly different times.
- The pressure increment is most pronounced in the 90-degree arc extending 45 degrees either side of the centreline.

| Pressure Transducer Location | Envelope Peak Pressure (kPa) | Co-existing Pressure for Peak Pressure at Top (kPa) |
|---|---|---|
| Left, horizontal | 1.98 | 0.15 |
| Top left, 45 degrees above horizontal | 11.74 | 11.44 |
| Top Left, 67.5 degrees above horizontal | 13.27 | 10.22 |
| Top | *28.07* | *28.07* |
| Top Right, 45 degrees above horizontal | 10.52 | 9.76 |
| Right, horizontal | 2.59 | 1.83 |
| Bottom | 1.52 | 1.52 |

***Table 1: Peak Pressure Distribution***

The envelope of peak pressure and co-existing pressure for the peak pressure at the top of the culvert for the gauges are tabulated as Table 1 and plotted in Figure 5.

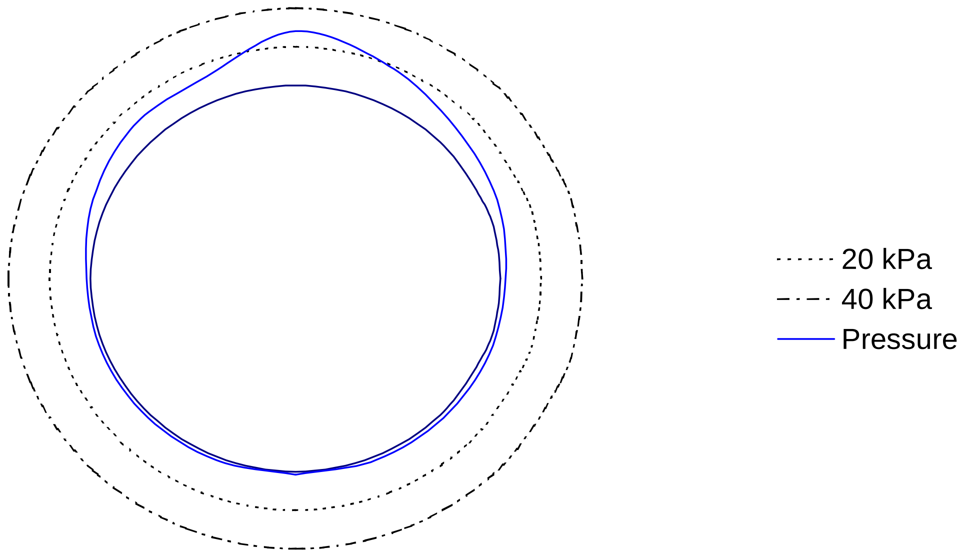


*Figure 5: Envelope Peak Pressure Distribution Around the Culvert*

### 5.3 Strain

Figure 6 shows the measured strain in all the gauges. At the top of the culvert and 67.5 degrees, a strain bridge was located on the extreme interior and exterior point of the culvert. At all other points, the strain bridge was located at the centroid of the section.

The gauges closest to the surface (top of culvert and 67.5 degrees left) measured peaks corresponding to individual axles. The other gauges show the passage of axle groups. It is noted that the interior and exterior strains at the top of the culvert were out of phase. At 67.5 degrees left, both interior and exterior strain gauges were in phase.

