Edmonton LRT – Diseño de un viaducto de tren ligero de 1.3km en Canadá

Edmonton LRT - Design of 1.3km of Light Rail Viaduct in Canada

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ABSTRACT

Edmonton Valley Line, LRT Project is located in Edmonton, Alberta, Canada. As part of Phase 1 of the project, Davies Elevated Guideway comprises 32no. spans of 35-46m post tensioned girders connecting Davies Elevated Station with the adjacent at grade sections. The guideway contains varying cross sections to meet the functional requirements and transitioning deck from double to single-track girders to facilitate bifurcation of tracks at Davies Station. In addition, strategic positioning of piers to avoid major utilities and existing highways resulted in a complex geometry. This paper focuses on the innovative approach to creating parametric analysis and 3D BIM models to accommodate changing alignment as the design developed.

RESUMEN

La línea de ferrocarril ligero Valle de Edmonton en Alberta, Canadá, que es parte de la fase 1 de este Proyecto, incluye el viaducto elevado Davies, que consta de 32 vanos isostáticos con luces variables entre 35 y 46 metros. Las vigas son secciones U postesadas de una o dos vías según la geometría del viaducto, que se bifurca para acoger la estación de Davies a mitad de recorrido del viaducto. Otro parámetro crítico del diseño fue la posición de las pilas, gobernada por los servicios y viales existentes. Esta ponencia presta especial atención al diseño paramétrico y la implementación BIM en conjunción con el trazado de la via.

PALABRAS CLAVE: LRT, post tensioned, rail-structure interaction, BIM, Automation, constructability, MIDAS

KEYWORDS: LRT, postesado, interacción via estructura, BIM, calculo automático, constructibilidad, MIDAS

1. Introduction & Project Background

Edmonton Valley Line Light Rail is a proposed 27km, low floor urban line running southeast to west, crossing through downtown Edmonton, Canada. Phase 1, due to be completed in 2020, comprises approximately 13km of light rapid transit (LRT) including 12 stations. Arup is currently operating as lead designer as part of the design consortium for the Design, Build, Finance, Maintain and Operate (DBFMO) contract for construction of Phase 1. Key features of the project include 500m of tunnel, a major cable-stayed bridge crossing, approximately 2km of elevated guideway, elevated and at-grade stations incorporating park & ride facilities and an operations and maintenance facility.

As lead designer delivering the detailed design for the construction joint venture (CJV) comprising Bechtel, Ellisdon and Bombardier, Arup was responsible for Civil Structures, Buildings, MEP, Rail, Tunnelling, Traffic, Geotechnical, Civil, Environmental and Acoustic Engineering Services as well as Project Management and Utilities Coordination.

Arup's Ireland Offices were responsible for the delivery of 1.3km of elevated guideway and elevated station at Davies Road providing Project Management, Rail, Civil Structures, Buildings and MEP services. Arup Dublin was also responsible for delivery of the rail and track form design for the entire 13km line including vertical and horizontal alignment definition.

The elevated guideway comprises of 32no. simply supported spans of 35-46m post tensioned U-shaped trough form girders supported on diamond shaped piers.

Davies Station is a 90m long elevated station with central platform, architectural curved timber roof, vertical lift and escalator passenger transfer systems and integrated passenger information systems.

This paper discusses the design and construction of the elevated guideway with a particular focus on the innovative approach to automation of the design, 3D modelling, space-proofing and clash detection.

2. Superstructure Form

The elevated guideway utilises a slender cast in-situ post-tensioned concrete U-shaped trough form, 11m wide and 2.5m deep to carry the low floor light rail carriages. The guideway starts at the 83rd Street Ramp where the first 24 spans approach the Davies Station with a 155 m radius curve to the left, and a 115 m radius curve to the right, before splitting into two single tracks before Davies Station. After exiting Davies Station in two single tracks, it merges into a single girder at the same time making a 135 m radius right curve and approaching the 75th Street Ramp descending to street level.

