ARCHIWUM INSTYTUTU INŻYNIERII LĄDOWEJ
Nr 12 ARCHIVES OF INSTITUTE OF CIVIL ENGINEERING 2012

NEW AND INNOVATIVE DEVELOPMENTS FOR DESIGN AND INSTALLATION OF DEEP CORRUGATED BURIED FLEXIBLE STEEL STRUCTURES

Kevin WILLIAMS, P.Eng.[*], Stephen MacKinnon, P.Eng.[**],
Dr. John Newhook, PhD, P.Eng.[***]
[*]) Senior Design Engineer, Atlantic Industries Limited, Ontario, Canada
[**]) VP International Operations, AIL Group of Companies, P.O., Canada
[***]) Professor, Dept. of Civil and Resource Engineering, Dalhousie University, Halifax, Nova Scotia, Canada

Abstract

Extreme long spans and high earth covers on buried flexible structures have long presented challenges to the design engineer. For deep corrugated products the technical challenges are primarily associated with joint capacities and bending moments. Atlantic Industries Limited has two new products: Ultra-Cor and four sided flanges for Ultra-Cor and Super-Cor plate.

Ultra-Cor plate has a corrugation profile that is deeper than Super-Cor, resulting in a large flexural capacity. In many applications, Ultra-Cor will permit bigger spans, heavier live loads, and lower rise structures. Four sided flange connections for Ultra-Cor and Super-Cor plate permit one sided assembly, simplify the assembly process, increase connection capacity and provide a means to more easily construct water-tight buried structures. These new products and features enable buried structure solutions for a wider range of applications.

Key words: Buried Flexible Structures, Deep Corrugated Plate, Flange, Super-Cor, Ultra-Cor

1. INTRODUCTION

In 1993, Atlantic Industries Limited (AIL) started producing a deep corrugated plate called Super-Cor. At the time, Super-Cor's corrugation profile which measures a pitch and depth of 381 mm x 140 mm respectively, was the latest evolution in corrugated metal structures. This product, which was originally developed with conventional lap joints, was developed to allow corrugated metal structures to grow in span, enable greater fill heights, and new large span, low rise structure shapes such as box culverts. Super-Cor plate, which is nine times stiffer than traditional shallow corrugated plate (152 mm pitch x 51 mm depth) has been used for corrugated structures reaching spans in excess of 25 m.

Through continual research and development AIL and their partners grew the range and market for deep corrugated Super-Cor product to new limits, far beyond those of the shallow corrugation. Special features such as factory produced continuous ribs and encased concrete ribs have expanded buried structural plate structures capabilities to an extent where they are a common solution in the small to medium bridge market.

Over time, AIL has found that several challenges remain for soil-steel structures including:

- Very heavy live load applications,
- Large spans beyond 27 m,
- Very low rise applications,
- Very high fill applications,
- Assembly challenges when plate thickness is great,
- Access restrictions during assembly that limit access to one side of the structure,
- Constructing water-tight structures, particularly those with thick plates.

AIL is continually developing products and features to meet customer's challenges. A new product and a new feature that help meet these challenges: Ultra-Cor plate and deep corrugated plate with four sided flanges are presented.

2. ULTRA-COR: A DEEPER CORRUGATED PLATE

Deep corrugated Ultra-Cor structural plate first appeared in the market in 2011 and measures a corrugation pitch and depth of 500 mm x 237 mm respectively. Ultra-Cor was developed to offer solutions for:

- Very heavy live load applications,
- Large spans,
- Very low rise applications.

Figure 1 illustrates a comparison between Ultra-Cor, Super-Cor and traditional 152 mm x 51 mm structural plate. Ultra-Cor's deeper corrugation profile was developed to deliver very high flexural capacity per unit area of steel. Ultra-Cor is fabricated from steel with a minimum yield strength of 300 MPa and at the time of this writing, Ultra-Cor can be produced from steel plate ranging from 7 mm to 12.7 mm thick.

During assembly, plates are connected at longitudinal seams, which are perpendicular to the corrugation, and circumferential seams, which are parallel to the corrugation. At the time of this writing, Ultra-Cor was available in lap seams as illustrated in Figure 2.

