# Innovations in Soil-Metal Bridges

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## ABSTRACT

Soil-metal structures are a popular form of constructing short span bridges. The design provisions for these structures are provided in the Buried Structures section of the Canadian Highway Bridge Design Code. Historically, the development of these structures grew out of the corrugated steel pipe industry. However, their use has expanded well beyond the basic pipe usage as a hydraulic conduit into a legitimate bridge form.

In keeping with the conference theme of ``Adjusting to New Realities``, the soil-metal structures industry has had to adjust its products to meet the demand of several new realties including optimizing designs to address the rising costs of raw materials and labour, more mechanistic design approaches relying on rigorous analysis rather than empirical rules, the demand for more durable structures and the need to span greater distances or sustained greater loads.

This paper will discuss the joint research work undertaken to address these demands. A key element of this research has been the implementation of structural monitoring systems in key projects prior to construction and backfill. The data collected from these structures has been used to verify safety and analytical assumptions. Typical design approaches rely on two dimensional models. Work at Dalhousie has also focused on the development of three dimensional modelling approaches. Aluminum is an attractive material from a durability perspective and has been used in the past for box-type structures with spans limited to less than 8 m. The paper will also review the development of a new stiffening rib product allowing aluminum to be used in box-type structures of up to 12 m spans. These innovations have allowed Canada to have some of the longest soil-metal bridge structures in the world.

## INTRODUCTION

Soil-metal structures are very flexible corrugated metal structures which gain load bearing capacity by interaction with the surrounding engineered backfill enabling them to carry significant overburden and vehicular loads (Abdel Sayed et at. 1993). These larger structures are made from corrugated metal plates that are bolted together to form either a large pipe shape, an arch shape or a box shape. The latter two types generally have an open profile resting on footings rather than the closed profile of a pipe or conduit. The soil-metal structures can be used to create hydraulic openings or to span roadways or train tracks. The corrugated plate can be formed from steel products or aluminum products. Figure 1 is an example of a large soil-steel arch.

Design methods have evolved from the empirical approaches for pipe design in the early part of the last century to more sophisticated and rigorous criteria reflecting increasing understanding of the soil-structure interaction (Bakht 2007). Keeping pace, the Canadian industry has developed innovations and employed new technologies such that Canada currently has the longest span soil-steel structure (Figure 1) and the longest span aluminum box structure (Figure 2) in the world.

The ‘new realities’ in the industry are driven by the need to be more efficient as the economic and carbon costs of raw materials increases, the need to create more durable structures as the code requirements become more demanding, the desire to expand the range of market applications and the need to pursue innovations while maintaining safety and reliability.

This paper will discuss two Canadian product innovations as well as the use of two advanced technologies which are allowing the industry to expand while adjusting to these new realities.

## LONGER SPAN ALUMINUM BOX STRUCTURES

The general configuration of a soil-metal box structure is shown in Figure 3. The Canadian Highway Bridge Design Code S6-06 (CSA 2006) provides simplified methods of analysis for structures up to 8 m spans. Structures exceeding this limit are permitted but rigorous analysis methods must be employed which generally involve finite element modelling of the soil-structure interaction and structural loads. A popular design software, developed by FHWA, is CANDE (Musser, 1989). NCHRP Report 473 (McGrath et al. 2002) provided guidance for modelling long-span culvert structures using this and other finite element software.

The availability of software, modelling guidelines and some simplified design expressions make it possible for engineers to rigorously analyze box structures beyond 8 m spans; however, the designer must still be able to detail a structural configuration capable of resisting the necessary deformation and stresses. To better understand this structural demand an overview of soil-metal box construction and behaviour is presented.

