Soil-Steel Structures and the Canadian Highway Bridge Design Code

Shane Finlay, P.Eng. (Presenting), Engineering Manager, Armtec Limited
Patrick Biro, B.Eng., Junior Designer, Armtec Limited
Heba Ahmed, B.Eng., Junior Designer, Armtec Limited

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ABSTRACT

The Canadian Highway Bridge Design Code (CHBDC) is the new Canadian design standard for bridge structures over three metres in span. Soil-steel structures fall into the category of buried structures, which is the subject of Section 7 of the Code.

Soil-steel structures have been in existence for over 100 years. A variety of design methods were developed during that period, each improving on the one before. Most of the soil-steel structure design methods used prior to the CHBDC were based on working stress, while the new CHBDC is based on the limit states design method developed for the Ontario Highway Bridge Design Code (OHBDC). The CHBDC also includes a specific check of strength requirements during construction which was not in the OHBDC. This part of the design method replaces the flexibility factor check of the previous design methods.

The purpose of this paper is to: review the historic design methods used for soil-steel structures, provide a detailed description of the philosophies used in the CHBDC and AISI (American Iron and Steel Institute) methods, including a description of the critical differences between the methods, and report on a comparison of design results using the two methods.

In order to compare design results from the two methods, a range of structure shapes and sizes were evaluated for numerous depths of cover. The study was limited to the 152 mm x 51 mm corrugation profile. Assumptions were required such that the comparison of methods using different design philosophies (working stress, limit states) are realistic.

In general, the CHBDC results in more liberal designs for shallow depths of cover and more conservative designs for large depths of cover. However, the differences between the methods compared are relatively small for the shorter span structures under mid-range depths of cover combined with normal highway loading.

1.0 Introduction

Flexible soil-steel structures derive their strength from the interaction between the soil and corrugated steel components of the system. The structural elements of a soil-steel structure consist of the corrugated steel and, in the case of structural plate pipes, high strength nut and bolt connections.

Most design methods consider pure ring compression as their main design criteria. Ring compression forces are most applicable and most important in cases of structures with high covers. However, as the span increases or cover decreases, bending forces become a more significant design consideration.

Soil-steel structures have, historically, been designed based on various methods ranging from prediction of deflections to simple ring compression to more complicated finite element analyses. The design methods include:

- *The Iowa Formula*: This formula, used for predicting the deflection of flexible pipes, resulted from the early efforts (1930) to rationalise the load-carrying capacity of these pipes. It is not currently used for design, but a study of the formula and it's variables provides an understanding of how soil-steel structures work.

- *The AISI Method*: The ring compression theory was developed in the late 1950's and early 1960's. The theory was developed into a rational design method through extensive research funded by the American Iron and Steel Institute in the late 1960's. The resulting ring compression design method is detailed in the corrugated steel pipe industry's Handbook of Steel Drainage and Highway Construction Products.

- *The ASTM Method*: The American Society for Testing and Materials has, through a consensus approach to specifications development, adopted the ring compression design method. The design method, first published in 1982, is detailed in ASTM A 796/A 796M "Standard Practice for Structural Design of Corrugated Steel Pipe, Pipe-Arches, and Arches for Storm and Sanitary Sewers and Other Buried Applications". The practice now includes both an Allowable Stress Design method and a Load and Resistance Factor Design method, which are both based on the ring compression theory.

- *The AASHTO Method*: The American Association of State Highway and Transportation Officials develop specifications on behalf of the states. They have adopted the ring compression design method for their specification, "Standard Specifications for Highway Bridges – Division I Design – Section 12 Soil-Corrugated Metal Structure Interaction Systems". The specification includes both a Service Load Design method and a Load Factor Design method, similar to the ASTM methods.

- *The Armtec (Proprietary) Super-Span Method*: This method, first used in 1967, introduced thrust beams and transverse rib stiffeners into the design of large span multi-radii soil-steel structures. The procedure considers combined bending and axial stresses in the top arc while treating the thrust beams as lateral supports.

- *The CANDE Program*: This finite element "Culvert ANalysis, DEsign" program is a Federal Highway Administration (FHWA) sponsored computer program which was developed in 1976.

- *The SCI Method*: The "Soil/Culvert Interaction" design method, published in 1978, utilises design graphs and formulae which are derived from finite element analyses.

- *The UBC Culvert Design Procedure*: This method is based on the SCI method. Bending moments and thrusts are checked against factors of safety with respect to seam strength and combined moment and axial stresses.

- *The OHBDC (Ontario Highway Bridge Design Code) Method*: This method was developed and first published in 1979 by the Ontario Ministry of Transportation as the first Limit States Design Code in North America specific to soil-structure design.

- *The CHBDC* (Canadian Highway Bridge Design Code) *Method*: This code was developed to replace the previous CSA specification and become the national standard for highway bridge design in Canada. The soil-structure design provisions are based on the OHBDC, but they have been rewritten so that they are applicable across Canada. It also includes some of the UBC method, particularly calculations dealing with constructability which replaces the empirical flexibility factor approach. The new code also contains revised requirements regarding highway live loads and metal box structures.

The historical design methods have been in existence and have been proven to work for many years. The impacts of new design methods or codes are still unclear.

It is the aim of this report to present effects on the design of structural plate corrugated steel pipe structures using the Canadian Highway Bridge Design Code in comparison to the AISI method. The following sections provide details regarding the design methods themselves.

2.0 AISI Method

The AISI Method is a working stress or allowable stress design method. The design approach is one in which forces and stresses are calculated and the results compared to factored (reduced) material section properties. A flowchart describing the AISI procedure is shown in *Figure 1*.

2.1 Design Limitations

In the AISI Method, minimum allowable depth of cover requirements are based on historical field observations. The method specifies a minimum allowable cover of 1/8 of the span for highway loads and 1/4 of the span for railway loads.

The minimum allowable cover requirement does not consider heavy construction loads. The amount of cover may therefore need to be increased if loads larger than standard highway design loads are anticipated. This decision must consider actual axle loads and resulting factors of safety. Designers often allow factors of safety below those used for design when loading conditions are temporary.

"Flexibility Factor" is the term used to define a maximum allowable flexibility (minimum required stiffness) requirement for construction. If the allowable flexibility factor is exceeded, it does not mean that a structure cannot be built with that wall thickness; it means that special measures may need to be taken to monitor the structure shape and control deflections. When the flexibility factor is exceeded for all possible steel gauges, structures are categorized as 'long-span'. If this is the case, other design methods must be used.

2.2 Design Method

2.2.1 Thrust

The compressive thrust in the structure wall is calculated by multiplying the radial pressure acting on the wall by the radius of the wall. The radial pressure is obtained by combining the dead and live load pressures.

