Operational Loads Measurement and Design Optimization of a Gold Mine Rail Hauling System Showing Fatigue Cracks

Mathieu Lussier ing. M.SC.A. MBA
(Optimec Consultants inc., Canada);

David Paquette ing.
(Agnico Eagle, Canada);

Tim Hunter, PhD, PE
(Wolf Star Technologies, LLC, USA);

Abstract

Agnico Eagle is a mining company operating a gold mine in Val D'or, North Quebec. They are using an innovative rail hauling system consisting of a train of 64 cars on a monorail moving up ore from down the mine. The train is driven up by several stations along the rail where electrical engines are pushing the cars up via tires in contact with both sides of the cars.

Cracks started showing up on the frame of the cars after only several months of operation indicating fatigue problem. Finite Element Analysis (FEA) was used to assess the situation and solve the problem. The loading applied to the car when passing through a drive station was assumed to be the main problem. In drive stations, a tire rotating horizontally on each side of the car applies a normal force and a shear force to propel the car forward.

In order to realize a fatigue assessment using simulation, loads amplitude and variation on the cars must be known, but these loads are quite dynamic and varying as the train goes up full of ore, or goes down empty. Indeed, as the train circulates, there is a constant push and pull between cars, added to the side loads coming from the drive stations that are not accurately known and varying along the car length due to a displacement driven load.

The first step of the project was to realize a fatigue analysis using ABAQUS and Fe-Safe using a set of approximated static loads. While the analysis was successful in identifying areas of crack appearances, it was decided to calculate more accurately the loads using the True-Load technology. The same FEA Model of the car was used and loads coming onto the car were decomposed into a set of individual unit load cases and linear analyses were run to obtain the strain results on the model. Then True-Load was used to calculate the optimal location of a set of strain gauges that were installed on the car.

Experimental tests were done at the mine to record strain histories when the train goes through a drive station while going up and going down.

Using the experimental strain histories, True-Load software was used to calculate loading functions in the FEA model that replicates the real strain histories. With these loading functions, FEA calculations were done showing the dynamic behaviour of the car in operation when passing through a drive station.

All load functions showed significantly more variation along the car's length than expected and predicted by the preliminary FEA analysis. As the car goes through a drive station, loads from the tire and loads at the handles vary significantly showing push and pull behaviour. It was observed that the large difference in lateral stiffness of the car structure from the front to the rear of the car is in part responsible for the load variation. Indeed, with a displacement-controlled system for the drive station, changes in stiffness will result in changes in loads. Design modification of the car structure was recommended.

In such a dynamic application, accurate loads assessment is almost impossible unless measuring them during operations. Furthermore, when fatigue is studied, understanding of loads variations is very important as it can have a large impact on results. True-Load technology combined with ABAQUS was a big help to understand the dynamic loads on the car, which is an important step in order to improve the design and solve the problem.

1. Introduction

Goldex mine, north of Quebec is using a new automatic hauling system of several trains operating on a monorail to move up ore containing gold. After the first few months of operation, cracks were detected on the side rails of train cars and loading from the numerous drive stations pushing the train forward was suspected to be the cause. Finite Element Analysis (FEA) was used to study this fatigue problem and provide insights to correct the problem.

Finite Element Analysis (FEA) is a common tool for the evaluation of structural components. For complex structures such as this system which undergoes moving loads, approximations of the operating conditions are often made. Shown in this paper will be the use of a series of static FEA analyses with contact to simulate the loading on the rail car using approximated loads. These loads will be shown to reproduce failure predictions at known areas of failure. However, the time and spatial variation of the loading is difficult to reproduce using these standard methods. Furthermore, as the rail system travels through various drive stations at various speeds and various payloads, it is nearly impossible to use traditional analytical tools to calculate the loading of the structure and develop accurate FEA response of the system. To fully capture the timing and spatial varying nature of the loading Wolf Star Technologies' True-Load software will be used to reconstruct the loads.

In order to understand the complex loading environment, ABAQUS FEA software was coupled to True-Load software together with experimental testing using strain gauges on one car. True-Load/Pre-Test uses the strain response from unit loads in the FEA to determine optimal strain gauge locations that effectively turn the structure into its own load transducer. A novel technique provided by True-Load known as 'Moving Loads' was used to fully understand the time varying and spatial varying nature of the loading. Using ABAQUS and True-Load technology allowed to better understand the magnitude and variation of the loads acting on the car and to have a better confidence in the FEA predictions to move ahead with design recommendations.

2. Background

Agnico Eagle is a mining company operating the underground gold mine Goldex, in Val d'Or, North of Quebec. The ore extraction started in 2013 and is expected to continue for about 11 years. Extraction is actually in operation in Deep 1 zone, which has a floor at a depth of 1200 m. An innovative automatic rail hauling system (designed by Rail-Veyor) is used to transport the ore from a depth of 1200 m up to 730 m. The rail system consists of several trains of 64 cars riding on a 3 km long monorail, moving ore up and going down empty.