### Overview of Metal Boxes

Newhook and Ford (2010) present the following overview of soil-metal box behaviour. In soil-metal structures, the corrugated metal plate is first bolted together to form the general profile of the structure. At this stage of construction, the structure is very flexible and can be distorted easily. The capacity of the metal structure itself is generally limited by global buckling. The flexibility of the structure, however, enables it to interact with the surrounding soil during the backfill process. The placement of the engineered fill is kept approximately even on either side of the structure. Initially the sidewalls are pushed inward by the backfill forces; however, as the fill reaches the haunch zones and then the crown shown in Figure 3, the weight of the soil pushes down of the structure causing a tendency for the structure to try to deform outward and oppose the bending moments created in the initial construction stages. The compacted backfill around the structure prevents this movement and hence the flexible structure gains rigidity from its interaction with the backfill. This interaction creates global stability and increases the loading required to produce buckling failure. Under these circumstances, the corrugated plate is often able to attain its material strength limits without a stability failure or excessive deflection. The distribution of bending and axial forces in the corrugated metal plate is highly dependent on the flexibility of the structure and the amount of interaction with the surrounding backfill.

The box shape shown in Figure 3 creates significant bending moments in the haunch and crown regions as well as deflection of the crown region. Metal box structures are generally constructed using corrugated plates with a shallow profile as shown in Figure 4. To reinforce these structure, stiffening ribs are often added to improve both bending capacity and stiffness (Abdel Sayed et al. 1993). With steel structures there is also the option to use deep corrugated plate  (Corrugated Steel Pipe Institute 2002) to meet the demands of longer spans. The corrugations in these plates are nominally 3 times the depth of those shown in Figure 4.

In many environments aluminum box structures must be used to meet the durability demands. This plate is also made in the profile shown in Figure 4 and must be reinforced to satisfy stiffness and strength demands due to the lower stiffness and strength  properties of aluminum compared to steel. ASTM B864M(American Society for Testing Materials 2008) permits several stiffener sizes based on an L-shaped stiffener shown in Figure 5. This figure shows a stiffener applied to the crest of each corrugation to provide the maximum effect. This heavy stiffening is required for longer spans. These l-shaped stiffeners have an unsymmetric cross-section with a large portion of metal at the top of the vertical leg. The shape is therefore prone to lateral buckling under compression which can limit the effectiveness. Newhook and Ford (2010) reproduced this buckling phenomenon in a laboratory test specimen shown in Figure 6.

Recently ASTM B864M approved an improved stiffener design for aluminum boxes shown in Figure 7. When bolted to the corrugated plate, as shown in Figure 8, the stiffener becomes a symmetric closed shaped providing greater resistance to buckling and allowing the full plastic moment capacity of the stiffener to be utilized in design.

Newhook and Ford (2010) demonstrated that the closed shaped stiffeners could provide strengths up to 25% greater than the equivalent area of L-shaped stiffeners. The new stiffener provides a 66% increase in flexural strength above the L-shaped stiffeners currently approved in ASTM B864M.

The increased capacity provided by this new stiffener allowed the aluminum metal box shown in Figure 2 to be constructed with a span of 12.0 m and a rise of 3.6 m thereby creating a longer span box solution with the field durability of aluminum.

## LONG SPAN SOIL STEEL ARCHES

Soil-steel arch structures generally take the form of a single radius or dual radius structure creating a circular or elliptical opening, respectively. As with soil-metal boxes, the demand is to create longer span structures which can also carry high vehicle loads. The structures are often used in mining road applications where the gross vehicle weights can greatly exceed those of normal highway trucks.

These structures are constructed from deep corrugated plate; but, similar to the long span metal boxes, they often require stiffening to achieve the necessary bending and thrust resistance. For these structures, a typical stiffening scheme would be to create a double plate configuration where the valley of a stiffening rib plate is bolted to the crest of the inside main plate.  Deep corrugated ribs stiffening plates covering a portion of the crown region of a soil steel arch can be seen in Figure 9.

The efficiency of these stiffening ribs is an important design consideration. The main concern is whether the bolted connection between the two plates is sufficient to achieve composite action between the two plates or whether they merely ensure displacement compatibility but the plates bend separately about their respective neutral axis. In the latter scenario the plates can be said to behave cumulatively but not compositely about a common neutral axis.

The structure shown in Figure 9 was instrumented with strain gauges and monitored during backfilling. Strain gauges were placed at the crest and valley of each corrugated plate. A strain plot with depth from the bottom of the inner plate to top of the stiffening rib on the vertical axis and strain magnitude on the horizontal axis is shown in Figure 10. Each plate is approximately 147 mm deep. The strain profile for three backfill depth is shown. From the plots it is clear that the plates are bending separately about their respective neutral axis. At the interface zone, slippage between the two plates is taking place such that there is flexural tensile strain in the top of the inner plate yet flexural compressive strain in the bottom of the stiffening rib. If the plates were behaving compositely, then the strain profile would have been approximately linear through the entire depth. Hence, for the configuration shown in Figure 9, the stiffening plate nominally doubles the flexural capacity and stiffness of a single plate.