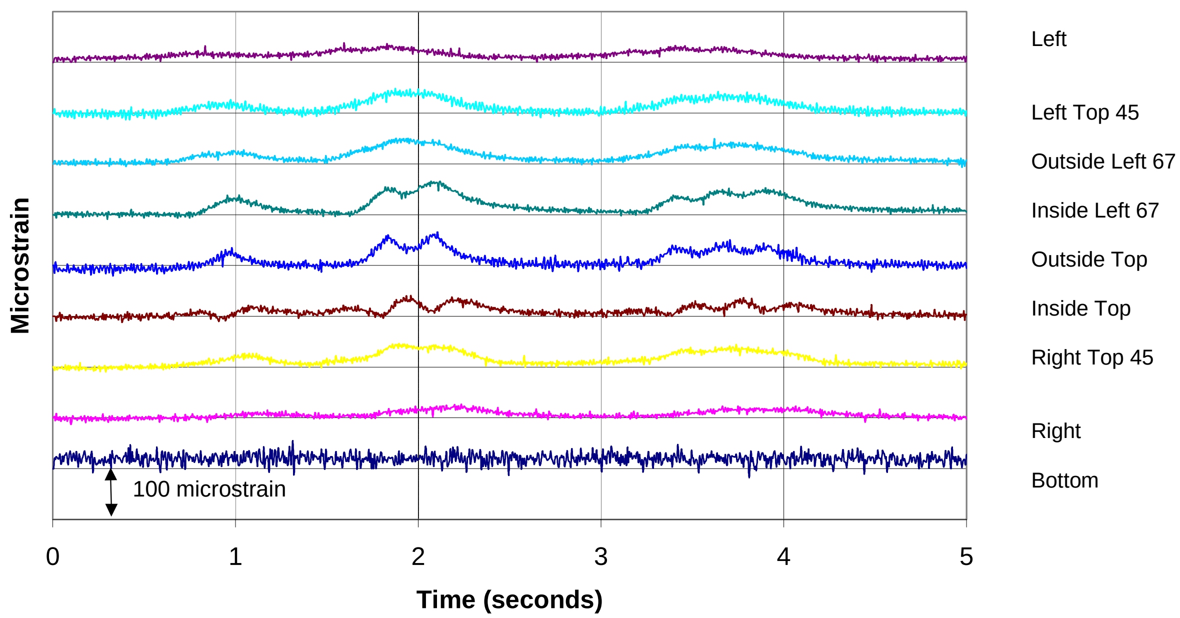


*Figure 6: Strain in All Gauges For Passage of Test Vehicle*

The maximum extreme fibre strains are tabulated in Table 2.

| Strain Gauge Location | Peak Strain (microstrain) |
|---|---|
| Top, outside face | 59 |
| Top, inside face | 32 |
| 67.5 degrees left, outside | 49 |
| 67.5 degrees left, inside | 61 |

***Table 2: Maximum Extreme Fibre Strain***

### 5.4 Displacement

No discernable deformation was measured during the passage of the test vehicle.

## 6 DISCUSSION OF TEST RESULTS

It is possible to present the strain data in a number of different formats including:

- Individual gauge strains.
- Inferred Hoop Strain.
- Strain associated with bending.

Figure 7 shows how the measured strains are converted into hoop and bending components. For the sinusoidal profile, which is symmetric, the hoop strain is the average of the top $\varepsilon_t$ and bottom strain $\varepsilon_b$. The strain due to bending is half of the difference between the top and bottom strains $(\varepsilon_t - \varepsilon_b)/2$.

