Pavement Response to Superheavy Load Movement

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ABSTRACT

With rapid growth and development of urban cities, rural areas have become the primary location for industrial plants. Depending on the type of facility, major components may be fabricated at a facility far from the location of the industrial plant. The size and weight of these components during transport can significantly exceed typical roadway load limits. The secure and successful transport of the superheavy loads from the fabrication plant to the final location becomes a challenging endeavor. There have been multiple research attempts to develop structural response models to predict pavement damage from superheavy loads. This paper is an update to the 2016 TAC paper "Modelling Pavement Response to Superheavy Load Movement" in which the outcome of several studies of superheavy load moves planned for the spring and winter months was discussed. This paper expands the research on the transport of a super heavy load in winter.

The transport of a Splitter from the Dacro Industries Inc. facility in Edmonton to the Inter Pipeline Propylene plant north of Scotford, Alberta was the heaviest-ever load on Alberta roads. The transport vehicle for the winter move comprised a double inter-combi trailer with a gross vehicle weight of approximately 1.5 million kilograms. This vehicle had two 24 axle line trailers with 1.5 m axle spacing. Due to the sophisticated nature of the project, and various shortcomings highlighted with previous research methods, non-linear dynamic finite element modelling (FEM) was used to determine the pavement layer stresses and strains when subjected to superheavy load moves. To facilitate the move, several trials were completed with various scenarios. The move was successfully completed on the first week of January 2019. This paper will summarize the methodology and results of various scenarios predicted and the pavement inspection result prior to and after the move.

Keywords: Superheavy load, finite element modelling, pavement impact analysis, shear failure analysis, pavement condition inspection.

INTRODUCTION

In the past decade the locations of industrial plants have been shifting out to more rural areas for both cost and regulatory reasons. Some of these facilities require very large, components that cannot be fabricated on site, and that cannot be transported using traditional methods due to their size and weight. The superheavy load movers designed to transport these components do not meet standard regulations for roadway vehicles.

Pavement performance is significantly influenced by the magnitude and frequency of heavy vehicle traffic loads. Many transportation agencies in North America have placed limits on truck weight and dimensions to ensure the longevity of the public roadways. They are beginning to require some form of a superheavy load movement pavement analysis before issuing permits for vehicles that exceed the limits. These analyses are used to verify that the loaded transporter will not cause excessive damage to the roadway along the route. To determine the potential of pavement damage, Alberta Transportation (AT) requested a pavement impact analysis along the transportation route to facilitate the permitting process. This paper discusses the predicted pavement damage for variable speed and summarizes the pre and post heavy move results.

The project involved the transport of a Splitter (super heavy load) from the Dacro Industries Inc. facility located at 9325-51st Ave NW in Edmonton to the Inter Pipeline Propylene Ltd. (IPPL) Propylene plant north of Scotford Alberta in January, 2019. The route length is approximately 142 km as shown in Figure 1. .

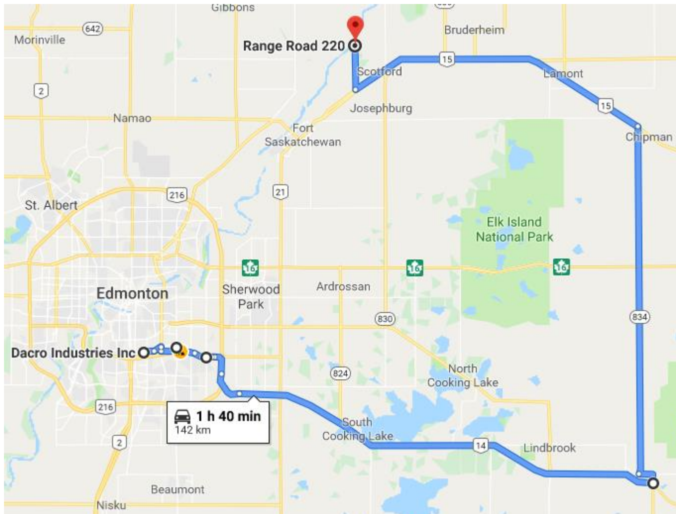

Figure 1. Superheavy Move Route from NW Edmonton to IPPL Plant.

Traditionally, the analysis procedures for superheavy load moves have been based on the layered elastic theory to predict the stresses and strains associated with the traffic load. There are different software applications available which use this method. However, the layered elastic theory does not take into account small differences in axle configurations, dynamic effects of the loading, or any non-linear properties of the roadway materials. Asphalt concrete is a non-linear material which is more accurately modeled using a visco-elastic material model with rate-dependent stiffness and recovery behavior.

A more accurate method for predicting the roadway response is to use finite element analysis (FEA). This is a method commonly used in many fields to perform structural, and failure analyses of solid mechanics problems. Dynamic explicit FEA allows us to accurately model the geometry, dynamics, and non-linear material behavior of the roadway. The challenge with FEA modeling of these problems comes from the size of the model relative to the detailed stress and strain output required, and the long duration of a slow-moving transporter passing over a section of roadway. Advances in high performance computing (HPC) have now enable researchers to run these large simulations, which would have been too costly and too time consuming in the past. Using the commercial FEA software, LS-Dyna[1], it was possible to simulate the roadway response to superheavy load movers and predict the stresses and strains seen in the pavement and subgrades. These stresses and strains can then be used to predict the potential for damage in the roadway.