This cumulative stiffening may be sufficient for many applications; however, achieving spans of 25 m as was the case for the structure in Figure 1 requires more effective composite action between the two plates. For this purpose, an encased concrete rib stiffening scheme has been developed. In this design, the void between the two ribs is filled with concrete.  Figure 11 shows a pumper truck filling the voids between the two plates for the Whitehorse Creek Structure prior to backfilling. The concrete acts as an effective shear transfer material, preventing slip and allowing composite action to develop. Figure 12 is similar to Figure 10 except it is generated from the Whitehorse Creek Structure which had encased concrete ribs. The strain profile for this case is approximately linear with only a small deviation at the plate interface. This indicates that the plate were behaving compositely.

The benefits of this composite behaviour were also verified by laboratory testing. The flexural setup testing of an encased concrete rib structure is shown in Figure 13. A normally stiffened rib structure (no concrete) was also tested in a similar manner. The applied moment versus mid-span deflection is shown in Figure 14 for each configuration. The significant improvement in strength and stiffness through composite action is evident.

## 3 DIMENSIONAL MODELLING

For modelling purposes, soil-metal structures are general modelled in finite element analysis as a two dimensional (2-D) plane strain problems. Only the cross-section of the structure is modelled. This 2-D assumption is adequate for backfill loads which comprise a significant portion of the total applied load, especially in structures which have deep backfill above the crown. However, some loadings including tire loads from design vehicles do not follow the 2-D plane strain assumptions. While current practice is to use equivalent load configurations in 2-D models or simplified design expressions (Peterson et al. 2009), there is an increasing need for the development of reliable three dimensional (3-D) models of soil-steel structure behaviour.

At Dalhousie University, research is being conducted to develop a 3-D model of long-span soil-steel box structures. In these box structures with low fill over the crown, the vehicle load is a significant component of the design load and more accurate modelling is desired to allow the construction of more efficient structures without compromising safety.

A full-scale experimental model was constructed on site at Atlantic Industries Limited in Dorchester, New Brunswick and tested under various design truck positions and backfill depths as shown in Figure 15. The box had a span of approximately 15 m.

A 3-D finite element model of the structure was created. Figure 16 shows an isometric view of half of the model and the soil stresses created from the heavy axles of the CHBDC design truck being place directly at mid-span of the structure. Figure 17 shows the same model in cross-section view. Figure 18 shows the respective bending stresses in the corrugated plate from this loading. This figure clearly shows the three dimensional distribution of vehicle tire loads in both the crown and haunch region.

Figure 19 shows a representative plot of the extreme fibre strain for the inside of the corrugated metal plate for the design truck on the crown of the structure. The solid line is predicted by FEA and the points represent field measurements. The agreement is very good providing confidence in the ability of the model to predict three dimensional effects.

Now that a modelling technique has been developed it can be used to analyse the effects of soil properties, culvert profile and varying wheel loads to produce optimized designs within the safety limits required by CHBDC.

## CONCLUSIONS

The soil-steel structure industry has grown over the past century from a corrugated steel pipe industry relying on empirical designs and field experience to an innovative product industry supported by sophisticated engineering design and rigorous research and analysis.

This paper presented an overview of some innovative activity leading to better stiffening products to produce longer spans safely. The new aluminum stiffening rib extends the applications of a solution that has improved durability over steel.

Field monitoring of actual behaviour supplemented with laboratory testing led to an improved understanding of stiffening rib behaviour on soil-steel arches with deep corrugations. Improved understanding led to the construction of a long-span arch. While only a fraction of the monitoring results were presented in this paper, the structure was continuously monitored during construction to ensure critical strain thresholds were not exceeded and that this innovative structure continued to meet the safety requirements of the code.