All guideway spans are simply supported, with a typical span length of approximately 35 meters. The longest span is a 46.5-meter single girder with a 135 m radius right curve. The superstructure is supported on pot bearings in all locations. Each girder contains varying height concrete rail plinths to accommodate the track superelevation and to ensure that passenger sight lines are above the trough girder parapets.

Each girder comprises 4 to 12 no. bottom tendons in the U-shaped trough and 1 to 3 no. draped tendons within the webs depending on the curvature of the span. The girders are designed and constructed as simply supported single spans cast off-line in a temporary precast facility set up on site. The girders are installed using SPMT transportation with jacking at 6m from the ends of the spans.

The guideway comprises the following superstructure forms:

1- Single span double track girders;
2- Single span varying width double track girders with width varying to accommodate bifurcation of the track and split to 2 no. single track girders
3- Single span single track girders to facilitate the central platform station

3. Substructure Form

The elevated viaduct substructure form generally comprises reinforced concrete piers with flaring diamond shaped pier heads and double arms tied together by a horizontal cross head supporting the viaduct bearings. All piers were constructed in-situ with a permanently cast in tremie pipe to facilitate a two-stage pour.

One of the complexities of the substructure solution was the support of the bifurcating track each side of the station and the transition of the superstructure from a varying width double track girder to 2 no. single track girders. Options such as hammered piers as shown in Figure 3 below and a double pier support as shown in Figure 4 below were considered.

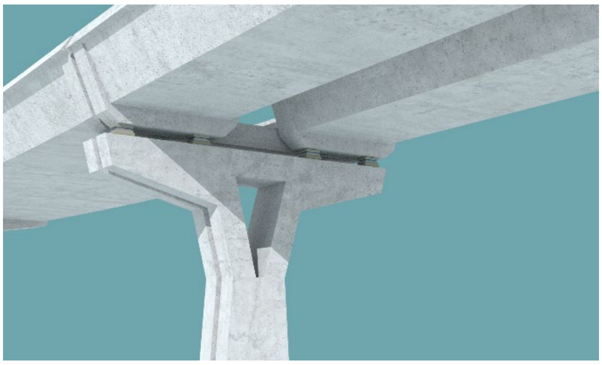

Figure 3. Concept development of hammer head pier at bifurcating tracks

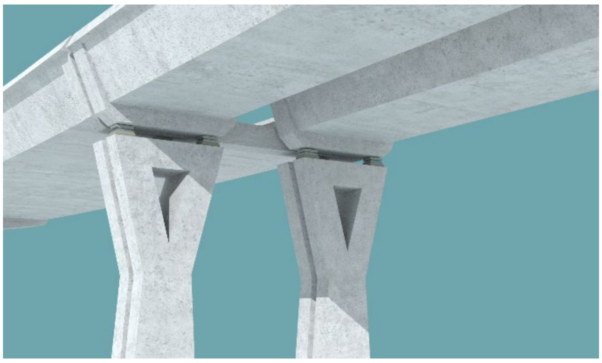

Figure 4. Concept development of double pier at bifurcating tracks

The double pier support was chosen to be taken forward to detailed design with a single diaphragm spanning between piers to support the varying width double track girder.

Longitudinally, the viaduct uses an alternating pattern of fixed bearings and expansion bearings, so that only every other pier has a longitudinal fixity with the superstructure. Transversely, the superstructure is fixed at each pier location.

4. Foundation Details

Depending on the location, piers are either supported on drilled dual pile foundations or single drilled piles referred to as mono shafts. The 2.5m diameter mono shafts do not require a pile cap and are connected to the pier via a connector cage detail, see Figure 5. The connector cage had to be designed to take into account pile construction tolerances to allow flexibility in positioning during construction.

Figure 5. **2.5m dia. drilled mono shaft to pier connection**

The mono shaft piles needed to be large enough to resist the lateral loading due to horizontal alignment curvature, train braking and hunting loads as well as wind loading on the train envelope. The vertical load on the piles were resisted solely by skin friction ignoring end bearing. This was due to the risks of relying on end bearing of a single pile without potential for load distribution between adjacent piles.

