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RESEARCH ADVANCING THE DESIGN OF LARGE SPAN DEEP CORRUGATED METAL CULVERTS

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While it has long been understood that culvert response to live load depends on three dimensional effects, and that design of these heavily redundant structures should account for ultimate strength, it has only recently been possible to measure and calculate this behaviour. Laboratory tests on a deep corrugated metal box culvert of 10m span are described, including tests before burial and one test of the shallow buried structure up to the ultimate strength limit. Three dimensional finite element analysis is then discussed. The ultimate strength test demonstrates the substantial reserve capacity due to three dimensional load spreading. Finally, the potential for undertaking design using parametric studies based on three dimensional finite element analyses is illustrated.

Key words: large span, deep corrugated, box culvert, arch culvert, three dimensional finite element analysis, joints, footings.

1. INTRODUCTION

Large span corrugated metal culverts were developed in Canada and the US during the 1960s, assembled from 152mm by 51mm corrugated steel plates. To manage the construction of these very flexible structures, special provisions were made to control deformations, including circumferential ribs to add stiffness. Design was initially based on concepts developed for corrugated steel pipes but was greatly enhanced with the development of two dimensional finite element analyses (e.g. Katona, 1978), and design methods for these structures culminated with the contributions of McGrath et al. (2002) to the AASHTO (2006) load and resistance factor design specifications. These procedures were based on large scale field testing of a low profile arch of 10m span (McGrath et al., 2002), two dimensional analyses for earth load effects (Taleb and Moore, 1999) and three dimensional elastic analyses to consider the effect of vehicle loads (Moore and Taleb, 1999).

However, another approach for controlling deformations is to employ stiffer corrugated plate, and the field testing reported by McCavour et al. (1998) and Vaslestad et al. (2003) demonstrates the benefits of the additional stiffness associated with deep corrugated plates (where corrugation depth is 140mm or more). Both the American (AASHTO, 2007) and Canadian (CSA, 2006) bridge design codes contain provisions for these structures, though the basis of those provisions is unclear, and it appears that the design theories produce results that are sometimes very conservative and in other situations very unconservative (Elshimi, 2011). In particular, while culvert designs are generally undertaken using two dimensional finite element analysis, it is unclear to what extent the two dimensional design models capture the real physical response under vehicle loads, which is certainly three dimensional.

At the same time as these new technologies have been developed, the research tools available for studying these systems have been transformed. In particular, the buried infrastructure research team at Queen's University has developed a large scale testing facility to study the behaviour of large span metal culverts and other structures in the laboratory, and computational capabilities have been transformed by the use of massively parallel computers. The objective of this paper therefore, is to illustrate the use of these new research capabilities to advance understanding of the behaviour and design of deep corrugated metal culverts. The experiments of Lougheed (2008) conducted on a 10m span deep corrugated metal box culvert are described, including the surface load test conducted up to the ultimate limit state of the structure. Then, the state of the art computational analyses developed by Elshimi (2011) are discussed, and their use in developing design solutions for this class of culvert structure. The paper concludes with recommendations regarding the use of these research tools to advance culvert design. Many of the experimental and computational details of this research are reported elsewhere, so this paper summarizes the research findings to illustrate how the new facilities and computational capabilities can advance the design of corrugated metal structures.

2. LABORATORY EXPERIMENTS

2.1. Test facilities

Test facilities commissioned at Queen`s University in 2006 permit field-scale testing of culverts and other buried infrastructure in the laboratory. The facility features a test pit 16 m long, 8 m wide, and 3 m deep. The top of the test pit is at ground level, so that after infrastructure is buried, trucks can be driven over the test structures to investigate infrastructure performance under service loads. The laboratory also has a 2 MN actuator that can be positioned over the test pit under a steel reaction frame anchored into the limestone below the floor of the facility. This actuator permits application of surface loads about 9 times larger than standard design vehicles, and is able to bring most buried structures to their ultimate limit states.

a. Erecting the 10m span box culvert b. Culvert being backfilled with GW-SW soil
Figure 1. General view (from Lougheed, 2008)

2.2. The test structure

Over the past six years the facility has been used for more than 100 tests on a variety of culverts and other buried structures. Figure 1 shows two views of a deep corrugated metal culvert being assembled in the pit, then backfilled with well graded sandy gravel (classified GW-SW) compacted to 90 to 95% of maximum dry unit weight from a standard Proctor test. This box culvert has 10 m span and 2.4 m rise, Figure 2, with long-radius plates at the sides and across the crown, and short-radius plates directly above the sidewalls. The test structure was 6m wide.