Figure 1. Ultra-Cor vs. Super-Cor vs. 152 x 51 mm Corrugation Profile

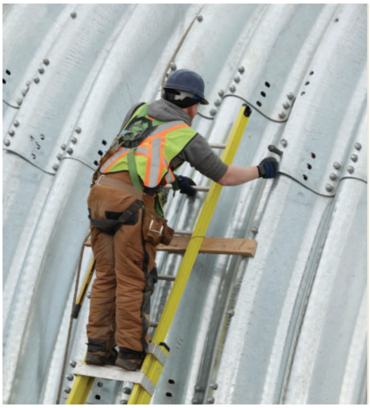

Figure 2. Ultra-Cor Structure with Lap Seams

2.1 Developmental Challenges

The development process of a deeper corrugation profile required consideration of elements such as material availability, manufacturability, design and assembly. Potential corrugation profiles were restricted by widths of commonly available steel sheets, thickness and grades. New tooling and manufacturing processes capable of forming thicker and stiffer plate were needed as well as a new design method properly accounting for the impact of a deeper, more rigid structure were required.

At the time of this writing, Ultra-Cor plate with lap seams is available and rib options for Ultra-Cor are in development.

2.2 Design

Design of deep corrugated structures requires consideration of the following ultimate limit states:

- global buckling,
- connections,
- formation of a plastic hinge from combined axial/bending loading,
- backfill.

Governing ultimate limit states for Super-Cor and Ultra-Cor structures are typically:

- Formation of a plastic hinge when backfill is near the crown,
- Formation of a plastic hinge during live load application at final height of cover,
- Connection capacity at final height of cover.

Backfill at Crown: When backfill is placed against the wall of the structure the crown of the structure is pushed upwards, inducing a negative bending moment at the crown. This moment, more commonly known as peaking moment, results in a peaking bending stress which must remain below a specific level as defined by the plate strength. One way of overcoming peaking moment concerns is use of a stiffer, deeper corrugation profile. Stiffer, deeper corrugation profiles are capable of withstanding greater peaking moments. In many applications, peaking stress of an Ultra-Cor structure is less than Super-Cor structures. This trend is most beneficial on large span (typically > 18 m) or high profile structures (typically large rise/span ratios > 0.6).

Final Height of Cover: When backfill and live load is placed above the crown of the structure the structure typically experiences an increase in positive crown moment and thrusts in the conduit wall. In applications when formation of a plastic hinge is the governing ultimate limit state, Ultra-Cor plate is often beneficial.

2.3 Testing

Laboratory and full-scale field testings were completed to determine and verify Ultra-Cor's performance.

Flexural Testing: Bolted and non-bolted plate specimens having a nominal thickness of 7 mm and a width of two corrugations were tested at Dalhousie University in Halifax, Nova Scotia, Canada. A typical test setup is illustrated in Figure 3. Bolted plates were assembled using a lap joint containing 7/8" diameter ASTM A449 bolts with a 1/2-inch shoulder complete with ASTM A563 grade C nuts. Bolts were torqued to 338 Nm (250 ft-lbs). Specimens were tested as a simple beam with two concentrated loads, creating a constant moment zone in the midspan region. Loading progressed until an ultimate load producing a dominant inelastic local buckling failure was reached. Local buckling in the non-bolted sample was not observed until after extensive inelastic straining and the sample flexural capacity exceeded theoretical plastic moment capacity predictions. Small reductions in moment capacity across a lap connection were realized (Roger Brockenbrough, 2011, p. 2).

Figure 3 Ultra-Cor Flexural Test (Dr. John Newhook, Philip Vickers, 2011a, p. 1)

Compression Testing: Bolted plate specimens having a nominal thickness of 7 mm were tested at lab facilities of the University of Calgary in collaboration with researchers at Dalhousie University. A typical test setup is illustrated in Figure 4. Bolted plates were assembled using a lap joint connected with 7/8" diameter ASTM A449 bolts with a 1/2-inch shoulder complete with ASTM A563 grade C nuts. Bolts were torqued to 338 Nm (250 ft-lbs). The lap joint consisted of three rows of bolts each having nine bolts for a total of twenty-seven bolts/sample. Load was applied until ultimate failure load was realized. Failure initiated with local buckling at the unsupported edges. As unsupported edges are typically not present in field applications, test results represent a scenario more severe than typical applications (Roger Brockenbrough, 2011, p. 3).