The 1.8m diameter drilled dual pile foundations on pile caps were utilised in locations where existing utilities such as gas and water mains were left in position with the pile cap designed to span over the utility. Dual drilled foundations were also chosen on sections of the track with tight radius bends to allow for push-pull resistance to lateral loads caused by radial track structure interaction loads.

5. Functional Cross Section

The primary aspects of bridge space-proofing include the Light Rail Vehicle (LRV) envelopes, the Overhead Catenary Structure (OCS), the egress envelope and walkway, the direct fixation trackwork and slab, the bridge drainage, and all of the relevant electrical systems.

The Davies functional cross section components are shown in Figure 6. Both the Northbound and Southbound LRT tracks are accommodated on a single through girder structure. An OCS pole and an egress walkway are provided between the tracks. The Track Clearance Envelope (TCE), along with egress and OCS pole are critical in determining the girder width and track spacing. Systems and utilities conduits are routed beneath the service walkway; this both conceals the duct banks from view and provides mechanical protection.

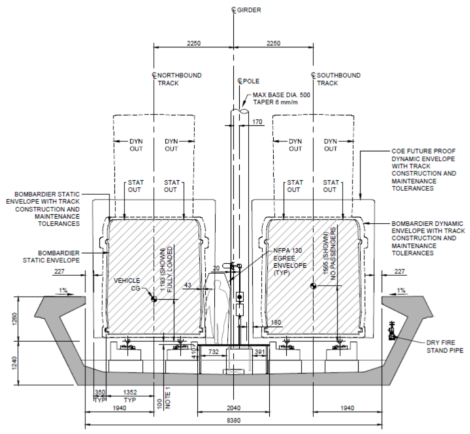

Figure 6. **Guideway functional cross section**

The LRV envelopes were established to abide by TCRP 155 and in conjunction with elements of the TCE, however, due to the variation in Vehicle Running Clearance (RC), to different structures, the methodology in creating the LRV's slightly differs to that of the TCRP 155's in creating the TCE. TCRP 155 states the TCE is defined as the maximum extent occupied by the rail vehicle, and the Structure Gauge (SG), which accounts for additional tolerances and clearances for wayside structures and systems.
In order to determine the TCE, the Vehicle Dynamic Envelope (VDE's) were established to take into account the track curvature and then applying the trackwork construction and

maintenance tolerances before the cant (superelevation) effects were applied.

Generally, the method for calculating the TCE is defined in accordance with TCRP 155 as shown below.

$$TCE = VDE + TT + C\&S + RC$$

where:

TCE = Track clearance envelope
VDE = Vehicle dynamic envelope width
TT = Trackwork construction and maintenance tolerances
C&S = Vehicle curve and Cant (superelevation) effects
RC = Vehicle running clearance

6. Parametric Analysis Modelling

The analysis of the foundations, substructure and superstructure was carried out in a global model using MIDAS Civil. Due to the risk of alterations to the alignment over the course of the design development and the subsequent loss of time, the global analysis model was set up using a parametric workflow between the track alignment (Civil 3D), Excel Visual Basic for Applications code (VBA) and Midas Civil.

The scale of the structure and complex geometry meant that generating models required an innovative approach. The challenge was to create the primary global analysis model and secondary local analysis models that could easily be updated and tracked to accommodate changing alignment.

Control points from the alignment file created in Civil 3D by track engineers were mapped through modules of VBA code contained within an Excel spreadsheet. The VBA code then generated the Midas Civil analysis model that could be updated with every alignment change.