METHODOLOGY

The splitter unit and transport vehicle weigh approximately 1,587,800 kilograms. The vehicle configuration is shown in Figure 2. The platform trailer on either end of the load consists of 26 axle lines, with 4 axles per line, 4 tires per axle, and a gross vehicle weight on the platform of 698,650 kg and weight per tire of 1,679 kg. This load was categorized by AT as the heaviest ever load on Alberta roads.

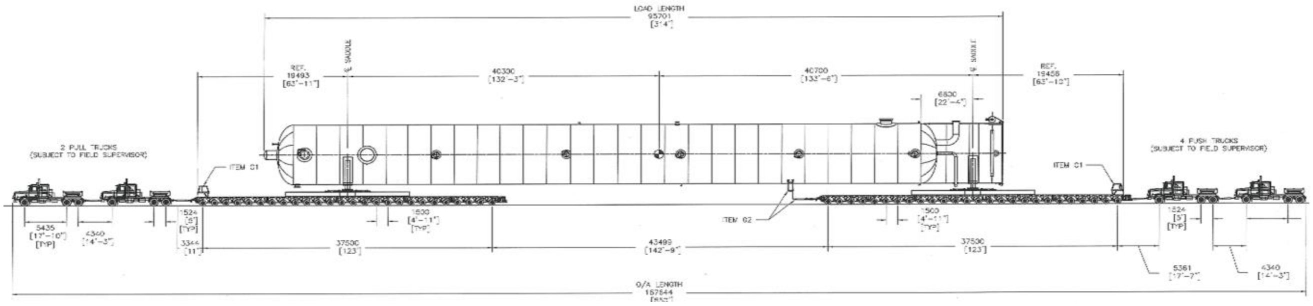

Figure 2. Transport Vehicle Configuration for Splitter Move.

A Finite Element Model was created using the information about the transport vehicle and roadway to predict the potential roadway damage caused by a super heavy load move. This model considers vehicle weight and axle configuration, pavement type and thickness, subgrade type and moisture condition, and environmental features. The pavement loads imparted by the trailer can be defined by the tire locations, tire contact patch shape, and the weight per tire. Since this is a transient problem, the speed of the trailer is also important.

The roadway material properties were gathered from AT's Falling Weight Deflectometer (FWD) tests performed on the route being used for the transport. The base and subgrade layers were modelled as linear elastic materials. Since asphalt concrete is a rate and temperature dependent material, a linear viscoelastic model was created for this layer. This model was validated using laboratory and FWD test results.

All analyses are performed with the LS-DYNA explicit FEA solver (version 9.1), which is well suited for modeling the load cases considered and is used widely for transportation infrastructure applications. LS-DYNA excels at modeling the nonlinear dynamic response of various materials including the visoelastic asphalt model used in the simulations. The output of FEA produces a detailed time-history of the deformations and stresses in the roadway. Finally, a pavement damage analysis of the overall load, i.e. 1.6 million kilograms of vehicle, was performed using the peak stresses and strains measured at specific locations in the roadway.

This model was used to run two independent simulations with one using the average speed of 15 km/hr and the other using the minimum speed of 5 km/hr. All other variables including transport configuration, load weight, and pavement information remained constant. The FEA model setup, simulation results, and pavement damage analysis are discussed in ensuing paragraphs.

Finite Element Analysis Model Setup

A section view of the pavement geometry as modelled is shown in Figure 3. In consideration of the length of the move and the large variety of different pavement sections along the haul route, the pavement thickness selected for modelling was based on the lower quartile of the pavement cross section thickness. The selected cross section does not represent the worst-case scenario of pavement structural capacity, but one considered to be relatively conservative and reasonable for analysis. The frost depth of 1.5 m from the top of the pavement surface was obtained from AT's frost probes throughout the Province. These probes provide the most recent subsurface information.

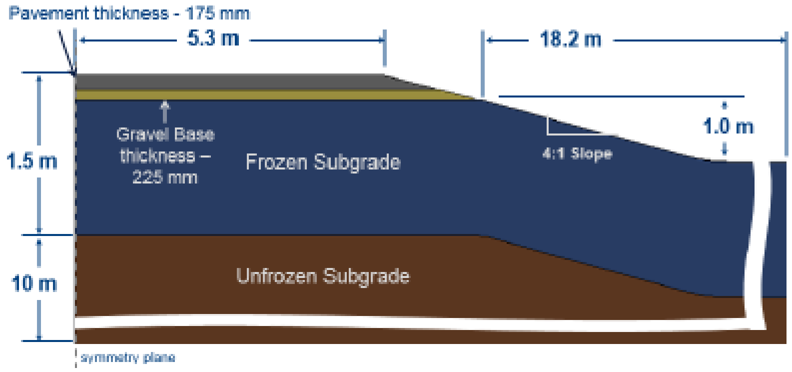

Figure 3. Roadway Model Section View for Winter Move.

For the majority of the route sections, the transport vehicle used the full width of the roadway during the move. To reduce the computation time by 50 percent, the problem is modeled as symmetric about the centerline. The pavement loading included half of the vehicle symmetrically positioned across the roadway as shown in Figure 4.

Figure 4. End View of Trailer Tires.