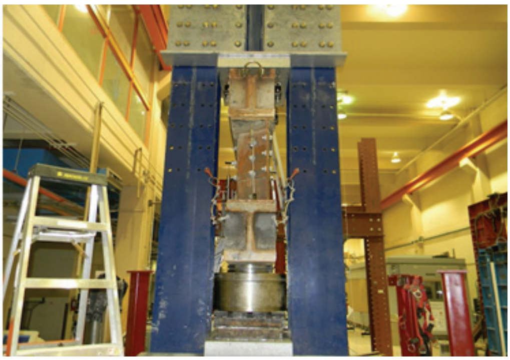

Figure 4. Ultra-Cor Compression Test (Dr. John Newhook, Philip Vickers, 2011b, p. 1)

Field Testing: At the time of this writing, construction of the first Ultra-Cor structure, a 13.2 m span x 5.3 m rise Ultra-Cor structure located in Corner Brook, Newfoundland, Canada is underway. The structure has been instrumented with deflection prism and strain gauges and measurements will be taken during and after backfill placement.

2.4 Future Developments

Several future Ultra-Cor developments are planned.

- Metal Ribs: The addition of corrugated Ultra-Cor plates connected circumferentially to the Ultra-Cor barrel plate.
- Encased Concrete Ribs: Metal ribs with shear studs and concrete placed in the void between the barrel and rib plate.
- Flange Connections: To simplify assembly of thick plates, circumferential and longitudinal flange seam connections detailed in Section 3.

3. FLANGE

Figure 5 depicts the four-sided flange connection for Super-Cor plate recently developed. The flange is intended for Super-Cor and Ultra-Cor plate and was developed to address:

- Assembly challenges when plate thickness is great.
- Access restrictions during assembly that limit access to one side of the structure.
- Constructing water-tight structures, particularly those with thick plates.

At the time of this writing, a four-sided flange is imminently available for Super-Cor plate where water-tightness is not required. Four sided-flanges were developed based on the requirement of having equivalent or better flexural and axial connection strength.

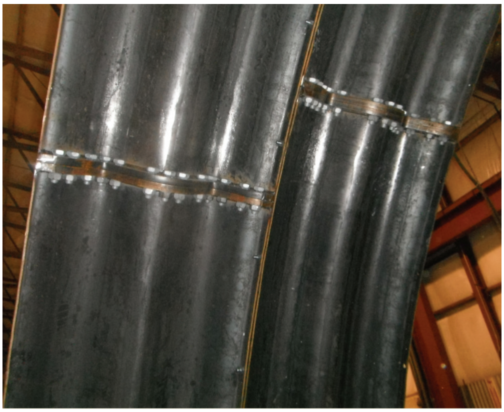

Figure 5. One-Sided Flange Connection

3.1 Developmental Challenges

A significant development challenge was determination of the flange configuration, in particular the flange connection for the longitudinal seam. Specific considerations included:

- Ability to effectively assemble from one side
- Ability to meet strength requirements
- Ability to provide water-tightness
- Ability to cost-effectively fabricate.

New tooling and manufacturing processes are required for the one-sided flange. At the time of this writing, pre-production mode fabrication issues are currently being resolved.

3.2 Design

Deep corrugated structure connections require sufficient flexural and axial capacity.

Flexural: Design codes typically define minimum flexural capacity across a bolted connection. AIL has developed the flange such that it provides a minimum connection capacity equal to 80% of a non-connection portion of the plate.

Axial: Design codes typically do not require a minimum seam strength. However, AIL is developing the flange with the requirement that its axial capacity is equivalent or greater than traditional lap joints. AIL anticipates flange connections having an axial capacity close to the yield capacity of the plate as typically failure modes associated with lap connections, bolt bearing or bolt shear failure, are likely eliminated as flange connections are end-bearing type connections. Higher seam strengths will permit greater fills.

Flexural and axial design capacities of the flange connection will be established through laboratory testing and analysis.

3.3 Testing

Testing to establish the flexural capacity across a bolted connection was completed at Dalhousie University in Halifax, Nova scotia, Canada. A typical test setup is illustrated in Figure 6. At the time of this writing, testing has been completed on a single plate width, 7 mm Super-Cor plate with a yield strength of 300 MPa. Flange connections were assembled using a 7/8” diameter ASTM A449 bolts complete with ASTM A563 grade C nuts. Bolts were torqued to 338 Nm (250 ft-lbs). The flange joint contained thirteen bolts arranged in one row and the joint was tested in both flexural compression and tension. An additional lap seam Super-Cor sample was tested in the same manner.