The dead load acting on the structure is calculated using a rectangular prism of soil above a horizontal plane located at the top of the pipe. The soil prism has a width equal to the span of the structure, and the dead load pressure is determined based on the unit weight of the backfill.

Live loads can be calculated as though the tire or axle loads are distributed through the cover, decreasing in intensity as the cover increases, to the top of the structure. A number of working stress design vehicles can be used, such as the AASHTO H-20 or HS-25, or the old CSA CS-600. Tables of live load pressures at various heights of cover are provided in the AISI handbook and other design method references, rather than a calculation method. The table values include impact as detailed in the AASHTO design code (up to an additional 20%, depending on the height of cover). Interpolation is used for heights of cover that do not appear in the tables.

2.2.2 Wall Strength in Compression

The AISI Method is based on the assumption that the structure wall will be subject to pure ring compression forces resulting from the axial thrust described above.

The ultimate compressive stress for a corrugation can be classified into three categories:

- Type 1 – Wall crushing or yielding
- Type 2 – A combination of wall yielding and buckling
- Type 3 – Wall buckling

The structure span and corrugation radius of gyration determine the ultimate compressive stress for a specific structure. Wall crushing is usually the dominant ultimate stress for small spans, but local wall buckling becomes dominant with increases in span.

The design procedure for this method requires that a radius of gyration be assumed for the initial calculations. The assumption of a radius of gyration does not introduce significant error into the calculations because it does not vary much (for a specific corrugation profile) as the wall thickness changes. The chosen radius of gyration can be checked once a wall thickness is determined.

A factor of safety of 2 is applied to the ultimate compressive stress to arrive at an allowable compressive stress.

2.2.3 Required Wall Area

The design thrust and the allowable compressive stress are used to calculate a minimum required wall area. Section property tables are consulted to determine a wall thickness that provides the required area. The tables also include the radius of gyration, moment of inertia, and ultimate seam strength for the wall thickness; properties that are used elsewhere in the calculations.

2.2.4 Construction Requirements

The flexibility factor is an empirical means of providing guidance regarding the ease of construction for a specific structure. The basic limit on the flexibility factor of structural plate corrugated steel structures is 0.114 mm/N. This value depends on the span of the structure and the stiffness (modulus of elasticity and moment of inertia) of the corrugation.

Table 1 shows calculated flexibility factors for various spans and wall thickness'. As the span increases, the flexibility factor requires that a thicker wall be used to ensure that construction proceeds as easily and quickly as possible. Structures having higher flexibility factors may be used if special features, such as wall bracing or cabling, thrust beams, and/or ribs are used.

Bracing and cabling are only used during construction until such time as the structure is encased in backfill. Long-span structures do not meet flexibility requirements and special features or designs are required.

2.2.5 Seam Strength

Ultimate seam strength values, for different corrugations and steel thickness', have been developed through testing. The calculated ring compression is compared to an allowable maximum ring compression (the ultimate longitudinal seam strength divided by a factor of safety of 2) to ensure that the structure has sufficient seam strength.

3.0 CHBDC

The Canadian Highway Bridge Design Code uses a limit states design philosophy. The design approach is one in which forces and stresses are calculated based on the influence of factored loads, with the results compared to factored (reduced) material section properties. Or, as described in the CHBDC, "Design shall be based on the consideration of limit states (those conditions beyond which the structure or component ceases to meet the criteria for which it was designed) in which, at the ultimate limit state, the factored resistance is required to exceed the total factored load effect." A flowchart describing the CHBDC process is presented in *Figure 2*.

3.1 Design Limitations

The CHBDC method (CAN/CSA-S6-00 Section 7.6) applies only to closed or open conduits with spans greater than or equal to 3 meters. This method was originally derived for a structural plate corrugation profile measuring 152 x 51 mm (pitch by depth). The Code has since been adapted for application to all corrugated steel profiles.

A minimum allowable depth of cover is specified in the Code, based on the shape of the structure and its effective span and rise. This minimum cover is intended to ensure that the design of the structure is governed primarily by thrust, to restrict bending moments due to live loads to levels which may be safely neglected in the design, and to address the possibility of a soil wedge upheaval resulting from unbalanced loading.

The minimum cover criteria were developed, as mentioned above, based on the 152 x 51 mm corrugation. Since that time, the industry has introduced much stiffer and stronger corrugations. Some structures are currently being designed and constructed using less than the code specified minimum allowable cover. The Code does state that shallower depths of cover may be acceptable if an approved method is used in the design of the structure.

3.2 Design Criteria

3.2.1 Thrust

The factored thrust in the structure wall is obtained by adding the thrust resulting from a factored dead load and the thrust resulting from a factored live load. The Code considers it sufficiently accurate to superimpose the separate load effects due to live and dead loads in this manner. The load factors are 1.25 for dead loads and 1.70 for live loads.

The dead load on the structure is determined by calculating the weight of the soil and pavement column directly over the structure. Two additional factors affect the calculation of thrust in the structure wall as a result of the dead load.

The first is the arching factor, A_f. This factor depends on the shape and size of the structure, as well as on the height of cover. The factor A_f always increases the calculated thrust. This suggests that soil arching over the structure will always exhibit negative arching (soil settlements increase the load on the structure) and that there is no possibility of positive soil arching (load being shed to the columns of soil on either side of the structure through shear in the soil).

The other important factor considered in the calculation of dead load thrust is an axial stiffness parameter, C_s, which is a function of soil modulus, the effective rise of the structure, and the modulus of elasticity and the area of the corrugated steel. This factor accounts for load being attracted to stiffness, so the thrust in the structure wall increases as the wall thickness increases.

Note that the design procedure for this method requires that a corrugation area be assumed for the initial dead load thrust calculation. This introduces a significant variable, rendering this design method a trial-and-error process.

The live load on the structure is determined by distributing individual wheel loads through the soil and pavement column to the top of the structure.

There are two standard live load vehicles defined in the CHBDC; the CL-625 truck and the CL-625-ONT truck. The CL-625 truck has two 125 kN axles loads spaced 1.2 m apart (center to center), while the CL-625-ONT truck has two 140 kN axle loads also spaced at 1.2 m. In both cases the wheel footprint measures 600 mm wide by 250 mm long. The CL-625-ONT truck is for use in the Province of Ontario.

The Code provides guidance for determining an equivalent uniformly distributed live load pressure at the top of the structure due to the dispersion of the unfactored live load. It indicates that one or more axles are to be positioned at the road surface above the structure symmetrically about the structure axis. However, the instructions in the OHBDC and in the CHBDC commentary clearly instruct that the two axles as described above be symmetrically positioned about the structure axis.