Finally rigorous analysis is being extended from 2-D work to 3-D modelling. There is still only a small amount of literature available relevant to this activity for soil-steel bridges. Research into modelling at Dalhousie University has some promising initial results that will allow for increased understanding of the three dimensional behaviour of these structures.

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Petersen, D.L.; Nelson, C.R.; Li, G.; McGrath, T. J and Kitane, Y. 2009. *NCHRP Report 647: Recommended Design Specifications for Live Load Distribution to Buried Structures,* Transportation Research Board, National Research Council, Washington, DC.


Figure 1. Whitehorse Creek Soil-Steel Arch Structure


Figure 2. Aluminum Metal Box Structure

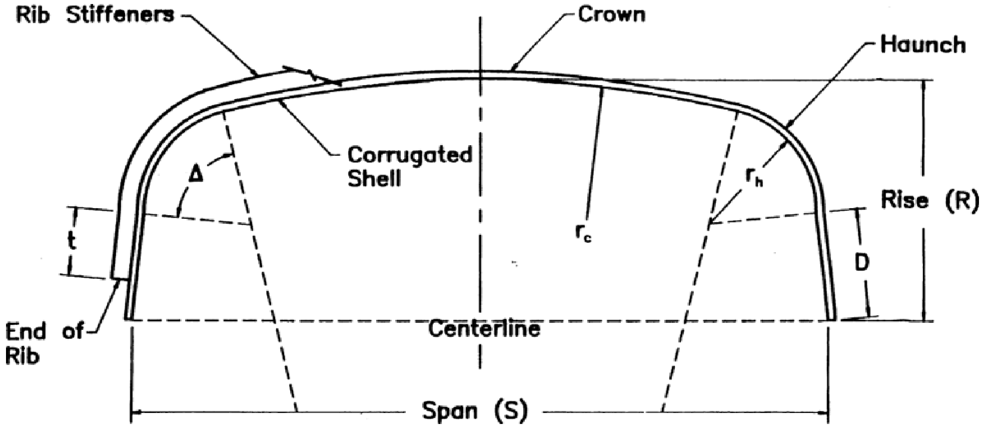

Figure 3. Configuration of metal box structures (from ASTM B864M)

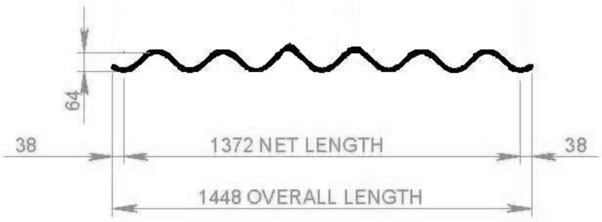

Figure 4. Typical shallow corrugation plate profile

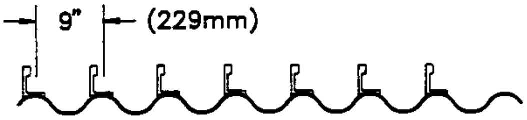

Figure 5. Aluminum stiffener (from ASTM B864M)

Figure 6. Buckling of L-shaped stiffener

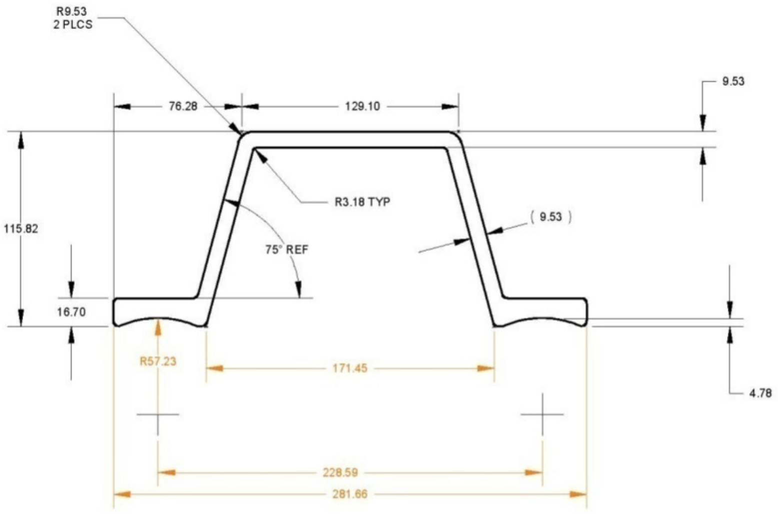

Figure 7. Dimensions of stiffener (mm)