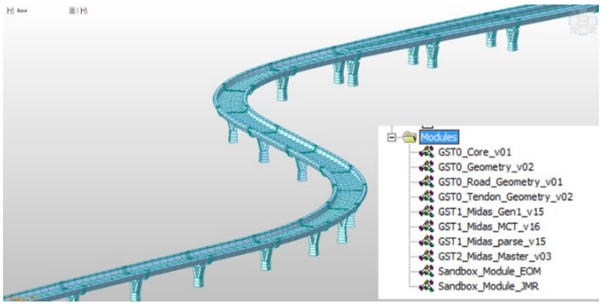

Figure 7. Midas Civil analysis model through VBA

A family of VBA modules, operating in a hierarchy, were set up in order to pre-process all the information required to create the analysis model. The VBA modular architecture consisted of the following:

- GST0: module containing the core subroutines used for basic functionalities, e.g.: string manipulation, target of cells/tabs, extract/write information from spreadsheet. These subroutines are independent of spreadsheet and analysis software used.

- GST1: module containing the basic functionalities dependent on the contents of spreadsheet and the analysis software used (Midas). Included the crucial parser module.

- GST2: higher level of nesting. It was specifically linked to the spreadsheet and serves as the nexus that links together all the previous modules to generate the final product: a text file containing instructions for the analysis software, in this case Midas Civil.

The generated file was a .MCT text file that could be read into Midas to create the full model. In total, 215190 lines of MCT script code were generated by the tool analysing 860 load cases and allowing global analysis models, pile models and track structure interaction models all to be generated parametrically from the same input files. The result was a robust and efficient virtual cycle from input to analysis to output in a structured approach as shown in Figure 7.

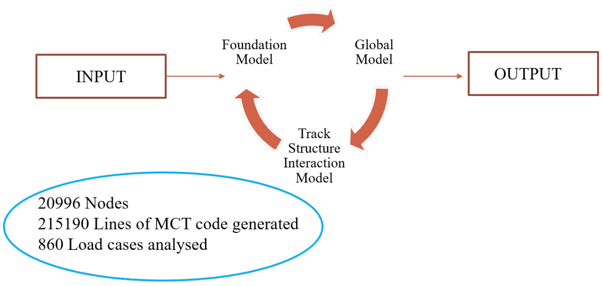

Figure 8. Virtual Analysis Cycle

The Guideway superstructure was modelled as two symmetric half sections containing 1-dimensional beam elements. The longitudinal half sections were connected via 1-dimensional cross beams representing the transverse ribs elements as shown in Figure 9.

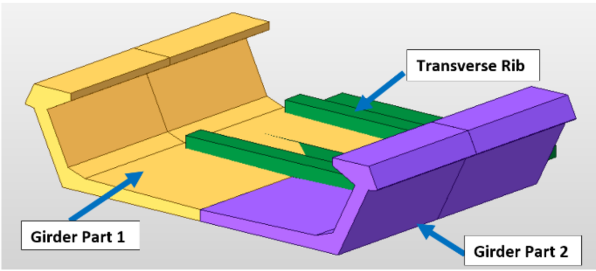

Figure 9. Section through girder showing half section and transverse ribs

Local transverse analysis of the superstructure was undertaken in Midas Civil using a combination of plate and beam elements to capture transverse bending and shear effects. Plate elements were used to model the bottom slab, webs and both transverse and longitudinal ribs, and beam elements were used to model the connection between the slab and webs.

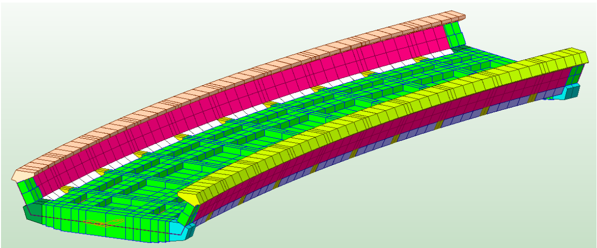

Figure 10. Transverse analysis model of a typical span

7. 3D BIM Modelling

A significant challenge for infrastructure projects is the modelling of complex geometry in linear alignments. In the case of Edmonton LRT the complexity in the geometry came from the varying radius curvature comprising clothoid curves and super elevation which proved quite difficult to model using the exiting 3D platforms.