The wheel loads are then distributed through the fill to a horizontal plane at the top of the structure. The distribution is at a slope of one vertically to one horizontally in the traffic direction (perpendicular to the structure axis) and two vertically to one horizontally in the longitudinal direction (parallel to the structure axis). To determine the equivalent uniformly distributed live load pressure, the total wheel loads are uniformly distributed over the single rectangular area whose limits enclose the individual rectangular areas defined by the load distribution through the fill.

There are two additional factors that affect the calculation of unfactored live load thrust in the structure wall.

It is possible for more than one vehicle to be crossing over the structure at one time, so the calculation of the live load thrust includes a modification factor for multilane loading. The live load is governed by one vehicle for covers less than 1.35 m. For larger heights of cover, two vehicle loads govern. There are no cases where more than two trucks produce the governing load condition. The modification factor for two vehicles is 0.90 (only 90% of the equivalent uniformly distributed pressure is used).

The unfactored live load thrust is calculated based on the equivalent uniformly distributed pressure at the top of the structure. The length of the load distribution (perpendicular to the structure axis) is used to calculate the pressure. However, that length may be larger than the span of the structure, in which case the span of the structure is used in the thrust calculation instead.

An additional multiplier is used in the calculation of the factored thrust. The dynamic load allowance (DLA) is a factor that increases the live load to compensate for the dynamic impact of a vehicle moving across a structure. The dynamic load allowance varies linearly, based on the height of cover, from 0.40 at the surface (no cover) to 0.10 at 1.5 m of cover. For larger heights of cover the DLA is constant at 0.10. For a DLA of 0.25, for instance, the multiplier is 1.25.

The CHBDC also provides guidance for the consideration of seismic loads. Soil-steel structures must be designed for a seismic event having a 10% chance of being exceeded in 50 years. The additional thrust resulting from earthquake loading is obtained by multiplying the unfactored dead load thrust by the vertical component of the earthquake acceleration ratio. The ratio is taken as 2/3 of the horizontal ground acceleration ratio, which is the zonal acceleration ratio defined in the Code. For the calculation of factored thrust, the load factor for seismic loads is 1.00. The effects of live loads are not considered simultaneously with those of earthquake loads.

3.2.2 Wall Strength in Compression

Like other design methods, the Code's design procedure is based on the design of the structure being governed primarily by ring compression (thrust). Unlike other design methods, resistance to the thrust is calculated, sometimes differently, for individual parts of a structure.

Excessive thrust in the structure wall may cause wall crushing, elastic buckling or a combination of the two. For the calculation of the elastic buckling load, the structure wall is considered as having two zones; the lower zone in which the radial displacements of the wall are towards the soil, and the upper zone in which the radial displacements of the wall are away from the soil.

The ultimate compressive stress resulting can be calculated in one of two ways, depending on how the structure wall radius compares to an equivalent wall radius. In one case the equation relates to inelastic behavior, while in the other case the equation relates to elastic behavior.

The equivalent radius depends on many factors, including the corrugation radius of gyration and moment of inertia, the relative stiffness of the structure wall with respect to the adjacent soil, the modulus of elasticity and yield stress of the structure wall, the secant modulus of the soil stiffness, the height of cover, and the wall radii of the structure.

The ultimate compressive stress calculations use a large number of the variables that were used to determine the equivalent radius. Additionally, a factor is used to reduce the ultimate compressive stress to account for installations which include multiple structures.

The calculated ultimate compressive stress is factored by a material resistance factor of 0.8, the result of which is compared to the compressive stress at the ultimate limit state. The ULS compressive stress is determined by dividing the factored thrust by the corrugation area.

3.2.3 Strength Requirements During Construction

Construction loads, especially during backfilling against the sides of a structure and under shallow covers, will cause bending moments as well as axial thrusts to develop in the structure wall. To prevent permanent deformation from taking place, the Code specifies that the combined effects of bending moment and axial thrust shall not exceed the factored plastic moment capacity of the section at all stages of construction. This requirement replaces the flexibility factor check, specified in the other design methods including the OHBDC.

Designers are required to specify, on their plans, the maximum allowable axle load of construction equipment that can be used above the structure.

Parameters used in the calculation of the combined bending moment and axial thrust include: the unit weight of the backfill and thus an unfactored dead load thrust; the construction equipment axle load and thus the additional thrust in the wall resulting from the construction axle load; the area, moment of inertia, yield strength, modulus of elasticity, and plastic moment capacity of the corrugated wall; the effective rise and effective span for the structure; the secant modulus of soil stiffness; and a number of empirical factors based on finite element analyses.

The calculated compressive strength and plastic moment capacity are factored by 0.70, the resistance factor for the formation of a plastic hinge.

3.2.4 Seam Strength

Ultimate seam strength values have been determined through testing and are published in standards. A resistance factor of 0.67 is specified in the Code for connections. The total factored thrust shall not exceed the ultimate seam strength multiplied by this resistance factor.

4.0 Study Approach

Select representative structural plate corrugated steel shapes and sizes were designed using both the AISI and CHBDC design methods. As part of this study, a required wall thickness was determined for a number of heights of cover.

The governing design criteria, resulting in an increase in the wall thickness, is often different in the two methods. Wall strength in compression, seam strength, and constructability were considerations in both methods. Under the AISI design, flexibility factor was a consideration, and under the CHBDC design, the construction strength requirement was a consideration.

Limiting covers, wall thickness' and stress ratios were determined for each analyzed structure.

The stress ratio is the applied stress divided by the allowable stress. Both applied and allowable stresses are derived and compared for the respective methods. While the stress ratios for each method normally include safety factors, load factors and material resistance factors as appropriate to each method, it is also useful to compare the results using unfactored applied and allowable stresses. The ratio gives an indication of the percent utilization of the strength of a structure for each design method.

Height of cover limit charts were also developed to allow a comparison of maximum and minimum covers for a number of structural plate corrugated steel shapes and plate thickness'.

5.0 Factors Impacting Results

The live load design vehicle used for the CHBDC designs was the CL-625 truck having tandem axles weighting 125 kN each and spaced 1.2 meters apart (center-to-center). The vehicle used for the AISI designs was the CS-600 truck with a single axle of 180 kN. The 250 kN total load used for the CHBDC designs was significantly larger than the 180 kN load used for the AISI designs. This has a greater impact on the results for low cover designs, and the influence it has on higher cover designs decreases as the cover increases.