The inside of the structure was instrumented with reflective prisms that were monitored using a servo-controlled total station (theodolite). This measures prism location and provides deformations in three directions to within 0.1 mm. The inside surface was also monitored using strain gages glued at the crest, sidewall or valley of the corrugation. These were placed at many different locations across the width and across the span of the structure. Strain was measured using a data acquisition system which provides strain to within 2 microstrain.

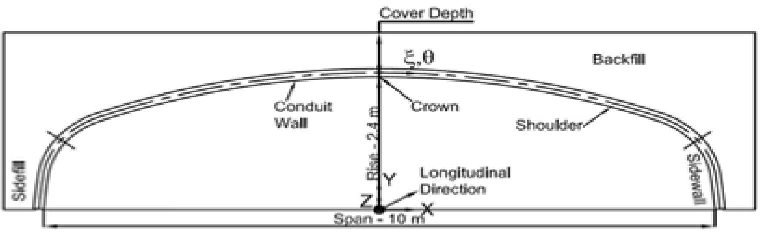


Figure 2. Cross-section of the large span box culvert (from Brachman et al. 2012)

2.3. Testing prior to burial

A series of experiments were performed on the steel structure prior to burial, examining its three dimensional response to loads applied above the crown. These tests were used to investigate the effect of the seams used to connect the corrugated metal plates (seen in Figure 1a) and the corrugated plate end walls (seen in Figure 1b). For example, deflections attenuated rapidly in the longitudinal direction (transverse to the span), and there was almost no change in stiffness under vertical load at the crown after installation of the endwalls. This occurs because the stiffness of the corrugated steel plates in the longitudinal direction is small compared to stiffness parallel to the span. Analysis of these tests is discussed in a later section.

2.4. Real and simulated axle loading

Once the structure was buried, it was tested at three different cover depths. Testing was performed using two different schemes. First, a loaded dump truck with approximately 24 tonnes acting on the rear (tandem) axles was parked at various locations across the structure, Figure 3a. Second, a steel frame with the standard Canadian tandem axle geometry (CSA, 2006) was loaded using the 2 MN actuator, Figure 3b. Comparisons of response from the truck and the axle load frame at the same load level demonstrated that the two are essentially equivalent.

2.5. Ultimate strength test

One final experiment was performed with 0.5m of soil over the crown of the culvert (measured from the valley of the corrugation), Brachman et al. (2010). With actuator centered over the structure, Figure 3b, load was increased until a limit load of approximately 800 kN was reached (curve #1 in Figure 4a shows the relationship between vertical force and vertical displacement of the midpoint of the structure). That limiting condition was associated with bearing failure of the backfill under the load plates of the axle loading frame.

Figure 3. Loading with tandem axle dump truck and tandem axle loading frame

The soil surface was repaired and hardwood blocks with 2.5 times larger contact area were placed under each of the steel load pads. The experiment was continued until another limit state was reached, as shown with load-displacement curve #2 in Figure 4a. The vertical force of 1100 kN corresponds to 1.7 times the fully factored tandem axle CHBDC design truck. This implies that the test structure has significant reserve capacity beyond the minimum strength requirements.

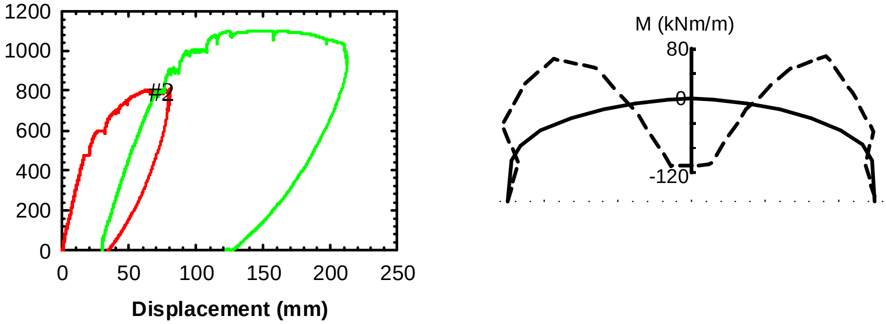
The failure mechanism is most easily understood examining the distribution of moments calculated from strain measurements, across the span of the structure, Figure 4b. The load limit is associated with full development of yield moments at the crown and at the shoulders of the test structure. The vertical deformations of the ground surface over the culvert were very three dimensional in nature, with a bowl of deformations forming around the surface load position. This first test of a deep corrugated box culvert up to its strength limit states demonstrated that:

a. the strength limit under surface load for an unpaved system is controlled by bearing failure under each \`wheel pairs\` (the steel pads resting on the ground surface as seen in Figure 3b);
b. if bearing failure is prevented (say by a pavement), then a plastic collapse mechanism develops associated with three plastic hinges;
c. even at minimum cover, the culvert has considerable reserve capacity;
d. significant three dimensional load spreading occurs; this is neglected by conventional two dimensional finite element design calculations.

3. THREE DIMENSIONAL FINITE ELEMENT ANALYSIS

3.1. Analysis using ABAQUS

Following completion of the test program, work was undertaken to develop full three dimensional finite element analyses of the tests using ABAQUS version 6.7 (Hibbitt et al., 2007). The objectives of these analyses were to:



a. Load versus vertical deflection at the crown b. Moment distribution at peak load
Figure 4. Ultimate load experiment

a. understand the test data, including response to earth and live loads;
b. determine the level of complexity needed to capture the culvert response at service loads as well as the ultimate limit state, including whether calculations can be performed using orthotropic shell theory for the culvert, or if full explicit modeling of the corrugated plate geometry is required;
c. understand the three dimensional culvert response under live load

Establish whether the most critical surface load condition involves a single truck, or vehicles in more than one lane;

d. investigate the influence of flexible pavements on culvert performance;
e. develop parametric design solutions considering culvert span, shape, plate thickness, and burial depth.

3.2. Analysis for unburied structure

Work commenced with analysis of the tests performed on the box culvert prior to burial, Brachman et al. (2012). Two structural models were employed to characterize the corrugated plate of 400 mm pitch and 150 mm depth, Figure 5a. The first involved explicit representation of the corrugated plates using shell elements, Figure 5b, where nine elements were used for each half-wavelength of the corrugated plate. Properties (thickness, elastic properties, and yield strength) for these elements were those for the corrugated steel plate. This explicit modeling of the corrugated geometry involved very large numbers of elements.

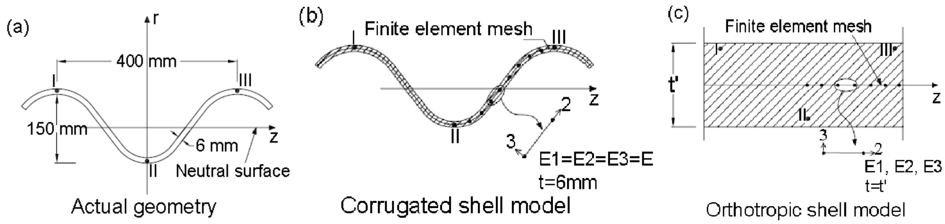
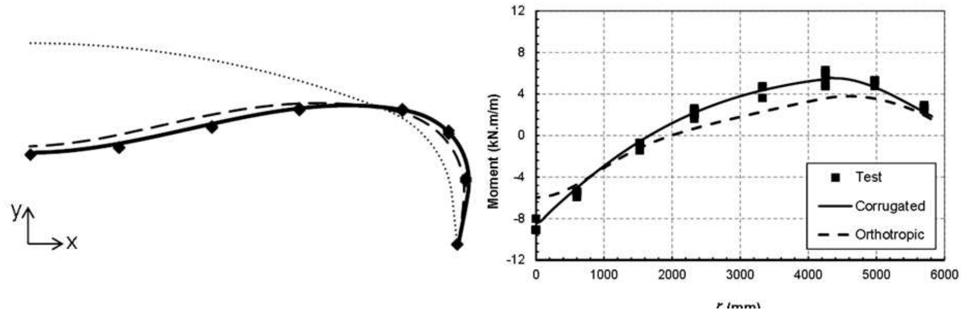


Figure 5. Corrugation geometry, ‘corrugated shell’ and ‘orthotropic shell’ models

The second approach involved representation of the structural characteristics of the corrugated plate using orthotropic shell theory, Figure 5c. For this approach explained in detail by Brachman et al. (2012), the plate is modeled as an equivalent plain shell of thickness t’. Three different elastic moduli are used to produce the different stiffness characteristics in different directions (high membrane and flexural stiffness across the span, and much lower values of membrane and flexural stiffness across the width of the culvert). Elshimi (2011) explains how nonlinear response can also be captured using orthotropic analysis. The orthotropic plate theory is much more efficient since it involves far fewer shell elements. However, this modeling is not expected to capture effects such as local buckling (not an issue for the structure only experiments, but of potential significance for the ultimate strength analyses of the buried structure).