The material properties for the pavement layers and subgrade considered are provided in Table 1. The asphalt concrete model was created from a linear viscoelastic master curve, based on historical test data collected by ARA on other projects. This model is adjusted based on the ground temperature at the time of the move. The resulting linear viscoelastic modulus curve for this move is shown in Figure 5. Comparisons between FWD test results and FWD simulations were done to validate the asphalt model at different temperatures.

Table 1. Pavement and Subgrade Material Properties.

Material	Model Type	Modulus (MPa)	Poisson's Ratio	Density (kg/m3)
Asphalt (-7°C)	Viscoelastic	rate dependent	0.35	2,400
Base	Elastic	6,900	0.35	2,200
Frozen Subgrade	Elastic	6,900	0.35	1,700
Unfrozen Subgrade	Elastic	23	0.35	1,700

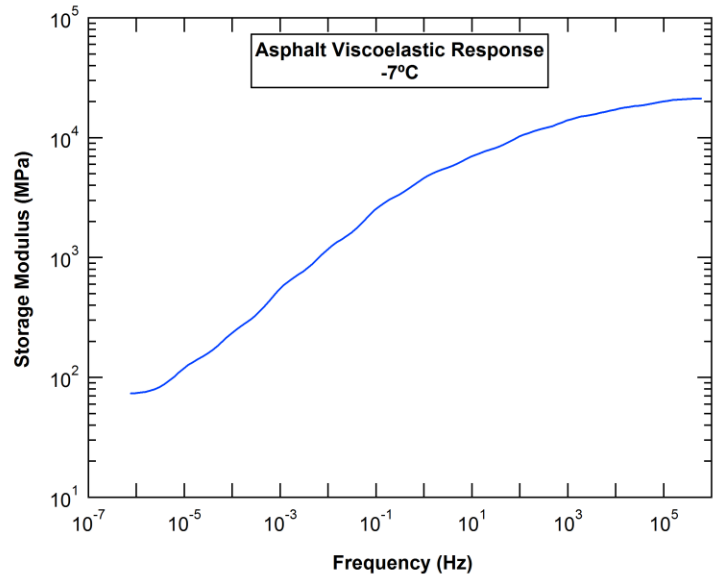

Figure 5. Linear Viscoelastic Material Behavior of Asphalt Concrete.

The trailer tire load is modeled as a pressure applied to the surface of the asphalt, shown in Figure 6. This applied pressure moves along the roadway at the velocity of the transporter to simulate the rolling tire loads. At the start of the simulation the loads are gradually increased from 0 to 100 percent to minimize the dynamic effects of applying the initial loads and achieve a steady-state scenario at an earlier stage.

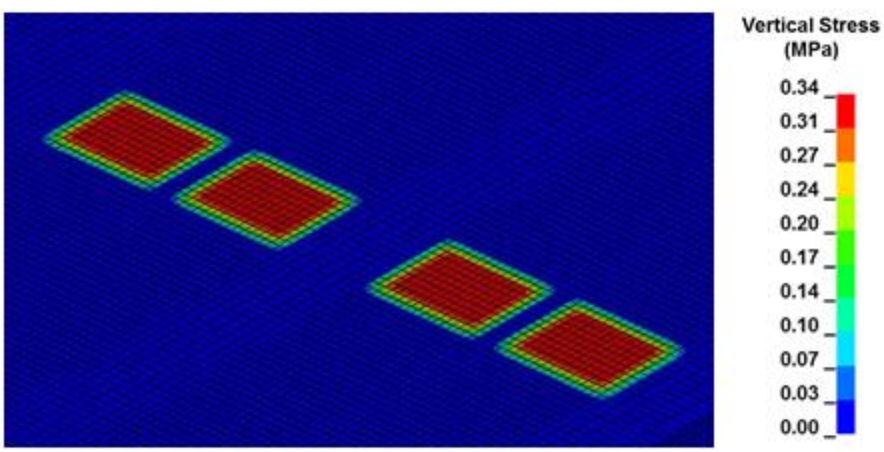

Figure 6. Applied Trailer Tire Loads.

Simulation Result

The simulation is allowed to run until the stresses and strains have converged to steady values. The resulting basin shape (deflections) along the centerline of the top surface of the asphalt is shown in Figure 7. The x-axis measures the distance from the front axle. The maximum vertical displacement was 1.4 mm. The extents of the model are long enough that we don't see any boundary effects on the basin.

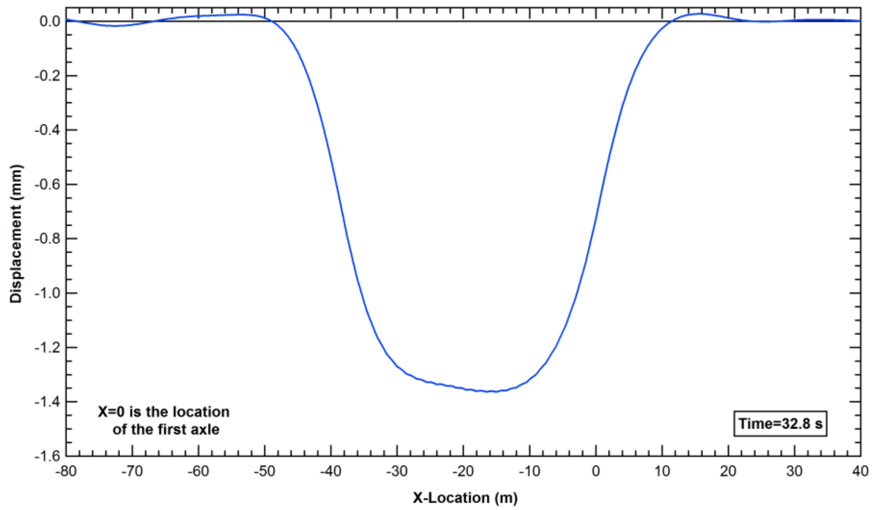

Figure 7. Roadway Basin Along Longitudinal Centerline.