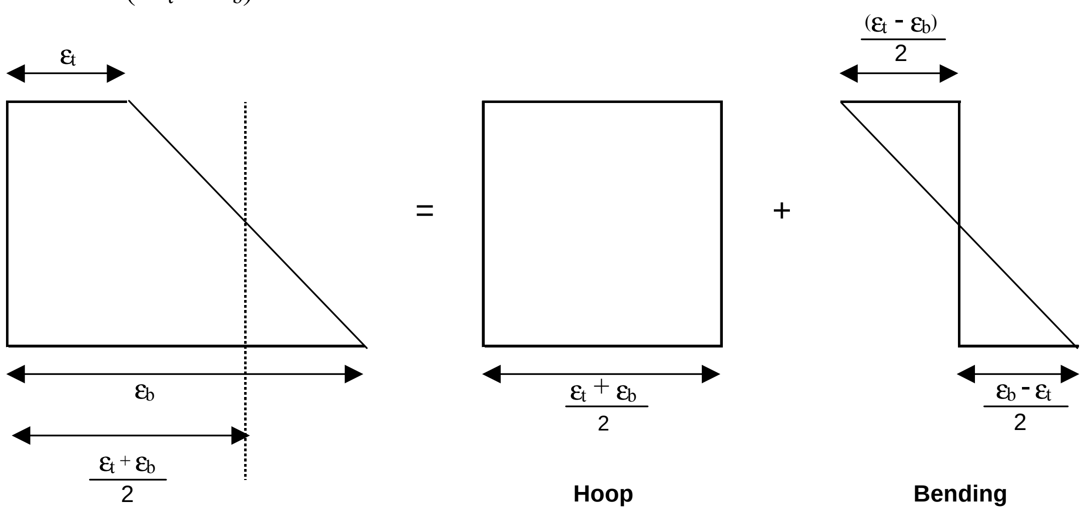


***Figure 7: Hoop and Bending Components of Strain***

### 6.1 Hoop Strain

Table 3 and Figure 8 detail the hoop strain at the gauge locations around the culvert. The bottom gauge location had significant noise in the signal and has been discarded from the analysis.

| Strain Bridge Location | Peak Hoop Strain (microstrain) |
|---|---|
| Left, horizontal | 33 |
| Top left, 45 degrees above horizontal | 44 |
| Top Left, 67.5 degrees above horizontal | 52 |
| Top | 39 |
| Top Right, 45 degrees above horizontal | 43 |
| Right, horizontal | 22 |
| Bottom | -- |

***Table 3: Peak Hoop Strain Distribution Around the Culvert***

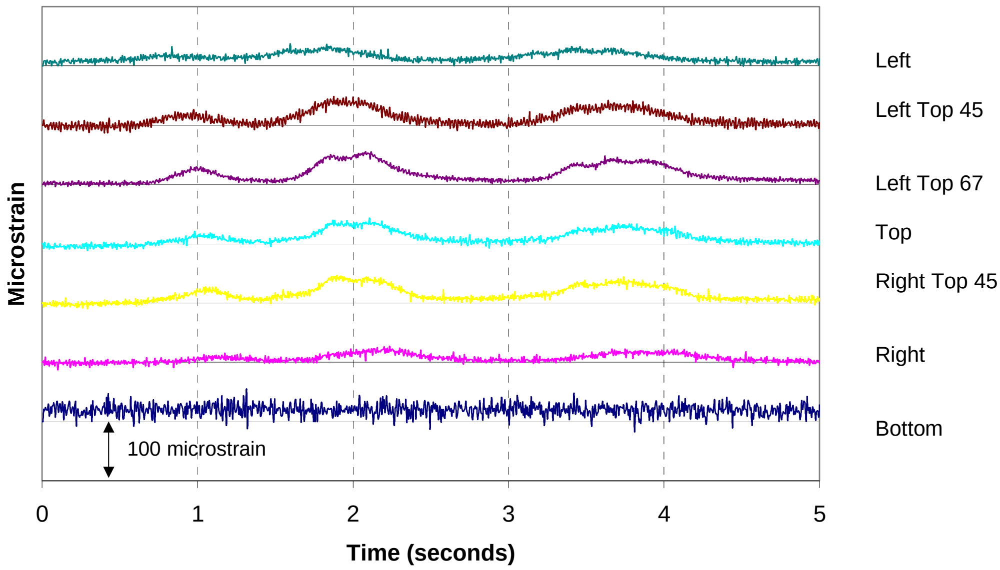


***Figure 8: Hoop Strains Due to Passage of Vehicle***

The peak hoop strain is reasonably uniform in the 90-degree arc extending 45 degrees either side of vertical. The hoop strain (Figure 9) is more constant around the culvert than the pressure, which rapidly attenuates as the distance from the crown increases.