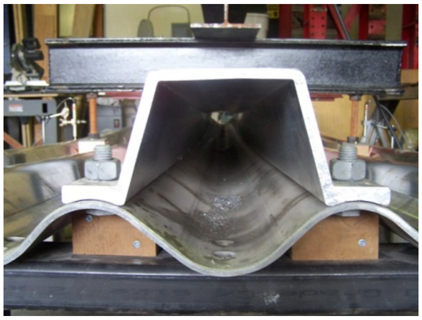

Figure 8. Stiffener bolted to plate

Figure 9. Steel arch with deep corrugated plate stiffeners on crown region

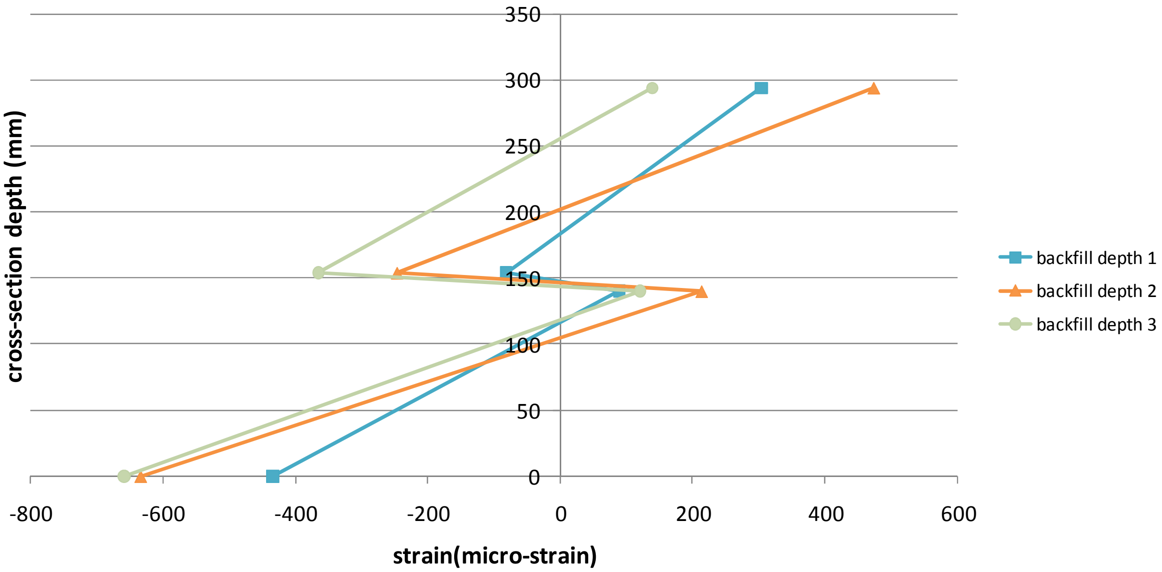

Figure 10. Strain profile through depth of corrugated plate for structure shown in Figure 9