The cause of fatigue cracking is tensile strain in the asphalt. In order to understand the cause of the asphalt tensile strain, the stress states in the asphalt must be considered. The maximum principal stress in the roadway is shown in Figure 8. The location of the trailer can be identified by the high compressive (negative) stress regions under the tires. The maximum principal stresses in the asphalt are mostly compressive (negative) stresses. These compressive stresses are caused by the bending of the pavement and the tire contact pressures. Small tensile stresses in the asphalt occur at the front and rear of the trailer and are caused by the curvature of the basin.

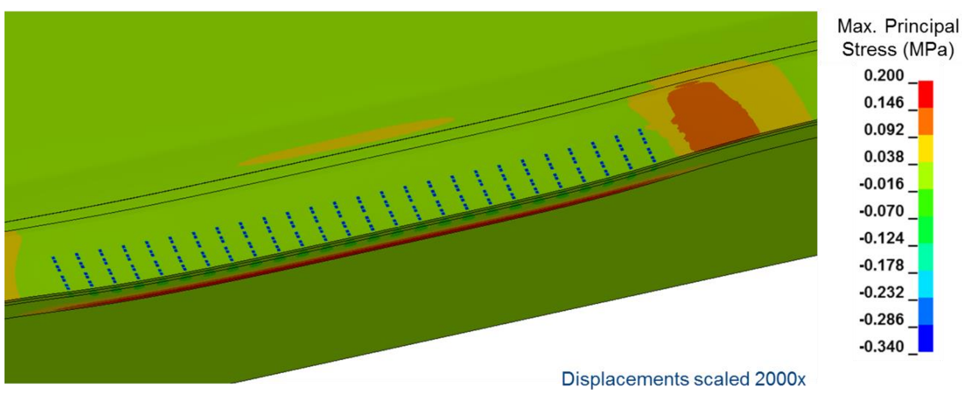

Figure 8. Maximum Compressive Stress on the Top of the Pavement.

The maximum tensile strains in the asphalt are found near the top surface between tire pairs. For a given axle line, the maximum tensile strains are between the inner tire pairs as shown in Figure 9. A section view of the asphalt showing the minimum and maximum principal strains is shown in Figure 10. The peak tensile strains between the tires are caused by the Poisson effect. The compressive stresses below the tires lead to lateral expansion outwards. The asphalt between the tires is then squeezed from both sides and expands vertically upwards where it is unconfined. This is the phenomenon that causes top down cracking or rutting in asphalt pavements depending on the location of maximum stress or strain. The additional horizontal stresses caused by the curvature of the asphalt also contribute to the vertical strains.

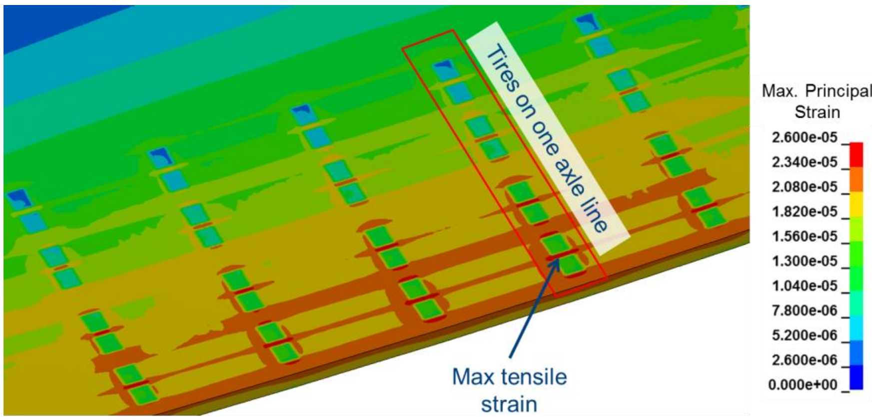

Figure 9. Maximum Principal Strains in the Asphalt.