The dynamic load allowance used in the CHBDC designs has a greater influence on the total live load than the impact factor used in the AISI designs. The CHBDC dynamic load allowance results in a 10 to 28 percent increase in the live load, as compared to the AISI impact factor which results in a 0 to 10 percent increase. The CHBDC factor reduces to 10% for covers exceeding 1.5 m, while the AISI factor is not applicable for covers exceeding 0.89 m. As with the effect of the different live loads, this only impacts the results for low cover designs, and the influence it has on higher cover designs decreases as the cover increases.

The calculation of the dead load acting on a structure, as defined by the AISI method, is based on the rectangular prism of soil above a horizontal plane located at the crown or top of the structure. The CHBDC method considers the additional soil segments beneath the plane and above the structure on either side of the structure. This increases the dead load used in CHBDC designs.

The CHBDC method also uses an arching factor to account for negative arching in the backfill. In all cases, this will increase the dead load in the designs. The AISI method also has an arching factor which allows a designer to account for positive arching when the cover on a structure is larger than the span of the structure; this factor was not used in this design comparison study.

The CHBDC method also uses an axial stiffness factor for determining the dead load on the structure, to account for stiffer structures attracting more load. The application of the factor results in a very slight reduction in the calculated dead load, as compared to if were not applied at all. Even though the factor reduces the dead load, it must be stressed that the factor is smaller for stiffer structures which results in larger dead loads for those structures.

In addition, the CHBDC method further increases the total thrust by factoring the dead and live load thrusts by 1.25 and 1.70 respectively. The AISI method does not factor loads as it is a working stress design method. While unfactored loads can be compared, this makes a meaningful direct comparison difficult.

Wall strength calculations in the two design methods are significantly different in approach and complexity. The CHBDC method also applies a material resistance factor of 0.8 to wall strength, while the AISI method applies a factor of 0.5 (divides the wall strength by a safety factor of 2).

The seam strength calculations in the two design methods are similar in approach. The CHBDC method applies a material resistance factor of 0.67 to ultimate seam strength, while the AISI method applies a factor of 0.5 (divides the ultimate seam strength by a safety factor of 2).

Table 2 is a summary of the factors that affect designs using the two methods.

6.0 Results

To illustrate how the two methods compare, a direct comparison of results can be made by investigating designs for identical installation conditions, but it can also be accomplished by removing the method specific factors that influence the designs.

Table 3 lists design results using the two methods for a number of different shapes having a variety of spans, 1.5 m of cover and a 3.0 mm wall thickness. Compressive wall strength was the only consideration for this table. While some of the designs would require an increase in wall thickness due to seam strength or constructability considerations, their results are presented to illustrate the applied and allowable loading differences between the two design methods.

The unfactored thrusts are higher using the CHBDC method. This trend is shown by comparing the CHBDC "T" and AISI "C" in the table.

The table also includes unfactored compressive stresses ("ρ" in the table) and stress ratios ("ρ/f_b" in the table), as well as factored stress ratios ("s_f/s_{all}" in the table). The unfactored applied stresses are higher using the CHBDC method, while the unfactored allowable stresses are higher using the AISI method. The unfactored stress ratio gives an indication of the strength utilization of a structure. Considering the structures shown in the table, the unfactored stress ratios are higher when using the CHBDC design method for strength in compression. The factored stress ratio also gives an indication of whether a design is acceptable. The factored stress ratios are usually higher when using the CHBDC design method, but there are designs of some larger structures where the AISI ratios are higher. However, in those cases, neither design would be acceptable based on compressive strength.

Figures 3 through 6 show the results of the analyses done on round, horizontal ellipse, low profile arch and high profile arch structures.

The results for round structures, summarized in *Figure 3*, show that the CHBDC method is in all cases conservative in comparison to the AISI method. The difference between the maximum allowable covers for the two methods decreases as the size of the structure increases, to the point where the results are essentially the same at the size where the allowable flexibility factor is reached. This applies to all except the lightest wall thickness.

The results for horizontal ellipses, summarized in *Figure 4*, show that the two methods produce very similar results. A relatively sharp reduction in the maximum allowable cover, starting around a 4 m span, is attributable to changes in the shape that occur in the 3.8 to 4.2 m range. For those structures, the length of the side plate changes which impacts the relationship of D_h and D_v, and which ultimately impacts the required wall thickness. The results from the two design methods are so close that the method resulting in a greater maximum allowable cover changes depending on wall thickness and span.

The results for low profile arches, summarized in *Figure 5*, show the same general trend as the horizontal ellipses. The AISI method produces greater maximum allowable covers for spans less than about 6.5 m, while the CHBDC produces greater covers for larger spans. The fluctuations in CHBDC allowable covers for spans between 4.0 and 6.5 m is related to the shape of the low profile arches. This family of shapes has increases in rise accompanied by small increases in span when the length of the side plates is increased, impacting the design as described above. It is also noted that the CHBDC minimum allowable cover is greater in all cases.

The results for high profile arches, summarized in *Figure 6*, show the same general trend and shape effects as horizontal ellipses and low profile arches. However, the maximum allowable covers determined by the two design methods are much closer to being the same. The CHBDC minimum allowable cover is greater in all cases.

Ultimate wall stresses considered by the AISI method are generally described as falling into a yield zone, a transition zone or a buckling zone. The ultimate stress for structures with short spans of less than 5 meters is usually in the yield zone. In this zone, high covers will result in the structure wall stresses reaching the yield strength. The ultimate stress for structures with 5 to 8.5 meter spans is usually in the transitional zone. In this zone, the structure will experience a combination of yielding and buckling depending on the height of cover. The ultimate stress for structures with spans exceeding 8.5 m is usually in the buckling zone. The cover at which this occurs varies by structure because the span of the structure is the major governing factor.

There are two levels of ultimate wall stress defined in the CHBDC method; inelastic and elastic. The governing stress for a specific part of a structure depends on the equivalent radius of the structure wall.

Most structure designs are governed by inelastic stresses, where the wall radius is smaller than the equivalent radius. Whether the structure behaves elastically or inelastically, failure can occur through buckling. Inelastic buckling is considered to start when the ultimate stress is equal to half the yield stress.

Structures which are governed by stresses in the elastic zone are typically large, flat structures, with low covers. The ultimate stress in the elastic zone is independent of the yield strength of the corrugated steel plate. Buckling will occur in the elastic zone due to the radial movements of the upper and lower zones of the structure, depending on the height of cover and the structure span.

The flexibility factor requirement in the AISI method governs in most cases of structures with spans exceeding 5 meters, regardless of the height of cover. The counterpart to the flexibility factor in the CHBDC is the construction load check. The CHBDC method uses the construction load check to investigate plastic hinge formation and to ensure that the structure has adequate strength under low covers and high construction loads.