Figure 6 provides distributions of deflections and moments along the centerline of the structure across the culvert span from the crown to the footing. Three sets of values are given: those from the laboratory test, those obtained using explicit modeling of the corrugated geometry, and those obtained using orthotropic shell modeling. These demonstrate that explicit analysis of the corrugated geometry provides the best calculations (displacements within 0.2% of the experimental observations at the crown, and moment within 3%). The orthotropic analysis provides the correct patterns of deflection and moment, though magnitudes have lower accuracy (4% error in displacement at the crown, and 30% error in moment).

Issues explored during analysis of the unburied structure included whether it is necessary to model the seams connecting corrugated plates, the effect of the end-walls on the structural performance, and development of the modeling approach for connections between the corrugated plates and the footings. This work established that seams do not need to be modeled, and that simple pinned connections can be modeled between the structure and the footings.



a. Deformations x 200 b. Moments

Figure 6. Measured and computed results from crown to footing before burial

3.3. Analysis of backfilling

It is more than three decades since two dimensional finite element analyses were developed to model the response of flexible metal culverts during backfilling (e.g. Katona, 1978). Both two and three dimensional analyses of the test structure responding to earth loads were developed, and these have been reported in detail by Elshimi et al. (2011). One issue explored during the study of backfilling was the impact of compaction on the culvert response. Use was made of the modeling technique developed by Taleb and Moore (1999) which produced significant additional deformation for the 152 mm by 51 mm corrugated plate structure those authors studied. For the deep corrugated structure, however, the inclusion of additional lateral earth pressures due to compaction leads to modest changes in crown deflection (4%) and crown moment (7%). This reflects the reduced sensitivity of deep corrugated plate structures to construction practice.

3.4. Surface load and ultimate strength calculations

The performance of the three dimensional finite element analyses for calculation of ultimate strength was also examined, modeling the tests described in section 2.5, above. Figure 7 shows the finite element mesh used for the analysis involving explicit modeling of the corrugated geometry (one of the loaded patches is shown, since the analysis capitalizes on the double symmetry of the geometry). Figure 8 shows the ‘measured’ moments along the centerline at peak applied load (i.e. calculated from measured strains, Brachman et al., 2010) with those obtained using the finite element analyses. This comparison demonstrates the ability of the finite element modeling to represent the correct pattern of moment from crown to footing. In particular, the analysis includes considerations of both shear failure in the soil under the applied loads, and zones of yield in the corrugated steel plates across the crown and at the shoulders (where moment is at or close to the full plastic moment capacity of the corrugated plates, 109 kN.m per m along the structure). As discussed earlier in relation to `structure-only’ testing, analysis based on orthotropic plate theory is effective, but not as accurate as analysis where the corrugated geometry is represented explicitly. Elshimi (2011) demonstrates how the three dimensional analyses are distinctly superior to the two dimensional approaches used for these structures in the past.

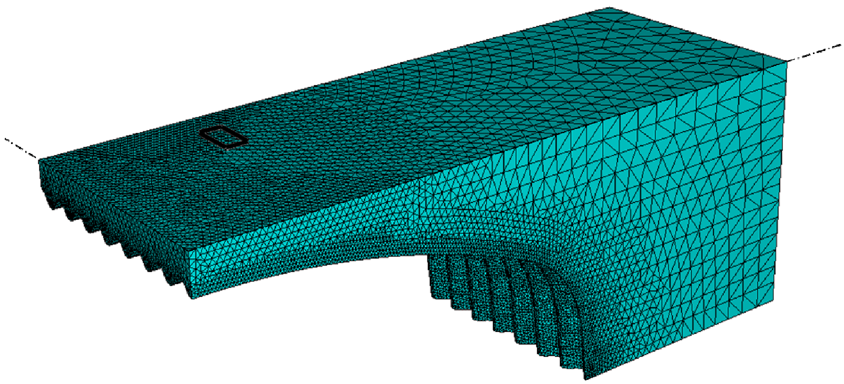


Figure 7. One quarter of the system modeled for the ultimate load test (Elshimi, 2011)