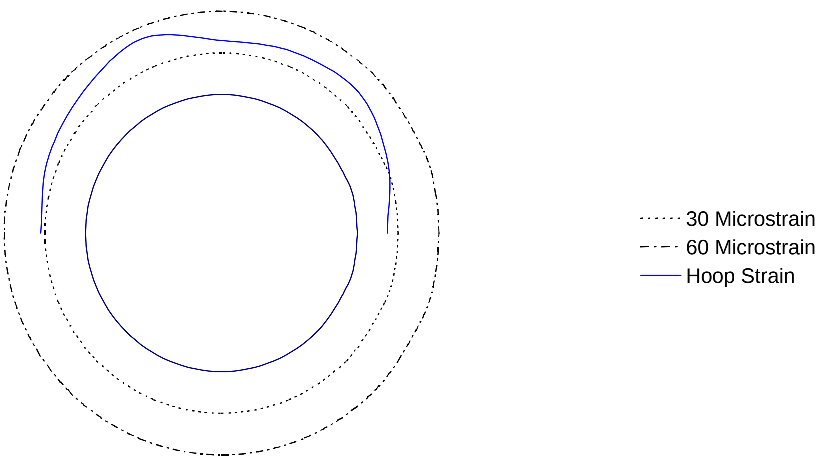


***Figure 9: Envelope Peak Hoop Strain Distribution Around the Culvert***

### 6.2 Combined Hoop and Bending Effects

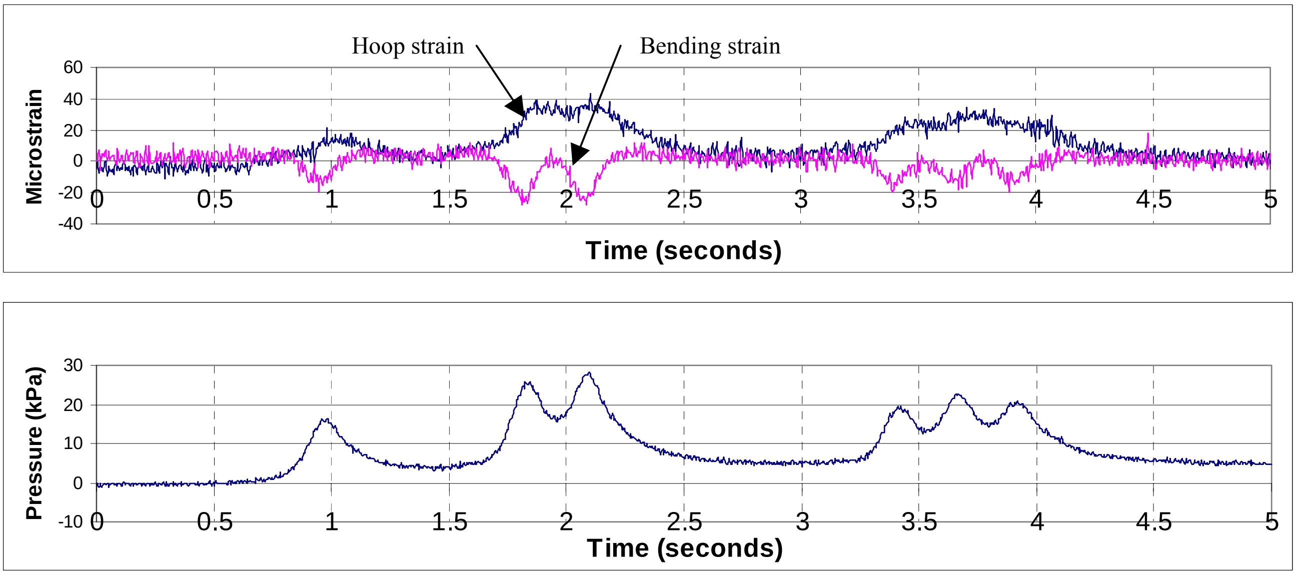


***Figure 10: Plot of Hoop and Bending Strain and Pressure at Top of Culvert***

A better understanding of the behaviour is obtained by plotting hoop strain and the bending strain in the culvert. Peak pressure at the top of the culvert indicates when each axle is located above the top of the culvert.

In Figure 10, the main observations are:

- The hoop strain is relatively constant for the passage of each axle group.
- The peaks in bending strain coincide with the peaks in pressure when the individual axles are located over the top of the culvert.
- The magnitude of bending strain is approximately 70 percent of the hoop strain. That is the bending effect is 40 percent of the total strain.