7.0 Summary and Conclusions

Differences between the AISI and the CHBDC design methods are difficult to compare. The AISI method is simple and has been used successfully for many years. The CHBDC adds more steps to the design calculations, but in doing so it attempts to address very specific design issues.

There is no clear answer as to which of the two methods is more conservative on a general scale. There are many factors that affect the outcome of a design, especially when using the CHBDC method.

Table 4 summarizes the behavior of structural plate corrugated steel structures based on the results obtained from this study.

In situations of high cover (or large live loads under shallow cover), the CHBDC method appears to yield more conservative results. The AISI method yields more conservative results for larger span structures, but only up to a limit dictated by the flexibility factor.

8.0 References

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Table 1: Flexibility Factors for Various Spans and Wall Thickness'

	Wall Thickness (mm)				
Span (mm)	3	4	5	6	7
3000	0.044	0.032	0.025	0.020	0.017
4000	0.078	0.056	0.044	0.036	0.031
5000	0.121	0.087	0.068	0.056	0.048
6000	0.173	0.126	0.098	0.080	0.068
7000	0.235	0.170	0.133	0.109	0.093
8000	0.306	0.222	0.174	0.142	0.121
9000	0.387	0.281	0.219	0.180	0.153
10000	0.478	0.346	0.270	0.222	0.189
11000	0.577	0.419	0.327	0.268	0.228

Note: shading indicates span – wall thickness combinations that do not meet flexibility requirement

Table 2: Design Factors

Description	**CHBDC**	**AISI**
Axle Load	125 kN	180 kN
Number of Axles	2	1
Factor Used to Calculate Live Load Pressure	DLA	Note a
Coefficients Used to Calculate Dead Load Thrust	A_f, C_s	
Live Load Factor Used to Calculate Total Thrust	1.70	
Dead Load Factor Used to Calculate Total Thrust	1.25	
Allowable Stress Factor of Safety	0.8	0.5
Construction Loads / Flexibility Factor	Note b	D^2/EI
Seam Strength Factor of Safety	0.67	0.5

Note: a - the AISI live load pressures are obtained from tables that include impact
b - the CHBDC construction load calculations used a 160 kN axle and 0.6 m of cover

Table 3: Structural Capacity Comparisons

		CHBDC [a]					AISI [a]				
Shape[f]	**Span** (mm)	**T [b]** (kN/m)	**ρ** (MPa)	**f_b [c]** (MPa)	**(ρ/f_b)[d]**	**s_f/s_{all}[e]**	**C** (kN/m)	**ρ** (MPa)	**f_b [c]** (MPa)	**(ρ/f_b)[d]**	**s_f/s_{all}[e]**
34N HE	3140	81.4	23.1	196.6	0.117	0.220	69.8	19.8	230.0	0.086	0.172
44N HE	4141	106.6	30.3	181.0	0.167	0.220	95.6	27.2	230.0	0.118	0.236
60N HE	5310	139.5	39.6	165.1	0.240	0.460	127.5	36.2	219.4	0.165	0.330
68N HE	6210	168.8	47.9	157.5	0.304	0.520	142.3	40.4	204.6	0.197	0.395
40N RD	3050	82.5	23.4	201.3	0.116	0.230	70.6	20.0	230.0	0.087	0.174
62N RD	4761	128.0	36.3	187.8	0.194	0.400	109.4	31.0	230.0	0.135	0.270
64N RD	4920	131.7	37.4	186.4	0.201	0.410	112.9	32.0	230.0	0.139	0.279
66N RD	5070	131.7	37.4	185.1	0.202	0.430	116.4	33.1	229.4	0.144	0.288
76N RD	5850	155.9	44.3	178.4	0.248	0.510	134.1	38.1	213.0	0.179	0.357
78N RD	6000	160.1	45.4	177.3	0.256	0.530	137.6	39.1	209.5	0.186	0.373
86N RD	6625	177.2	50.3	171.3	0.294	0.600	151.9	43.1	194.4	0.222	0.444
96N RD	7400	224.8	63.8	164.0	0.389	0.710	168.3	47.8	173.4	0.276	0.551
18N SRA	3050	88.8	25.2	201.0	0.125	0.226	70.5	20.0	230.0	0.087	0.174
30N SRA	5180	137.5	39.1	183.6	0.213	0.435	118.6	33.7	227.5	0.148	0.296
39N SRA	6100	162.7	46.2	176.1	0.262	0.535	139.8	39.7	207.2	0.192	0.383
21N LPA	3217	90.5	25.7	195.6	0.131	0.231	74.2	21.1	230.0	0.092	0.183
37N LPA	5612	144.5	41.0	171.6	0.239	0.462	128.6	36.5	218.3	0.167	0.335
61N LPA	10490	273.7	77.7	60.0	1.295	1.404	238.4	67.7	92.8	0.730	1.459
23N HPA	3018	85.6	24.3	195.6	0.124	0.207	69.8	19.8	230.0	0.086	0.172
42N HPA	5637	137.5	39.1	168.4	0.232	0.453	124.6	35.4	222.1	0.159	0.319
52N HPA	7670	189.0	53.7	133.3	0.403	0.683	175.6	49.9	165.4	0.301	0.603
67N HPA	9450	236.4	67.1	89.4	0.751	1.047	215.2	61.1	114.3	0.534	1.069
87N HPA	11350	310.8	88.2	56.5	1.562	1.643	258.4	73.4	79.2	0.926	1.852
44N VE	3200	94.3	26.8	202.3	0.132	0.254	74.1	21.0	230.0	0.091	0.183
76N VE	5540	151.3	43.0	183.6	0.234	0.515	127.0	36.1	219.8	0.164	0.328
84N VE	6120	168.1	47.7	179.0	0.267	0.591	140.6	39.9	206.4	0.193	0.387

Notes: a – calculations are for 1.5 m of cover using 3.0 mm plate
b – unfactored thrust
c – unfactored allowable stress
d – unfactored stress ratio
e – factored stress ratio, based on results for specific design method
f – ##N is an indication of the periphery or total circumferential plate length of a structure, where N is 9.6 in. or 244 mm. The shape types include horizontal ellipse (HE), round (RD), single radius arch (SRA), low profile arch (LPA), high profile arch (HPA), and vertical ellipse (VE).