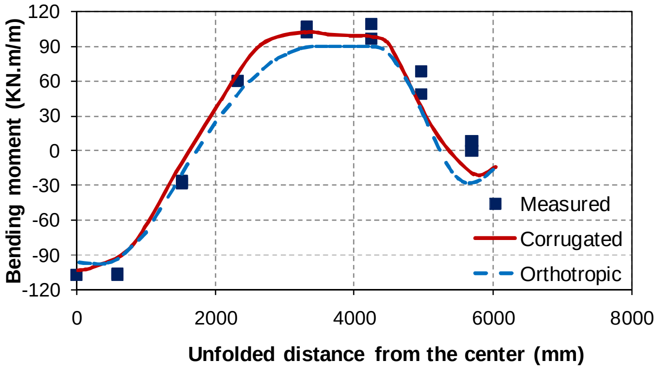


Figure 8. Moment distribution along centerline from crown to footing: calculated from measured strains and using ABAQUS at peak load (Elshimi, 2011)

4. PARAMETRIC INVESTIGATIONS

Following the development of finite element analyses capable of representing the behavior of the structure, parametric studies were undertaken for deep corrugated box culverts as well as deep corrugated arch culverts. Figure 9 shows one set of results where peak moment resulting from live loads is examined for the box culvert with three different spans and three different burial depths. Results were obtained for thrust, moment, and deformation associated with earth load and vehicle loads. Most design quantities like the peak moment shown in Figure 9 are nonlinear functions of the geometrical variables (span and burial depth). However, since the functions are not strongly nonlinear, interpolation can be used to estimate peak live load moment at intermediate values of span and cover depth.

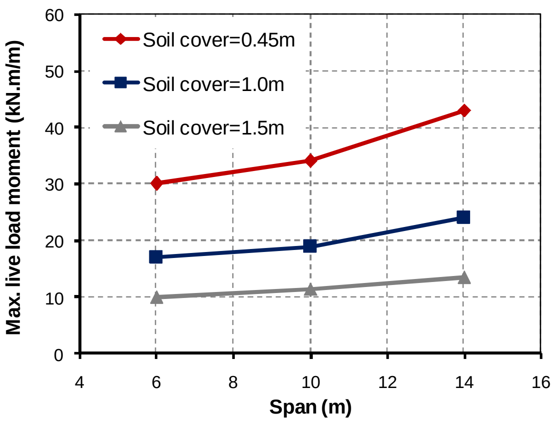


Figure 9. Peak bending moment due to surface load (from Elshimi, 2011)

5. CONCLUSIONS

New experimental facilities permit laboratory tests on large span metal culverts and provide valuable data on culvert performance at both service and ultimate loads. Computer modeling capabilities also continue to improve, and it is now possible to develop full three dimensional analyses that explicitly represent the geometry of the corrugated structure, and capture the nonlinear characteristics of the corrugated steel plates and the overlying soil. These permit design solutions that capture the three dimensional nature of culvert response, and avoid the excess conservatism associated with the two dimensional finite element analyses that are usually used for design of large span metal culverts. These three dimensional analyses also provide effective calculations of ultimate strength and capitalize on the potential benefits of load and resistance factor design, and there is great potential for these methods to be used to study other corrugated metal structures.

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Streszczenie

Mimo tego, że od dawna rozumiemy, że reakcja przepustów na obciążenia zmienne zależy od sił działających w trzech wymiarach, a podczas projektowania tych wysoce redundantnych konstrukcji należy brać pod uwagę ich wytrzymałość graniczną, dopiero niedawno pojawiła się możliwość mierzenia i obliczania takiego zachowania. W tej pracy opisano testy laboratoryjne przepustu skrzynkowego ze stalowej blachy falistej o głębokiej fali o rozpiętości 10 m, w tym testy przed zasypaniem oraz jeden test konstrukcji z płytkim naziomem aż do granicy wytrzymałości. Następnie omówiona jest trójwymiarowa analiza elementów skończonych. Test wytrzymałości granicznej pokazuje znaczącą rezerwę wytrzymałości dzięki rozprzestrzenianiu się obciążeń w trzech wymiarach. Na koniec przedstawiono potencjał projektowania przy użyciu badań parametrycznych opartych o trójwymiarowe analizy elementów skończonych.

Słowa kluczowe: duża rozpiętość, głęboka fala, przepust skrzynkowy, przepust łukowy, trójwymiarowa analiza elementów skończonych, złącza, posadowienie.