Specimens were tested as a simple beam with two concentrated loads, creating a constant moment zone in the midspan region. Loading progressed until an ultimate load was realized. Failure mode of the negative moment test is local buckling along the edge of the plate under the loading beam. Failure mode of the positive moment test was local buckling of the plate under the loading beam. Gaps at the flange are minimal and depicted in Figure 7. Generally, failure was initiated in the non-connection portion of the plate due to the unsupported longitudinal edge and minimal reduction in flexural capacity was observed due to the presence of the flange connection (Dr. John Newhook, Philip Vickers, 2011c, p. 7).

Figure 6. Super-Cor Flange Test Configuration
(Dr. John Newhook, Philip Vickers, 2011c, p. 3)

Figure 7. Flange Connection Gap after Testing
(Dr. John Newhook, Philip Vickers, 2011c, p. 10)

At the time of this writing, compression testing on the flange connection had not been completed. Future compression testing and flexural testing on various plate thicknesses is scheduled.

3.4 Future Developments

Several future flange developments are planned including:

- Incorporation of features that permit water-tight structures.
- Development of a flange connection for Ultra-Cor.
- Development of a flange connection that permits assembly of structures with ribs through access of one side only.

4. APPLICATIONS

Anticipated applications for Ultra-Cor and the four sided flange are as follows:
Ultra-Cor

- Wide and low clearance boxes resulting in low rise, large span structures.
- Applications with very heavy live loads.
- Very large spans.

Flange

- Seam strength is a common failure mode for corrugated steel structures with a lap joint in high cover situations. The flange connection will help in high cover projects due to increased seam strength of the connection.
- Connection of preassembled sections is easier with four-sided flange plates.
- Structure assembly will be faster and safer as work can be preformed from the inside only, eliminating the complication of tying workers off from the outside of the structure.
- The flange connection will allow for water tight connections. Currently, it is difficult to construct lap joint corrugated plate structures water tight due to gaps at plate laps. It is noted gap sizes at plate laps increase with metal thickness.
- Structures with lap joints require bolts connecting three plates in some locations. Flange structures are easier to assembly as four-sided flanges require a maximum of two plates being connected with a bolt.

5. CONCLUSIONS

AIL has developed two new products which increase the capabilities of buried metal structures and enable their use in more diverse applications. Ultra-Cor structures are currently being fabricated for non-rib applications and Ultra-Cor plate provides the market with a product that provides solutions to larger spans, heavier live loads, and lower rise applications. Four sided flanges are currently being fabricated for Super-Cor applications and are in development for Ultra-Cor applications. Four sided flanges simplify structure assembly, offer greater connection capacities and provide an easier means to watertight structures when compared to traditional lap joint connections.

REFERENCES

1. Dr. John Newhook, Philip Vickers. (2011a). *Ultra Cor Flexural Strength Testing*. Centre for Innovation in Infrastructure, Dalhousie University, Halifax, Canada.
2. Dr. John Newhook, Philip Vickers. (2011b). *Ultra Cor Compressive Strength Testing*. Centre for Innovation in Infrastructure, Dalhousie University, Halifax, Canada.
3. Dr. John Newhook, Philip Vickers. (2011c). *Flexural Strength Testing of Modelled Flange Seam Design*.
4. Roger Brockenbrough. (2011). *Design Capacities for 7 mm Ultra Cor*.

Streszczenie

Skrajnie długie rozpiętości i wysoki naziom gruntowy podziemnych konstrukcji podatnych od dawna stanowią wyzwanie dla konstruktorów. W przypadku konstrukcji z blachy falistej umieszczonych głęboko pod poziomem gruntu problemy techniczne wiążą się głównie z nośnością złączy i momentami zginającymi. Firma Atlantic Industries Limited oferuje dwa nowe produkty: Ultra-Cor oraz czterostronne kołnierze do blach Ultra-Cor i Super-Cor.

Blacha Ultra-Cor ma głębszy profil fali od blachy Super-Cor, co zapewnia większą wytrzymałość na zginanie. W wielu zastosowaniach Ultra-Cor pozwala na uzyskiwanie większych rozpiętości, wyższych obciążeń zmiennych oraz konstrukcji o mniejszej wysokości. Czterostronne złącza kołnierzowe do blach Ultra-Cor i Super-Cor pozwalają na montaż jednostronny, co upraszcza procedurę montażu, zwiększa wytrzymałość złącza i umożliwia łatwiejszą budowę wodoszczelnych konstrukcji podziemnych. Te nowe produkty i własności zwiększają zakres stosowania konstrukcji podziemnych.

Słowa kluczowe: podziemne konstrukcje podatne, blacha o głębokiej fali, kołnierz, Super-Cor, Ultra-Cor