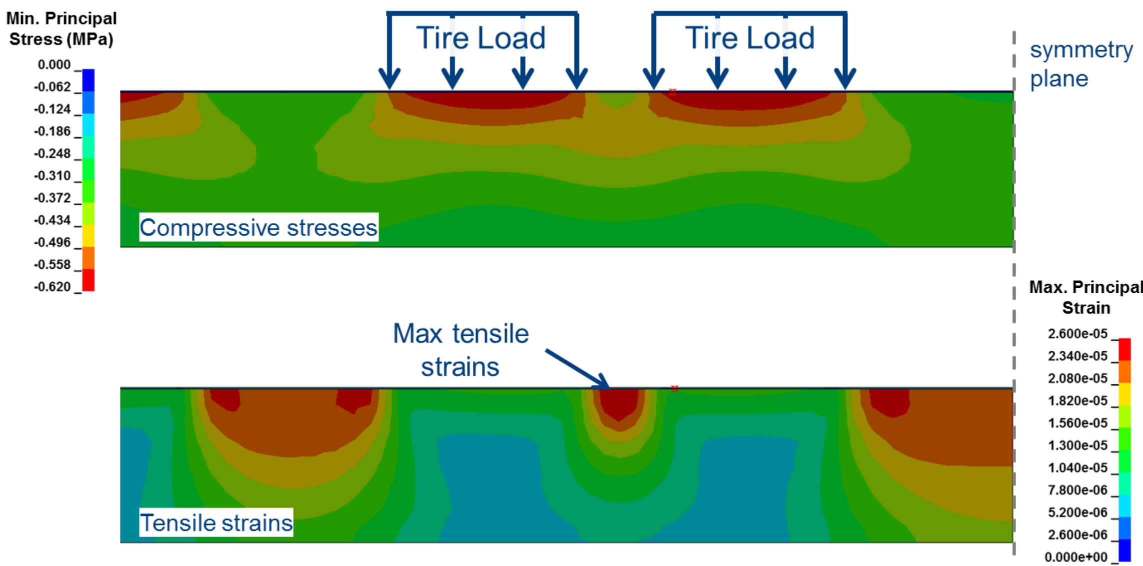

Figure 10. Horizontal Tensile Strains between the Tire Loads.

The combined effects of the basin and the tires cause the maximum tensile strains in the asphalt concrete layer below each axle resulting in cyclic strains. The tensile strains are the lowest for the outer two axles on each end and highest at the rear of the trailer between the tires. The asphalt at this location has undergone repeated load cycles which has enabled strain to build up in the viscoelastic material. The maximum tensile strain in the asphalt concrete was 27 microstrain and occurs at the 23rd axle (4th axle from the rear) as illustrated in Figure 11. The tensile strain below the first axle is 15 microstrain. This measurement can be used to predict the fatigue cracking damage.

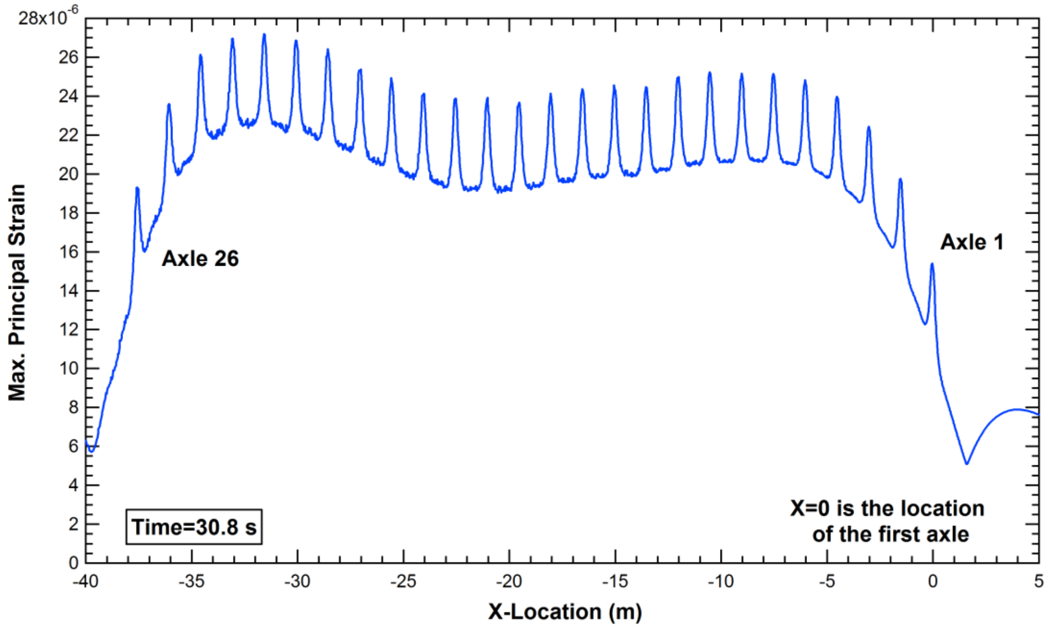

Figure 11. Maximum Tensile Strains Along the Roadway Between Tire Pairs.

Subgrade Vertical Compressive Strains

The passage of the transporter also causes the roadway to deflect vertically downwards which causes stresses and strains in the pavement and subgrade layers. Non-recoverable vertical compressive strains cause rutting of the pavement structure. The minimum principal stresses in the frozen and unfrozen subgrades are shown in Figure 12. Due to the depth of the subgrade below the pavement, the pavement surface load is distributed over a wider area than the tire/pavement surface interaction. The stiff frozen subgrade also reduces the load concentrations in the unfrozen subgrade by further distributing the load. The maximum compressive strain is 21 microstrain in the frozen subgrade and 170 microstrain in the unfrozen subgrade. The peak compressive strain in the frozen subgrade is an order of magnitude smaller than in the unfrozen subgrade due to the difference in stiffness.