Table 4: Design Result Summary

	Low Cover (1 - 5 m)	*Medium Cover (5 - 15 m)*	*High Cover (15 - 25 m)*
Short Span (3050 - 4761 mm)	Both methods yield similar results	CHBDC is more conservative	Both methods yield same results for short spans - CHBDC becomes more conservative at larger spans
Medium Span (4761 - 5070 mm)	AISI is more conservative under minimum cover	CHBDC is more conservative	CHBDC is more conservative (maximum cover is 20 m) – AISI works for higher covers
Large Span (5070 - 7400 mm)	AISI is more conservative due to flexibility factor requirements	CHBDC is more conservative, AISI catches up towards higher spans	CHBDC is more conservative (maximum cover is 16 m) – AISI works for covers up to 20 m

Figure 1 – AISI Design Methodology

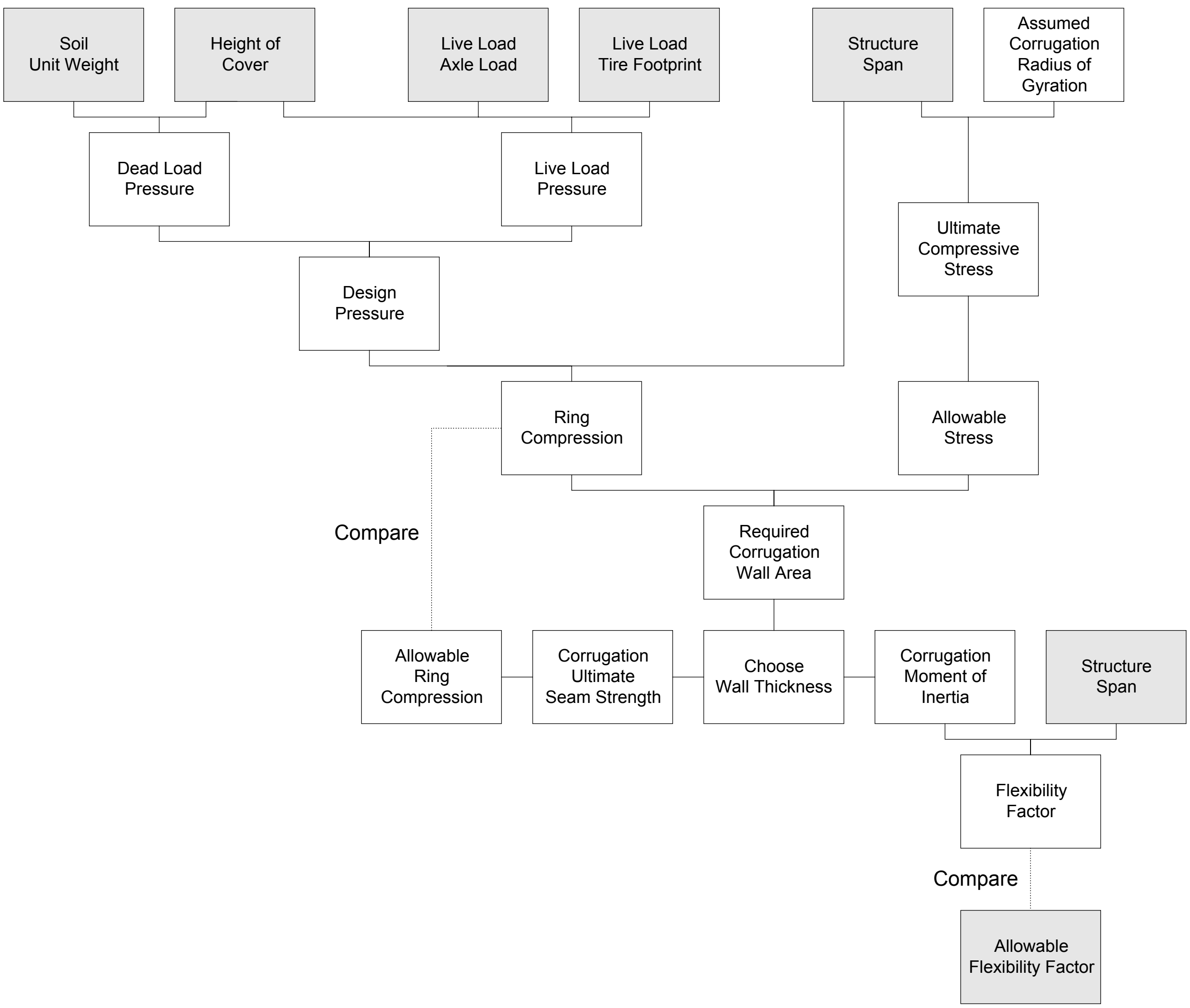