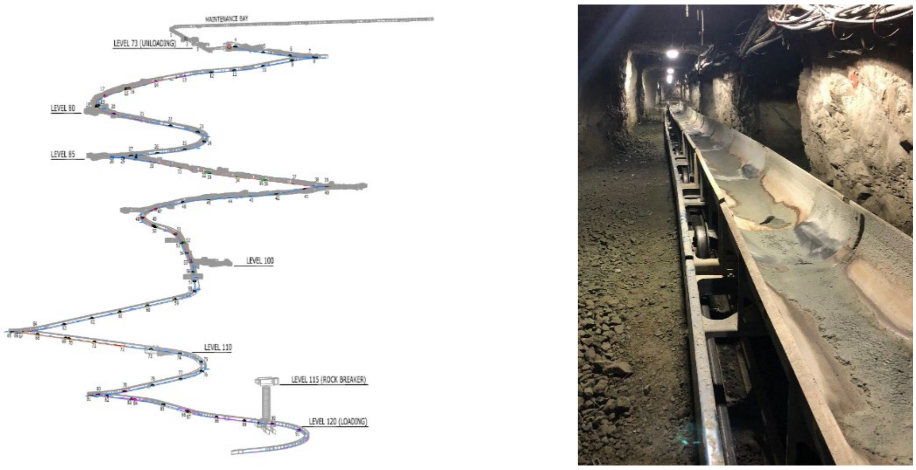

Figure 1: 3 km rail inside underground mine with train photo

The driving system of the train consists of 91 drive stations positioned along the length of the rail from bottom to top. On each side of the train, these drive stations have an electrical engine driving a tire horizontally (along a vertical axle). When a car enters a drive station, tires on each side accelerates the car by contact and friction on its side panels (Figure 2). For this to work efficiently, the distance between both tires is adjusted manually to be smaller than the width of the cars. This creates a compressive force on the car sides and assures sufficient contact and friction to accelerate the train.

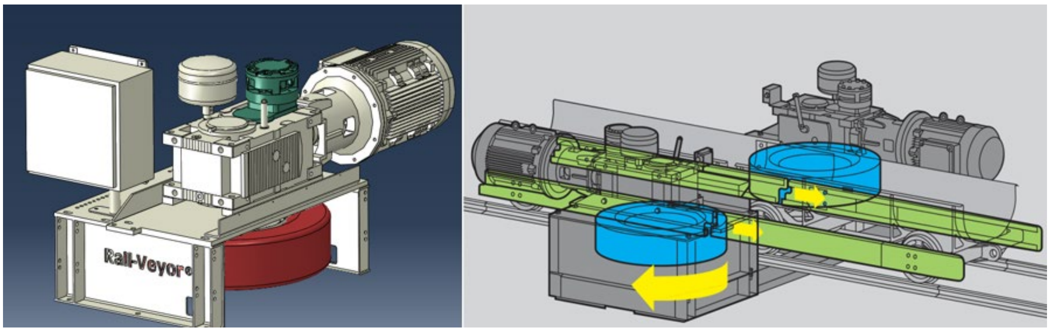

Figure 2: Drive station system (Courteously provided by Rail-Veyor.com)

After months of operation, cracks started to appear at several locations on the side panels of cars. A fatigue assessment was requested to understand and solve this problem. Cracks were appearing at both end of the cars, close to the wheel's attachment point and at two locations where cross members were joining the side panels. The assumption was that the loads on the side panels when passing through a drive station were creating the cracks. Another problem involved the driving capacity of the tires which is a function of the friction force efficiency on the side panels. In order to get enough friction forces to accelerate the train, enough compressive force on the side panel is required. Furthermore, the drive system is a displacement-controlled system where the position of both tires will be set and then fixed. The compression of the tires is not forced controlled, the compression is displacement controlled.