Most software vendors are adapting quickly to address these challenges, however tools maturity for infrastructure projects still remains lower than that of buildings. As specialist disciplines find the best software to meet their individual needs the challenge still lies in the collective search for efficient interoperability between software used by each specialist discipline within often large multidisciplinary infrastructure projects.

The essence of successful BIM implementation is to complete the virtual circle through the design phases from concept to the operations and maintenance stages with minimal amount of information lost, duplicated or having to be recreated. This applies to all aspects of the design process, from setting out the spatial geometry, details, analysis models, costing and design and construction schedules. Figure 11 shows a robust virtual cycle containing the common data environment (CDE) at its core with the flow of information from geometry definition, 3D model development, design analysis, fabrication/supplier data sheets and as-built information in an unbroken cycle.

Figure 11. **BIM Virtual Cycle**

The choice of modelling tools on Edmonton LRT was based on the need to ensure easy transfer of information, interoperability between the disciplines, flexibility to easily accommodate change and the ability to feed into the analysis that was being run in tandem. To avoid being restrictive on which software we could use to develop alignments, structural models and analysis models, we looked to develop tools to allow the easy transfer of information between the specialist models.

The alignment, containing clothoid spiral curvature to satisfy track alignment, was developed using Autodesk Civil 3D with Autodesk Revit chosen as the modelling tool for the elevated guideway, station structure, architecture and MEP. To allow generation of the elevated guideway, 3D model Subassembly Composer was used in Civil 3D to generate the bridge element. This solid object was then swept through the alignment path before being transferred to Revit as a solid object.

A drawback with this approach was that the bridge deck structure contained within Revit was a solid object and could not be altered parametrically. Unlike pier and foundation elements which were modelled using families within Revit, any amendments to the deck geometry had to be done manually. In addition to this, Revit's inability to produced developed elevations along curved alignments meant that elevation drawings had to be drawn in 2D with other drawings cut directly from the Revit model.

The intention on this project was to create a dynamic link between the early stage inputs and the 3D modelling and design software. On subsequent projects, we have adopted parametric programming tools such as Dynamo and Grasshopper to create a dynamic and fully parametric link between the early stage inputs and the detailed design stages. Figure 12 illustrates how scripting tools such as Dynamo and Grasshopper can be used to ensure the first steps of the BIM virtual cycle remains unbroken.

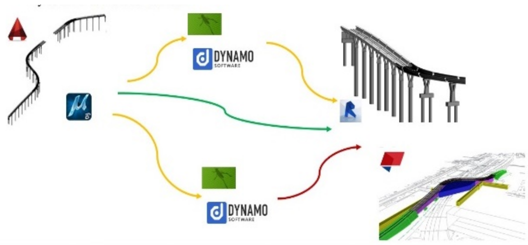

Figure 12. **Dynamic link between design phases**

With the introduction of open-source parametric modelling/visual programming tools, a robust workflow can be set up to ensure interoperability between different software packages through the various phases of design development.

One of the major benefits of BIM modelling on Edmonton LRT was 3D clash detection during the design phase. Carrying out clash detection in Navisworks by federating Guideway models in Revit with 3D utilities drawings in Civil 3D, the design team were able to evaluate the impact of the alignment on the existing utilities and coordinate utility relocation early in the design process. Figures 13 and 14 illustrate the utility clash detection carried out in Navisworks.