Figure 2 – CHBDC Design Methodology

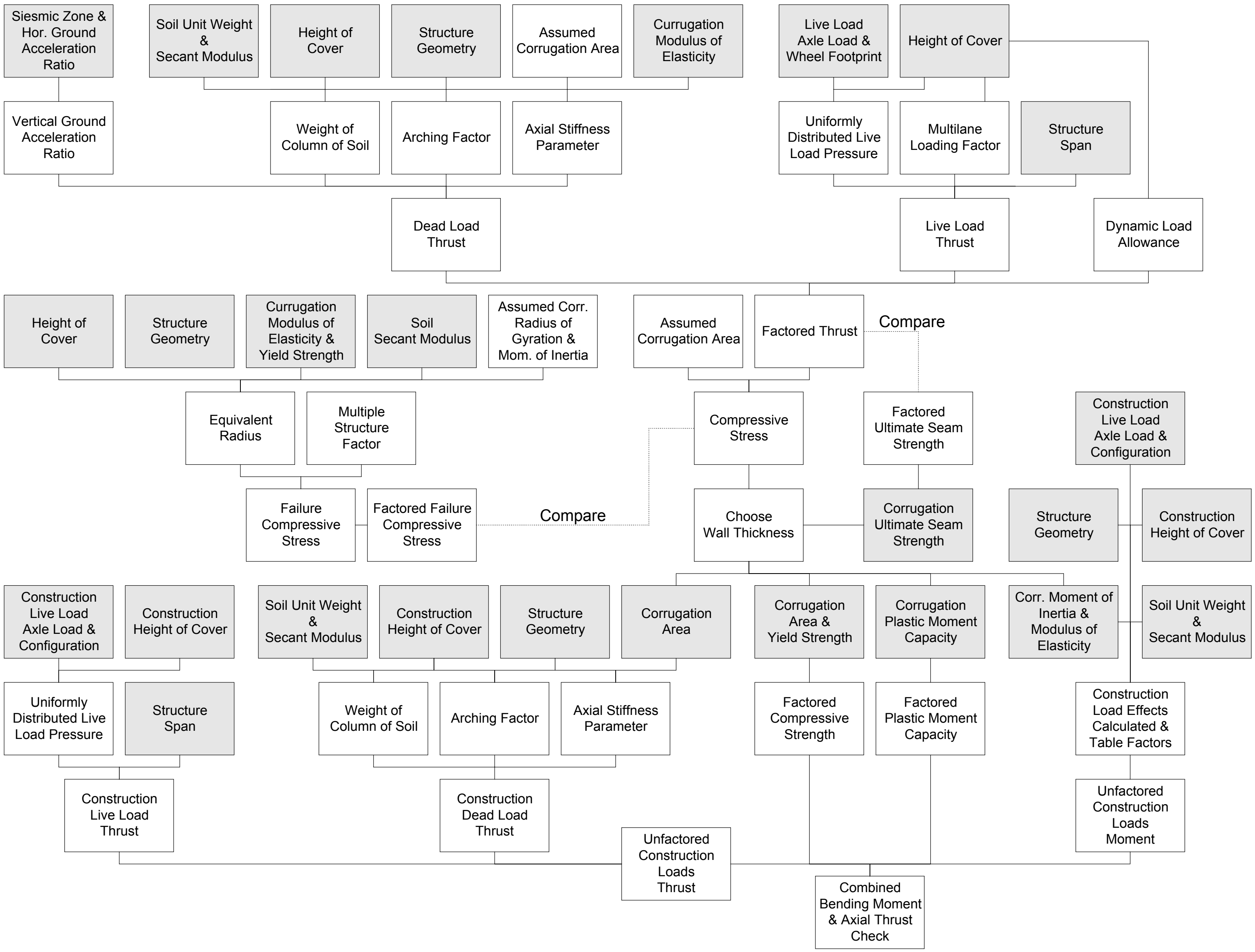

Figure 3 – Round Maximum Cover Results

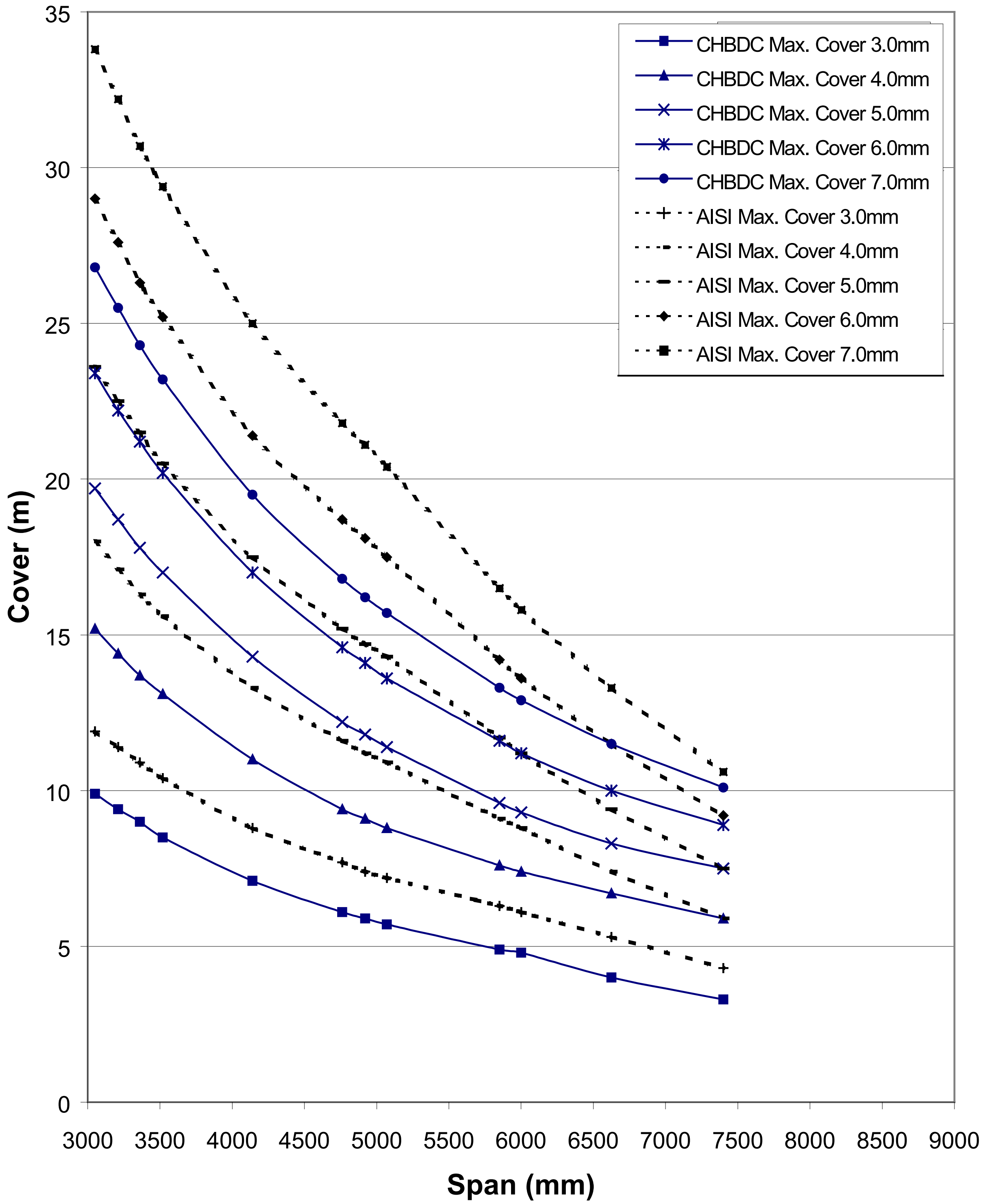

Figure 4 – Horizontal Ellipse Maximum Cover Results

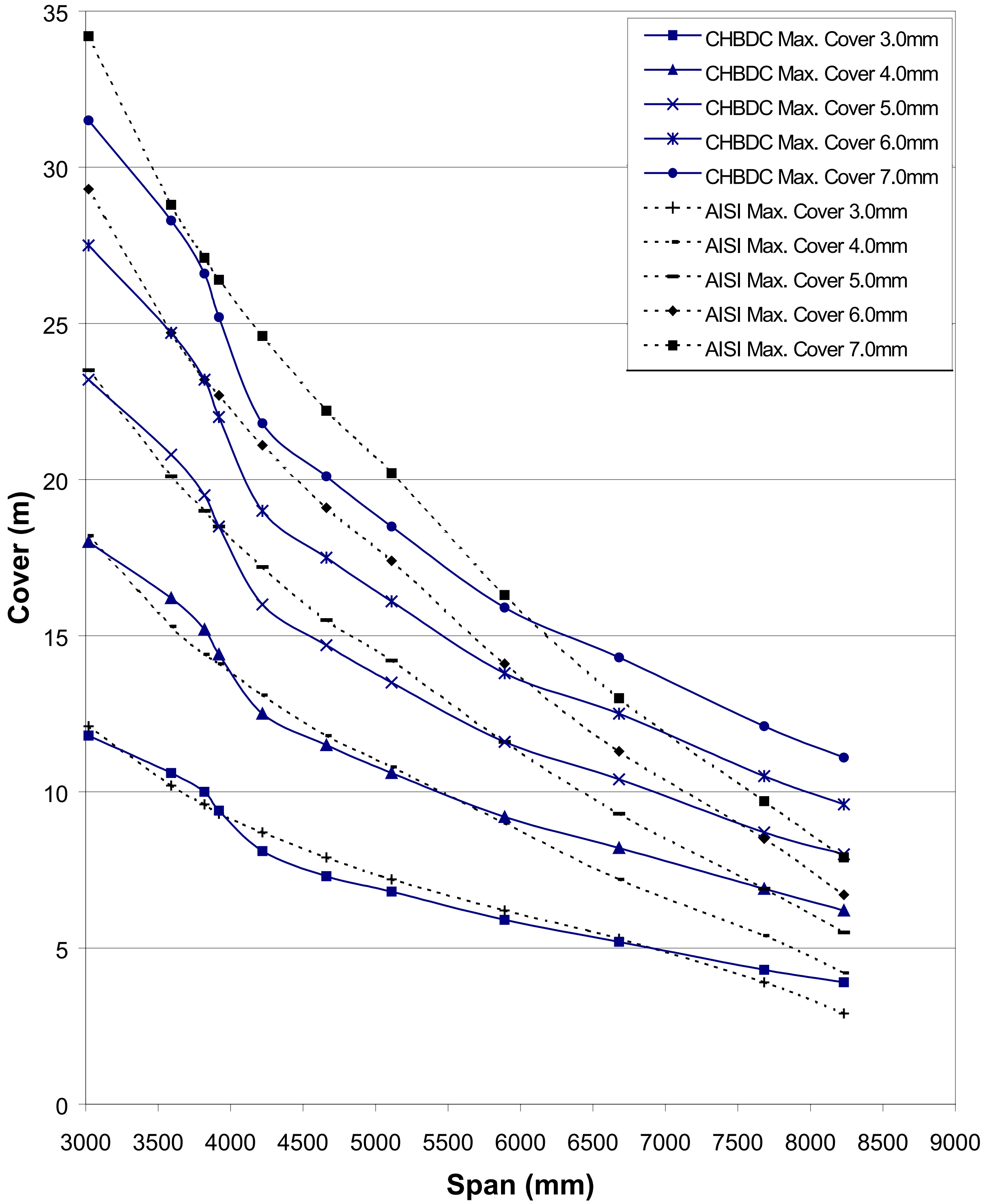

Figure 5 – Low Profile Arch Maximum Cover Results

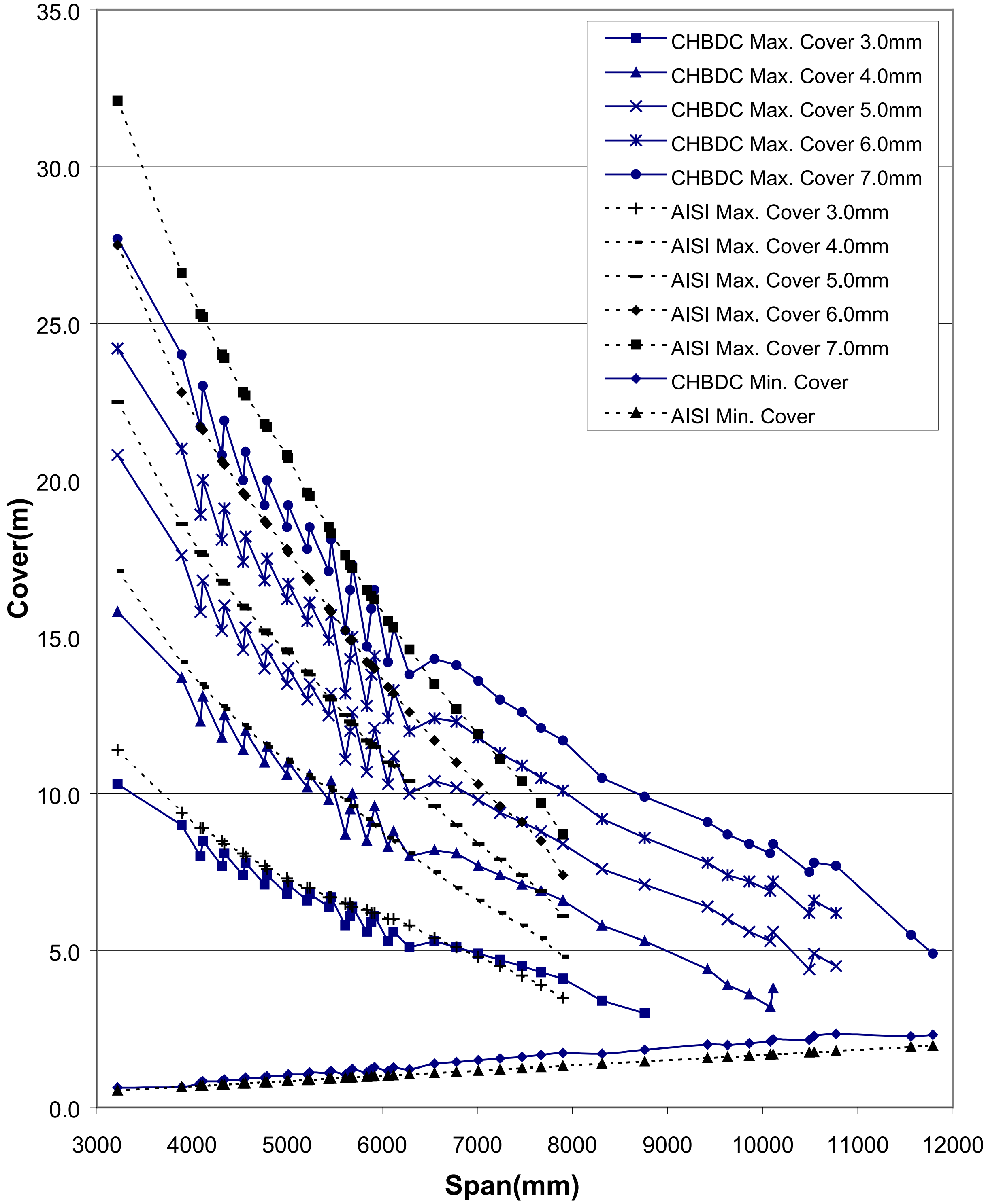

Figure 6 – High Profile Arch Maximum Cover Results