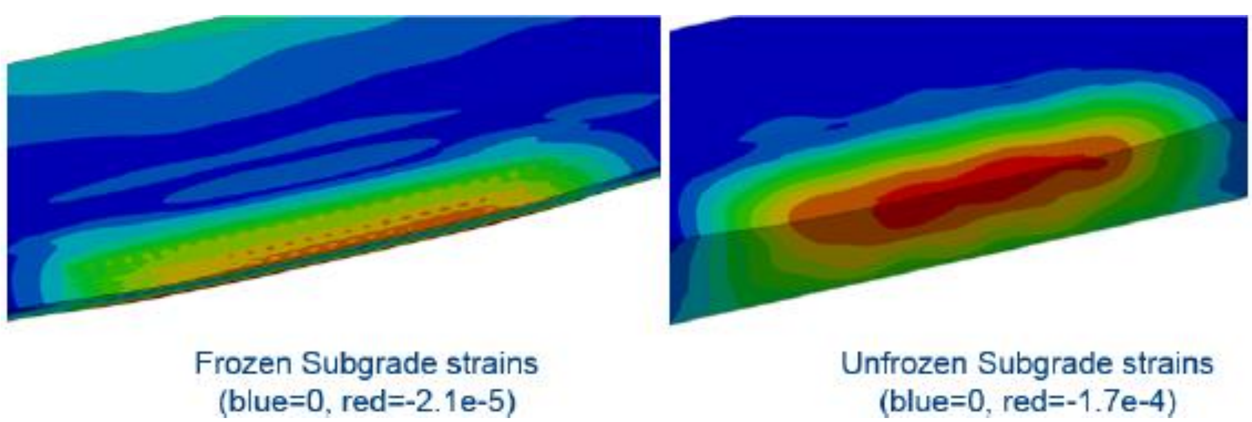

Figure 12. Subgrade Vertical Compressive Strains.

PAVEMENT DAMAGE ANALYSIS

Pavement damage is typically assessed in terms of the number of equivalent single axle loads that the asphalt concrete can withstand until the percentage of cracking in the wheelpath reaches a critical level. This is usually defined as 10 percent cracking along the length of the wheelpath. A similar criteria is established for subgrade rutting due to non-recoverable vertical compressive strain. The critical trigger value for subgrade rutting is usually set at 12.5 mm.

Asphalt Concrete Fatigue Cracking

To determine the impact of the movement of the heavy load on cracking in the asphalt concrete, the first step is to consider the absolute value of the asphalt strain. The National Center for Asphalt Technology (NCAT) in Auburn, Alabama has recommended an asphalt strain endurance limit based on asphalt temperature. This limit is 70 microstrain at the intermediate temperature.

In some cases, where fatigue endurance limit data are not available, the use of 70 microstrain value is recommended to be conservative. Therefore, strains less than 70 microstrain would indicate that the asphalt concrete would still be in the elastic range and therefore the applied load would not cause any permanent damage from structural loading. Since the models show that the transporter is expected to impart a maximum tensile strain of 27 microstrain (Figure 11), it is not expected that the heavy move will cause any significant fatigue damage to the asphalt concrete layer.

Subgrade Rutting

The passage of the transporter also causes the pavement to deflect vertically downwards which causes stresses and strains on the top of the subgrade layer. To avoid rutting, it is expected that the vertical compressive strains at the top of the subgrade are lower than the design thresholds. A value of 200 microstrain has been proposed for the vertical strain limit.

In this analysis, the maximum compressive strain at the top of the frozen subgrade was 21 microstrain and 170 microstrain at the top of the unfrozen subgrade. In this case, the frozen pavement layer and upper subgrade layers have very high stiffness values in the order of 6,900 MPa. This causes the load from the trailer to be dispersed over a large area. This large area supporting the load reduces the magnitude of the peak compressive strains in the unfrozen subgrade.

As shown in Figure 12, there is one peak compressive strain near the center of the trailer rather than at each axle of the trailer. On either side of this peak value, the compressive strains decrease towards zero just beyond the first and last axles. For this reason, this peak compressive strain on the subgrade can be considered as one cycle. The super heavy load mover has two of these trailers hence the subgrade will experience two peak compressive cycle. Based on the discussion of strains and predicted damage, the permanent subgrade deformation as a result of this move is well below the proposed vertical strain limit. The damage is predicted to be negligible when the subgrade is in a frozen condition as modeled.

Pavement Response Comparison at Various Rolling Speed

As previously noted, this model was used to run two independent simulations with one using the average speed of 15 km/hr and the other using the minimum speed of 5 km/hr. All other variables including transport configuration, load weight and pavement information remained constant. The predicted strains are presented in Table 2.

Table 2. Pavement Response Comparison for Various Rolling Speed.

Details	Rolling Speed	
	15km/hr	5km/hr
Tensile strain* (microstrain)	24	27
Compressive strain ** (microstrain)	160	170

* Fatigue endurance limit – 70 microstrain ** Vertical strain limit – 200 microstrain

It is generally expected that there will be higher amounts of pavement damage with slower speed vehicle as compared to higher speed. The tensile strain on the asphalt surface and compressive strain on the subgrade imparted by 5km/hr speed transport truck as compared with the vehicle rolling at 15km/hr was computed to be slightly higher. Only a slight change in the pavement reponse is also due to the 1.5 m frost depth from the top of the asphalt surface. This comparison shows the beneficial effects of a frozen subgrade horizon for the heavy move.