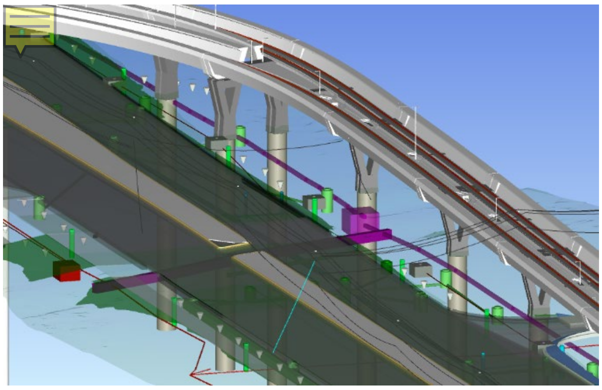

Figure 13. **Navisworks utilities clash detection**

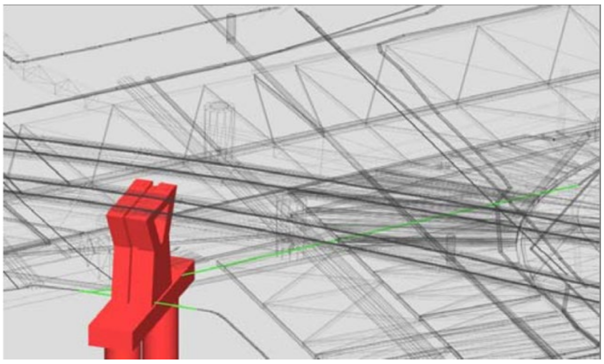

Figure 14. **Navisworks utilities clash detection**

The use of Navisworks to combine Architectural, Structural and MEP models allowed the design team to produce and review clash reports on a weekly basis. This allowed specialist disciplines to coordinate layouts in real time and set up action plans for working towards a clash resolvable final design for handover to our client. It also facilitated full spatial coordination and clash detection between the structure, track clearance envelope and utility zones during the design development phase. This resulted in the overall width and functional cross section of the girder being optimised to a high degree of accuracy.

In addition, 3D models of complex reinforcement interfaces were developed to enable early construction planning. Figure 15 illustrates a 3D reinforcement model of a typical pier to bearing interface. The 3D reinforcement model allowed the site team to coordinate reinforcement placement to avoid clashes with bearing shear studs in an extremely congested zone.

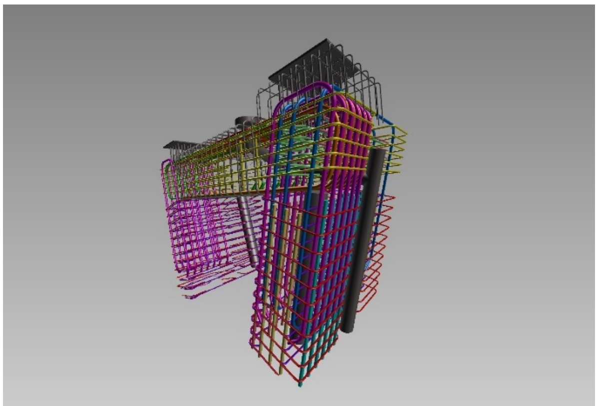

Figure 15. **3D Pier reinforcement model**

8. Track Structure Interaction

The Track Structure Interaction (TSI) model was set up in Midas Civil and was used to specifically calculate the nonlinear effects due to the presence of the rails in the longitudinal direction of the structure, specifically for:

- thermal cases
- vehicle acceleration and deceleration
- rail induced reactions due to vertical live loads.

Track structure interaction imposes significant design loads on the guideway foundations. On straight track, longitudinal forces are transferred to the foundations through the rails and via the bearings while on curved track, both longitudinal and transverse forces occur. These can have a significant effect on the foundation design, particularly for the mono pile foundation solution.

The non-linear static analysis model included all major structural components, including the deck sections, concrete piers, longitudinally guided or fixed bearings at piers, rails, and rail clips. Components were modelled to realistically capture relative stiffness of the elements and the various load effects, including loads from LRVs and imposed thermal strains. Guidance on modelling for track-structure interaction effects was taken from the UIC Code 774-3, “Track/Bridge Interaction”. The UIC is an internationally recognized standard Authority in the Railway industry.