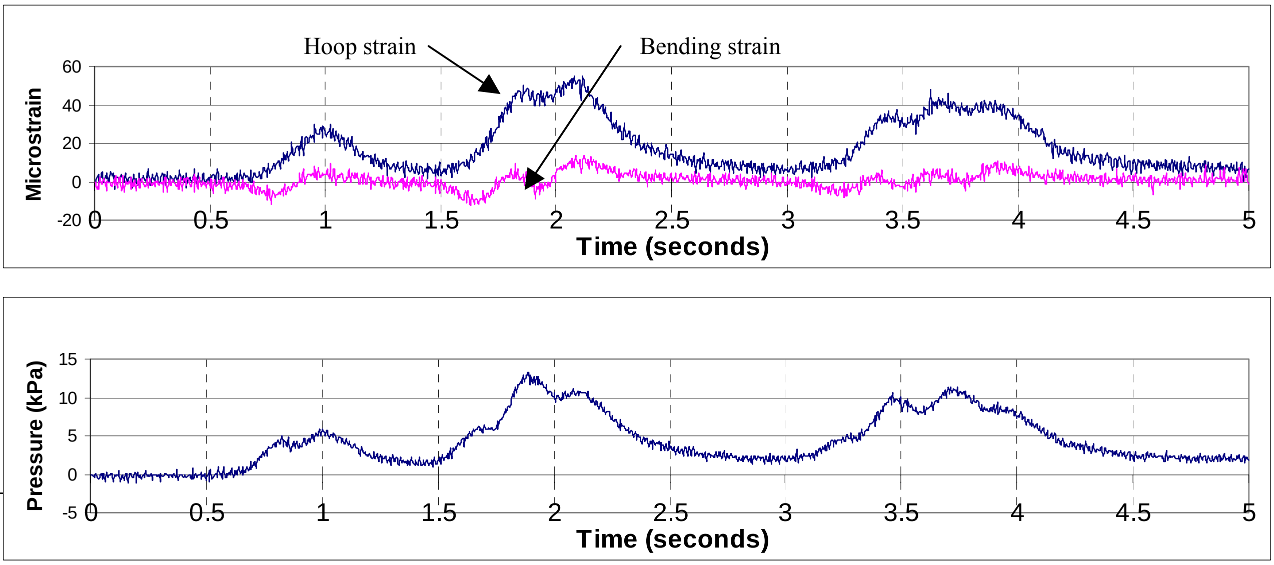


***Figure 11: Plot of Hoop and Bending Strains and Pressure at Top left, 67.5 degrees Above Horizontal of Culvert***

Figure 11 plots similar details are for a point top left, 67.5 degrees above the horizontal.

There are a number of important differences between Figures 10 and 11. These include:

- The pressure associated with the individual axles in Figure 11 is not as distinct as they were at the top of the culvert (Figure 10).
- There is a significant reduction in bending strain at 67.5 degrees left above the horizontal compared to the top of the culvert.
- The magnitude of the bending strain is approximately 20 percent of the hoop strain.
- The bending strain at the top of the culvert is predominately in tension on the inside of the culvert. At 67.5 degrees, the bending strain changes sign during the passage of an axle.

The key measured strain values and inferred hoop and bending strain are contained in Table 4.

| **Parameter** | **Strain (microstrain)** | |
|---|---|---|
| | **Top** | **67½ Left above Horz.** |
| Hoop strain | 39 | 52 |
| Bending component | 25 | -10 to 11 |
| Max. /Min. Outside Extreme fibre | 59/32 | 49 |
| Max. /Min. Inside Extreme Fibre | 32/15 | 61/45 |

***Table 4: Key Strain Values for Test Run***

### 6.3 Hoop Force and Bending Moment

The hoop force C can be calculated from the measured hoop strain by the equation:

$$C = E\,\varepsilon A \qquad \ldots\ldots (1)$$

The area of a 125 x 25 sinusoidal culvert (1.6 mm wall thickness) is $1.76 \times 10^{-3} m^2/m$ and E is 200,000 MPa.

The calculated hoop force is 13.7 kN/m.