Figure 11. Concrete being pumped into voids between corrugated plates

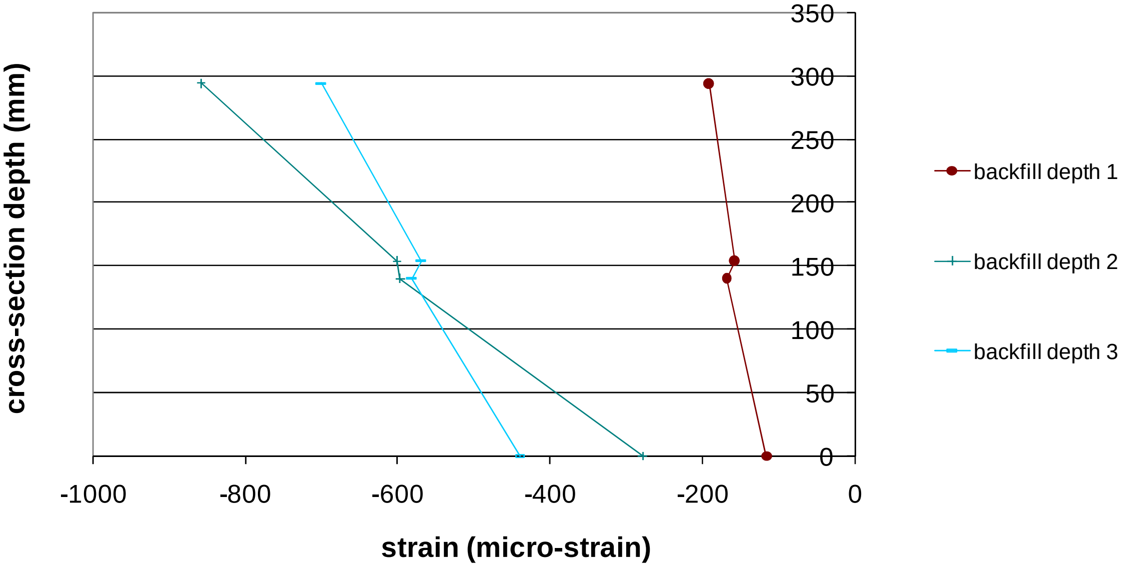

Figure 12. Strain profile through depth of encased concrete rib structure shown in Figure 11

Figure 13. Flexural testing of encased concrete rib specimen

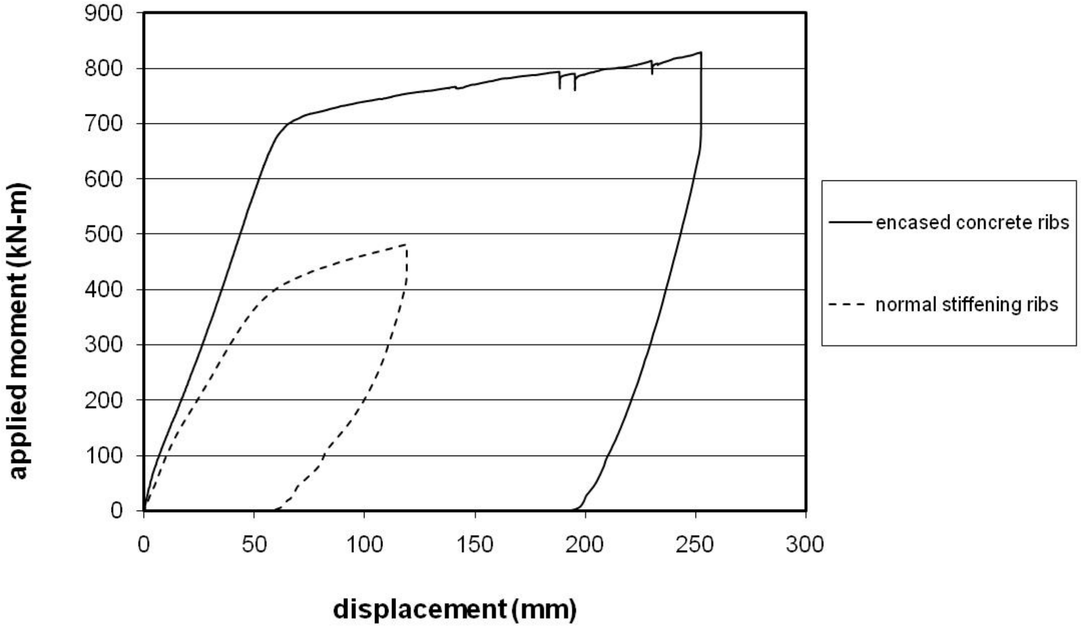

Figure 14. Flexural test results of encased concrete rib versus normal stiffening rib configurations