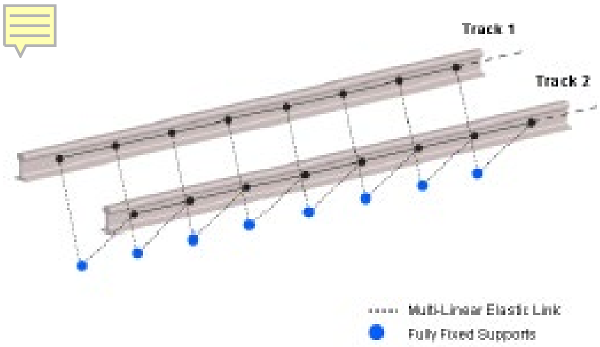

Figure 16. Model of track structure connectivity

The rail was assumed to be continuously welded along the full length of the structure. As there are no rail joints proposed on or adjacent to the structure, continuous rail was also modelled for approximately 150 m beyond the abutments. This ensures effective fixity of the continuous welded rail (CWR) at both abutments.

The vertical and transverse stiffness of the rail clips is assumed infinite. Longitudinally, the fastener restraint is non-linear, allowing slippage of the rail relative to the track support structure. A bi-linear coupling spring was modelled to represent one pair of clips fixed to each rail at the clip which is consistent with the direct fixation assembly used on the structure as per Figure 17. The maximum resistance of the spring is modelled as 20 kN/m/rail, with the yield point occurring at a displacement of 0.50 mm. This is in accordance with the recommendations of the UIC code for direct fixation tracks and is based on a clip spacing of 750 mm along the length of the structure.

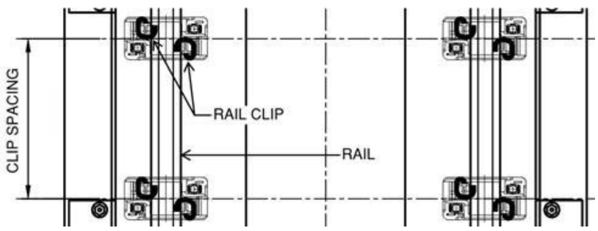

Figure 17. Direct fixation on Elevated Guideways, typical plan view of rail-clip assembly

In addition to this, zero stiffness clips were utilised within 12m of expansion joints (EJs) (approximately 20 no. clips either side of EJs). The use of this arrangement was introduced to minimise the interaction forces between the CWR and the structure. The impact of the zero stiffness toe clips can be seen in the plateau sections of Figure 18 which would otherwise correspond to peak stresses at the EJs.

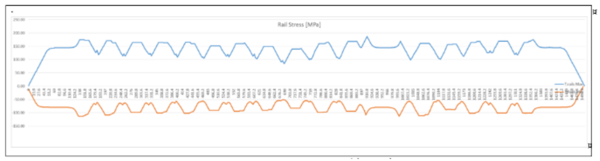

Figure 18. Rail Stress Envelope under all load cases

Both temperature increase, and temperature decrease are taken into account to achieve the most onerous loads on the structure. The relative temperature difference between the rail and the structure was considered as a separate load case added to the atmospheric temperature change loads. The relative temperature differences between the rail and the structure used to determine the design forces were:

- At least 30°C for a temperature rise with the rail being warmer; and
- At least 40°C for a temperature fall with the rail being colder.

The effect of rail breathing around curves has been considered in the analysis by applying the temperature changes above. Rail breathing is the effect on horizontal curved sections of track whereby the expansion and contraction of the rail due to temperature changes results in radial forces on the structure.

Rail break was also included in the design forces acting on the structure by considering the force from a single rail breaking. When one rail breaks, the built-up tension is dissipated through the other three rails, and then distributed to the deck through the rail clips. The force in the broken rail was determined from the worst case tensile force in the rail and the corresponding gap determined from the track clip resistance available to limit the opening up of the rail gap.

Per the Project Agreement, the force in the broken rail was determined based on a maximum rail break gap size of 50 mm.