The peak bending strain allows the equivalent peak bending moment under the wheel to be calculated from the equation:

$$\sigma = \frac{M}{Z} = E\,\varepsilon \qquad \ldots\ldots (2)$$

$$M = E\,\varepsilon\,Z \qquad \ldots\ldots (3)$$

Where:
E 200,000MPa
$\varepsilon$ $25 \times 10^{-6}$ (Measured value)
Z $10.4 mm^3/mm = 10.4 \times 10^{-6} m^3/m$ (AS 1762)

$$M = 5.2 \times 10^{-5}\ MNm/m = 0.52\ kNm/m = 520\ Nm/m \ldots\ldots (4)$$

The passage of the vehicle has generated a peak force of 13.7 kN/n and a bending moment of 0.52 kNm/m.

## 7 COMPARISON WITH CURRENT DESIGN METHODS

AS 1762 has a design live load pressure of 21 kPa for 900 mm of fill.

The design method in AS 1762 is based on ring compression. This method relates the pressure at the top of the culvert to the hoop force in the culvert by the equation: -

$$C = \frac{P\,S_s}{2000} \qquad \text{(AS 1762, Clause 2.4)} \qquad \ldots\ldots (5)$$

Where:

- $C$ is the force in the culvert (kN/m)
- $P$ is the pressure in kPa
- $S_s$ is the diameter in mm
- $F_a$ is compressive stress

C = 21 x 3000/2000 = 31 kN/m

Table 5 details the design and measured parameters for the culvert

| Parameter | AS 1762 | Measured Values |
|---|---|---|
| Pressure at crown | 21 kPa | 28 kPa |
| Hoop Force | 31 kN/m | 13.7 kN/m |
| Bending Moment | Nil | 0.52 kNm/m |

The measured pressure and design pressure are similar.

The measured hoop force is approximately half the design force from the code. AS 1762 assumes a uniform pressure distribution around the culvert in calculating the hoop force. The measured pressure distribution has a rapid attenuation with distance from the crown of the culvert. This explains why the measured hoop force is significantly less than the code value.

AS 1762 assumes ring compression with no associated moment. The measured results at the crown of the culvert have shown that the bending strain is significant. The magnitude of the bending strain is 70 percent of the measured hoop strain. This proves that bending is a significant effect that should be considered in design.

## 8 VERIFICATION OF HOOP FORCE FROM MEASURED PRESSURE

In any research program, it is essential to have a method of validating the test data. The measured hoop force C in a circular culvert can be verified from the measured pressure by the equation:

$$C = \frac{\sum P\,\delta l \cos\theta}{2} \qquad \ldots\ldots (6)$$

Where
- $P$ is the pressure
- $\delta l$ is the increment in length
- $\theta$ angle between the radial pressure and the vertical

The hoop force of 21.6 kN/m was calculated in steps of 11.25 degrees. The measured hoop force was 13.7 kN/m. It should be noted that the calculated force is expected to be larger than the measured value. The pressure has been measured at the gauge locations shown in Figure 2. There is a rapid attenuation of pressure at the crown of the culvert. Gauges at the top, 67.5 degrees above horizontal left and 45 degrees above horizontal right meant that the pressure attenuation cannot be accurately predicted at all points for the integration. The piecewise approximation assumes constant pressure within each segment of angular increment.

This calculation has verified that the measured pressure is consistent with the measured force.

## 9 CONCLUSIONS

The major conclusions are:

- The culvert experiences both hoop and bending effects due to the passage of a test vehicle. The bending effect is significant, accounting for up to 40 percent of the total strain.

- The Australian Standard AS 1762 does not consider bending effects. The current Australian Standard only considers hoop effects in the culvert.

- The measured peak hoop force is uniform around the culvert.

- The measured maximum pressure is at the crown. The peak pressure appears to attenuate rapidly from the crown.

These observations are significantly different from the design assumption of the current Australian standard.

## 10 RECOMMENDATIONS

- This paper is based on one live load test run. More research is necessary to fully understand the response of helical culverts to live load.

- Consideration should be given to reviewing the Australian Standard on this subject.

## 11 REFERENCES

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