Figure 15. Construction of metal box test structure in Dorchester, New Brunswick

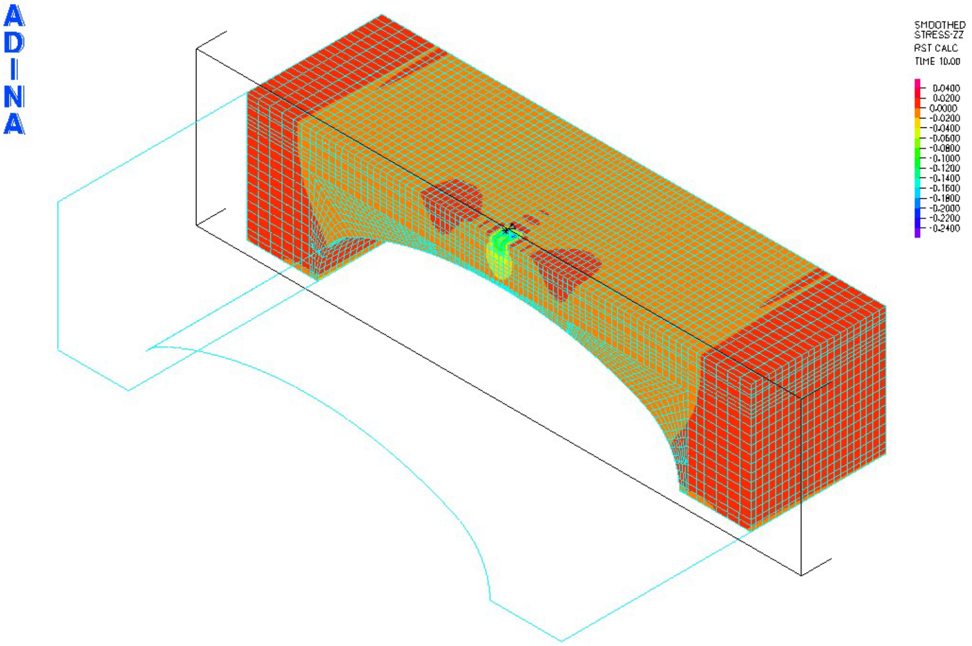

Figure 16. Isometric view of 3-D finite element model of test structure showing soil stresses

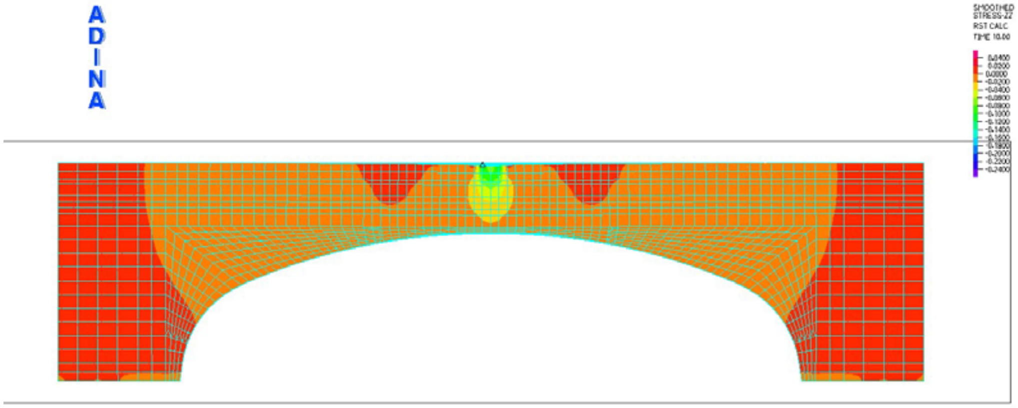

Figure 17. Cross-section view of model showing soil stresses from wheel loads above the crown