TCRP Report 155 gives the following guidance on the rail break gap:
The size of the rail gap is usually limited based on the diameter of the vehicle's wheel. Typically accepted rail gaps are in the range of 2 inches [50 mm] for a 16-inch [400 mm] diameter wheel. Notably, wheels that small are seldom seen in rail transit vehicles, so there is a considerable factor of safety in limiting the rail gap to 2 inches.
This statement is a reflection of geometry of the wheel/rail interface in that a large diameter wheel can cross over a larger gap compared to a smaller sized wheel. The implication of TCRP 155 is that a 400mm diameter wheel can traverse a 50mm gap. The wheel diameter for the Edmonton design vehicle is 640 mm. By proportion, the equivalent rail gap size would be 50*640/400 = 80mm. Therefore, the design of the elevated guideways allowed for the forces from a rail break gap of 50mm while limiting the rail gap to 80mm. In our case, the size of the rail gap was determined for the case of a single rail break. For the rail clip stiffness of 20 kN/m used in this analysis, the rail gap was 74 mm.

Rail stresses for each of the load cases described above were looked at in combination with the train acceleration and braking forces, the deformation effects of the vertical live load and the effects of the rail prestress force. The resulting maximum and minimum rail stress envelopes over the length of the structure were as follows:

- 187 MPa tension; and
- 113 MPa compression.

These stresses include the effects of all load cases considered for the TSI assessment. Direct comparison of these rail stresses with the permissible additional stresses recommended by the UIC 774-3 is not possible because the UIC recommendations have been developed based on the stability of a ballasted track on concrete sleepers with a minimum radius of 1500 m. Permissible stresses for the Davies Guideway were based on the actual configuration of the non-ballasted track.

It is known that there are a number of components of the capacity of a rail that have been pre-allocated to cater for particular stresses such as bending stress from wheel loads and the stress increase that results from reduction in section due to rail wear. The interaction stress represents only the stress capacity that remains after the other stresses have been accommodated. In this particular case, because the LRV wheel loads are less than for other classes of rail vehicle and because clip spacing had been reduced to the normal minimum, it was considered reasonable that the un-used bending stress allowance that this represents would be available for interaction effects.

In conclusion, a balance of continuous welded rail with no rail joints was used for the entire length of structure with a typical average rail stiffness of 20kN/m/rail with zero stiffness clips used within 12m of EJs. This arrangement was chosen to both minimise the resulting stresses in the rail and structure while keeping the size of the rail break gap to within the 80mm limit. Generally, the arrangement of continuous welded rail with no rail joints reduces maintenance costs often associated with the use of rail expansion devices.

9. Construcción

The construction of the viaduct started in 2018 and it is expected to be completed in late 2020. The following pictures below show different states of the construction.

Figure 19. Substructure construction.

Figure 20. Precast yard.

The beams have been precast and post-tensioned in a different location and transported and lifted using heavy lifting equipment.

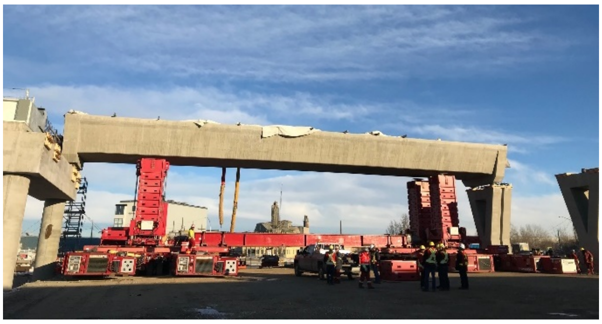

Figure 22. Erection of a single track beam.(© TransED LRT).

10. Conclusion

Davies Elevated Guideway is a post-tensioned concrete U-shaped trough girder largely no different to many examples of light rail elevated guideway construction across the world. What was innovative about this project was the approach to digital advancement of the design process, combining the latest software available on the market with cutting edge coding expertise to generate a robust and parametric workflow bringing enhanced efficiency to the design process.

It has brought about a step change in our organisation having identified a path and further development opportunities to allow us step into the world of fully digital and parametric design.

11. Acknowledgements

The authors want to thank our Arup colleagues from the Toronto and New York offices for their support, expertise and contribution throughout the course of the project.

Also, the contribution of the construction joint venture (CJV) of Bechtel, Ellisdon and Bombardier for their expertise throughout the construction of the project.

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