SHEAR FAILURE ANALYSIS

A shear failure analysis for this move was also completed as a part of permitting process. The primary focus was to investigate shear failure in the subgrade layers, both frozen and unfrozen subgrade. In order to investigate the likelihood of shear failure, the shear strength parameters (friction angle, ϕ, and cohesion, c) of the subgrade layers in addition to the load-induced pavement responses are required. The pavement responses were obtained from the Finite Element Model (FEM) analysis at the top of the frozen and the unfrozen subgrade, directly below the tire. Since the strength parameters were not readily available, they were estimated based on the soil classification obtained from a geotechnical investigation report provided for a portion of the route. Based on the report, the subgrade soil was classified as high plasticity clay (CH). In some locations, silty sand (SM) was also encountered.

Localized Shear Failure Analysis

Localized shear failure examines the likelihood of onset of failure in the subgrade layers. It was possible that a superheavy vehicle would induce a state of stress in the pavement structure that could cause the pavement to reach the failure state. Comparing the induced stresses on top of the subgrade layers with the corresponding yield criterion was considered in the localized shear failure analysis. The Drucker–Prager yield criterion which involves the shear strength parameters of the unbound material (friction angle, ϕ and cohesion, c) is a well-accepted criterion in soil plasticity for evaluating the yielding (i.e., failure) of soil materials (Drucker and Prager, 1952). The calculated factor of safety (FOS) with time for the induced state of stresses on top of frozen subgrade and unfrozen subgrade with varying friction angle and cohesion for both high plasticity clay (CH) and silty sand (SM) are shown in the Table 3.

Table 3. Summary of Minimum FOS for Frozen and Unfrozen Subgrade.

Soil Type	Frozen Subgrade			Unfrozen Subgrade		
	Friction Angle, ϕ (°)	Cohesion, c (kPa)	Min. FOS	Friction Angle, ϕ (°)	Cohesion, c (kPa)	Min. FOS

Soil Type	Frozen Subgrade			Unfrozen Subgrade		
	Friction Angle, ϕ (°)	Cohesion, c (kPa)	Min. FOS	Friction Angle, ϕ (°)	Cohesion, c (kPa)	Min. FOS
High Plasticity Clay (CH)	45	145	3.4	30	21	5.7
	30	100	2.5	20	14	3.8
	30	70	2.0	10	14	3.4
Silty Sand (SM)	45	70	2.2	35	7	3.0
	35	70	2.0	30	7	2.7

It can be seen that the minimum FOS for the frozen subgrade can be as low as 2 for either CH soil or SM soil. In the case of unfrozen subgrade, the minimum FOS of 2.7 and 3.4 was calculated for SM soil and CH soil, respectively. In general, since the calculated FOS for both frozen and unfrozen subgrade condition with the consideration of different possible shear strength parameters are greater than 1.0, the likelihood of localized shear failure should not be a concern.

Ultimate Shear Failure Analysis

Ultimate or global shear failure is a bearing capacity type of a failure which focuses on the overturning of the super heavy load vehicle due the instantaneous failure of pavement layers/subgrade. This type of failure resembles the failure of a shallow foundation subjected to an excessive large load. This analysis was not completed in the first round due to the assumption that the subgrade and base layer will be frozen and the possibility of instantaneous global failure was less of a concern. However, three days prior to the scheduled Splitter move on January 6, 2019, Spring like conditions in Edmonton raised the concern of insufficient frost penetration. The frost depth during the pavement impact analysis was assumed to be 1.5 m. The measured frost depth was only 1.2 m in the first week of January. To provide confidence in the super heavy load moving operation, AT requested instantaneous failure analysis with new frost depth parameters.

Meyerhof's bearing capacity for layered soil medium was used for the analysis. Figure 13 shows Meyerhof's theory for a shallow, continuous foundation supported by a stronger soil layer, underlain by a weaker soil. Accordingly, the vehicle was simulated as a static load which is applied on top of the frozen subgrade underlain by an unfrozen subgrade.

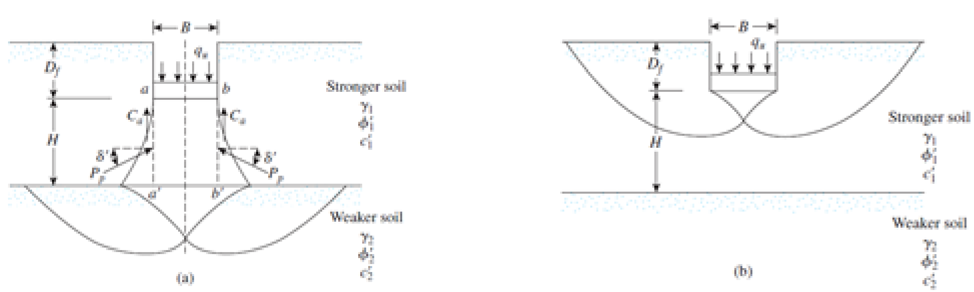

Figure 13. Meyerhof's Theory for Bearing Capacity of a Layered Soil System

As shown in Figure 13(a), if the thickness of the upper soil layer (H) is relatively small compared with the foundation width (B), a punching shear failure will occur in the upper soil layer, followed by a general shear failure in the bottom soil layer. However, as shown in Figure 13(b), for a relatively large H, the general failure will occur in the upper soil layer (failure surface in the upper soil layer). In this analysis, since the width of the vehicle is 6.4 m, compared to the depth of frozen soil (1.2 m was assumed), the failure surface will be extended into the unfrozen subgrade. The calculated FOS for the assumed shear strength parameters are summarized in Table 4.