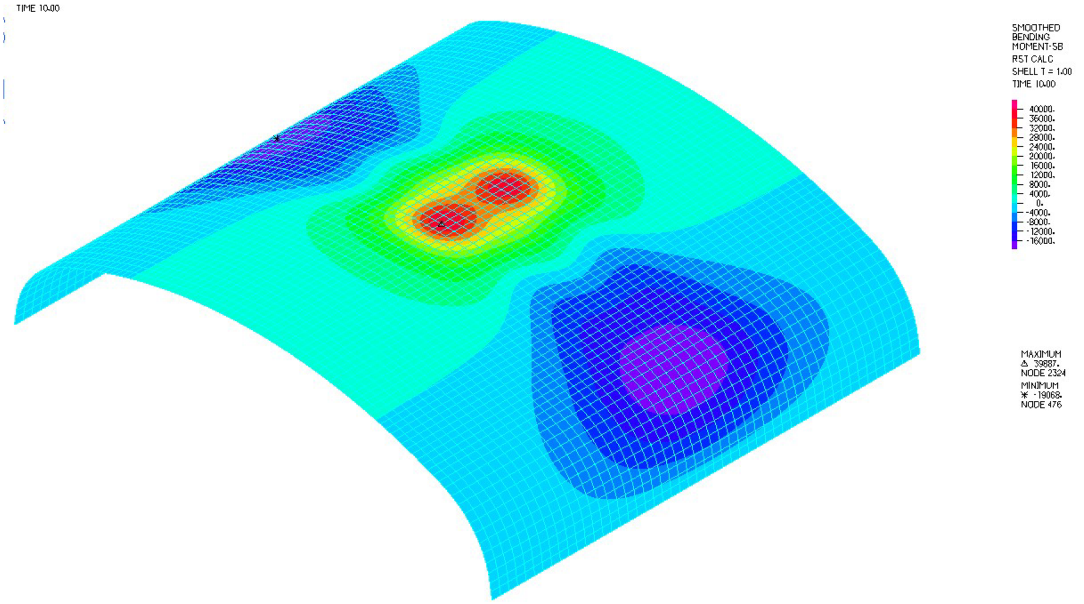

Figure 18. Isometric view of model showing bending stresses in the corrugated plate

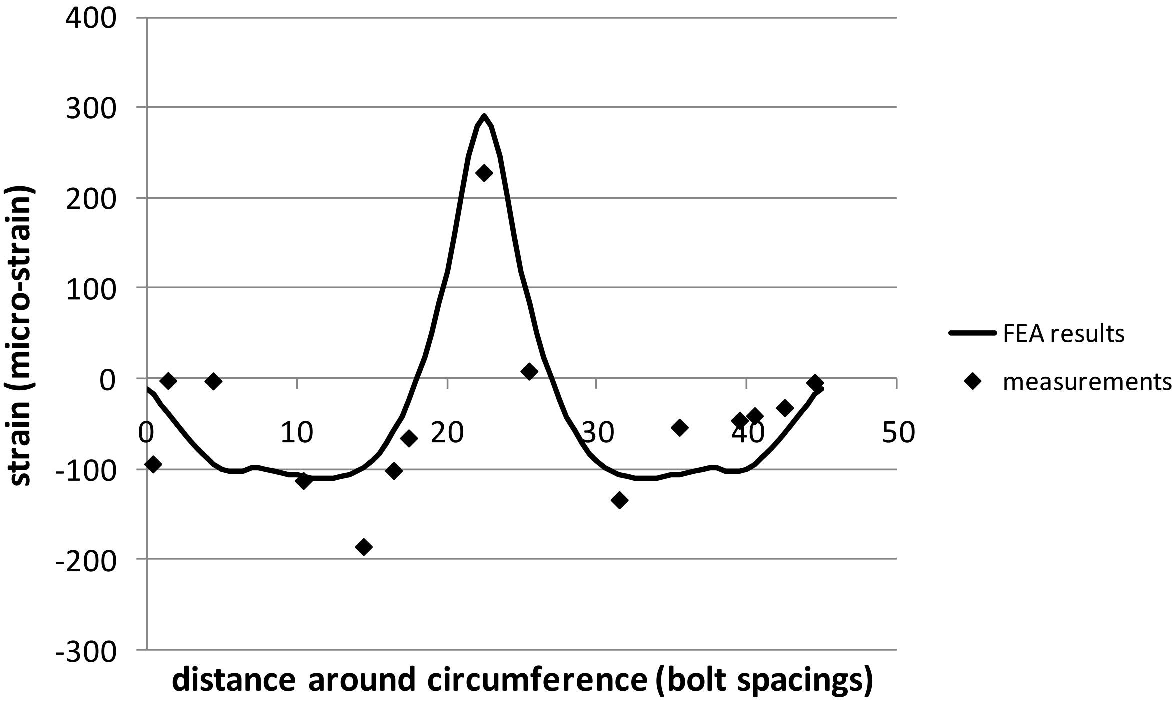

Figure 19. Comparison of finite element analysis results and field measurements of plate strains at middle of structure