Table 4. Summary of FOS for bearing capacity analysis.

Frozen Subgrade		Unfrozen Subgrade		q_b (kPa)	q_t (kPa)	c_a (kPa)	K_s (kPa)	FOS
Friction Angle, ϕ (°)	Cohesion, c (kPa)	Friction Angle, ϕ (°)	Cohesion, c (kPa)					
35	70	20	2	435	6000	47.6	1.25	15
		15	2	234		42	1.05	8
35	0	20	2	435	2387	0	2.0	14.5
		15	2	234		0	1.25	7.5

In general, the calculated FOS are noticeably greater than 3.0, which indicates that the likelihood of ultimate shear failure should not be a concern.

PRE AND POST MOVE PAVEMENT CONDITION INSPECTIONS

Three super heavy load vehicles were scheduled to move between January and March of 2019 including the Splitter, which was the heaviest load on Alberta's roadways. A pavement condition inspection was completed prior to the splitter move to document the baseline condition, and subsequently two other surveys were completed after the remaining moves. The three superheavy moves included a Splitter, Stripper, and Depropanizer. A snapshot of the equipment/vehicle characteristics is shown in Table 5.

Table 5. Super Heavy Move Details.

Move Date	Survey Date	Load type	Total weight (kg)	Weight per tire (kg)	Total number of tires
January 6, 2019	January 2-4	Splitter	1,587,800	1,679	832
January 24, 2019	January 28-30	Stripper	1,342,952	1,690	640
March 3, 2019	March 25-27	Depropanizer	581,989	1,596	204

Pre- move pavement condition inspections were completed on January 2 to 4. The pavement condition inspections were completed in general accordance the Alberta Transportation Surface Condition Rating Manual (August 2003). The inspection included a windshield survey of the pavement surface conditions along the transport route and a 'detailed' visual survey of gauging segments that were considered to be representative of the section pavement condition. A major focus during the inspections was the incidence of wheel track rutting and cracking, including transverse cracking, longitudinal wheel path cracking, and fatigue cracking as the primary mode of structural damage.

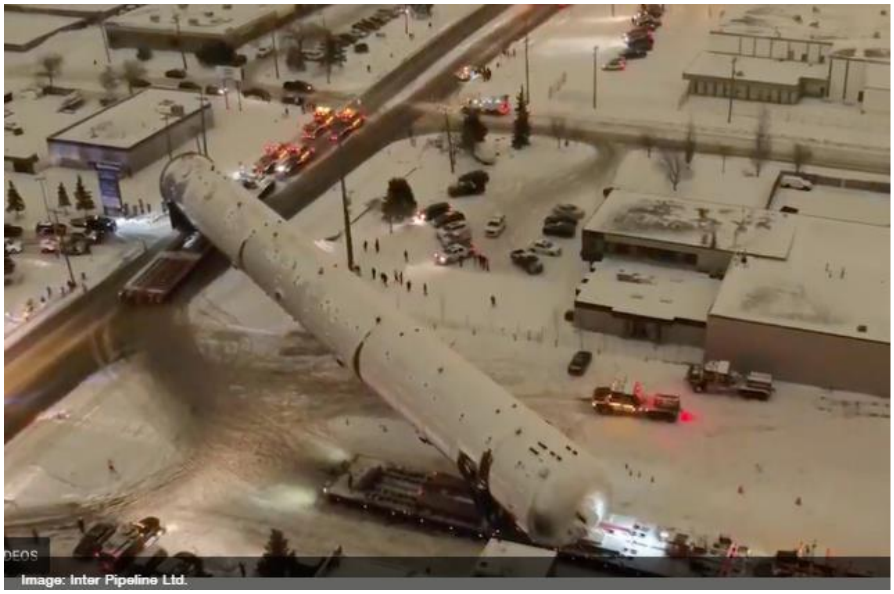

Figure 14. Turning Movement of the Splitter – Heaviest – Ever Move in Alberta Roads. *(Image source: IPL)*

Figure 14 shows the turning movement of the Splitter coming out of Dacro Industries to 51 Avenue Northwest in Edmonton. The route comprised of 5 major sections; Whitemud Drive Northwest, Anthony Henday Drive, Highway 14 Eastbound, Highway 834 Northbound and Highway 15 Westbound.

Pavement condition re-inspection was completed on January 28 to 30 and on March 25 to 27. The re-inspection did not observe any new or worsening pavement damage in comparison with the January 2 to 4 pre-move survey.

CONCLUSION

A finite element model analysis was used to carry out a pavement impact study for two different scenarios of superheavy load move with different vehicle rolling speed. The model was used to predict the stress and strains in the pavement when subjected to a superheavy load travelling along the route. The stresses and strains determined using the FEM were then used to calculate and predict the key types of pavement damage; fatigue cracking of the asphalt concrete and rutting of the subgrade. Slower speed move had about 12 percent higher asphalt tensile strain and 6 percent higher vertical compressive strain as compared to the faster speed.

For those interested in viewing the video of the heaviest ever move in Alberta, it can be viewed at following link: https://www.jwnenergy.com/article/2019/1/drone-footage-inter-pipeline-petrochemical-plant-construction-and-arrival-massive-splitter/

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