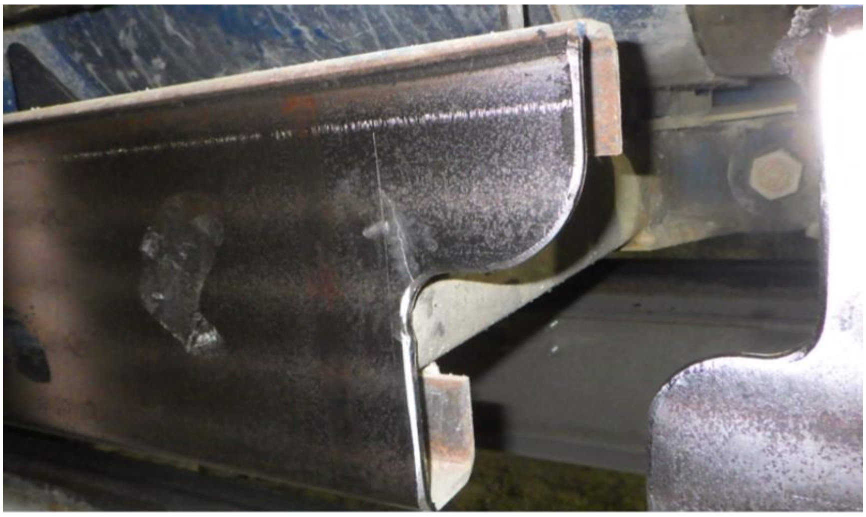

Figure 3: Vertical Crack at front end of the side panel

At this point Finite Element Analysis (FEA) was planned, but the loads acting on the cars during operations were not known precisely. The compressive load created by the tires in drive station was evaluated to be about 12,000 lbf. Additional loads on the car consist of the shear force created by the friction from the tires to propel the train, plus the loads at handles (front and rear) attaching cars together. Apart from the 12,000 lbf normal force evaluated by calibration, the other loads were unknown.

It was decided to build an FEA Model of a car, and make a preliminary fatigue analysis by assuming load values in order to verify if we can reproduce the crack initiation locations. Then, in a second step, True-Load technology was used to calculate loads to verify the difference with the assumed loads of the preliminary analysis.

3. Methodology

It was determined that the cracks were caused by the loading on the side panels when passing through each drive station. When going up, the train goes through 81 drive stations, and when going down, 66 drive stations. The focus of the FEA Analysis was put on the loads created during the time a car is passing through a drive station. Loading on the cars when riding freely between drive stations was neglected.

ABAQUS was used to create a FEA Model of a car and assumed load values were used in a series of static analyses to evaluate stresses. To realize a fatigue analysis of the car passing through a drive station, several static analyses were done by varying the position of the tire from the front to the rear of the car. Then fe-safe® fatigue software was used to combine these analyses into a sequence to evaluate fatigue life under a duty cycle representing one passage in a drive station.

After analysing results of this preliminary analysis, True-Load technology was used to calculate dynamic loads during operations, meaning a train going up full of ore from the bottom of the mine to the end of the rail, and the opposite going down empty. The True-Load software deployed a moving loads technology that can account for the load moving along the length of the rails as the cars move through the drive station. The same ABAQUS FEA Model was used for True-Load software and strain gauges were used to capture strain data. Results of forces vs time was extracted and compared with the assumed ones to draw conclusions and propose design changes.

4. Preliminary Fatigue Assessment

Finite Element Model

Using the 3D CAD geometry, a FEA Model was constructed of half of a car using ABAQUS/CAE software (Figure 4). Since the focus was about loads when the car is in a drive station, it was assumed that the loading of both tires is symmetric along its length, allowing the use of a symmetric FE Model. On the front and rear handles (which are centred laterally on the car), lateral forces were assumed small enough to ignore. These forces would come into play when the train is turning between drive stations, but when passing in a drive station, the train is always going straight. Only longitudinal loads were then considered on the handles. These loads are present when cars are decelerating and accelerating in a drive station.

FE Model was mainly built using thin shell elements S4R, with some continuum shell elements (SC8R) on the side rail and some quadratic tetrahedral elements (C3D10) and hexahedral elements (C3D8R) on thick parts.

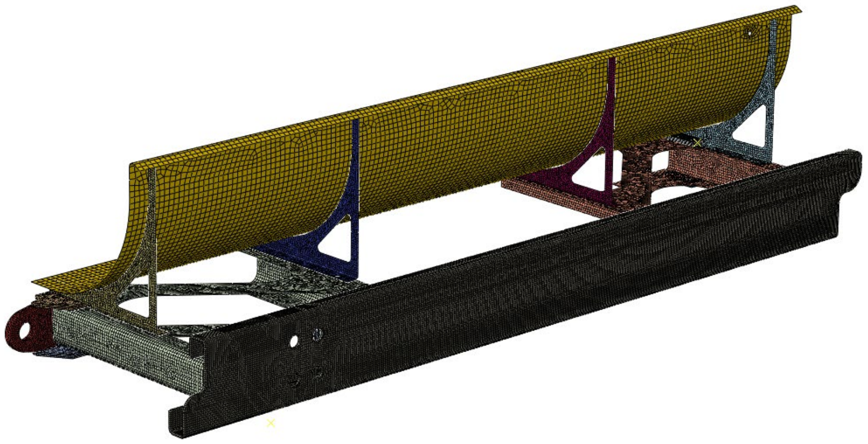

Figure 4: ABAQUS Finite Element Model

Load cases

Three (3) load cases were used for this preliminary analysis. First the payload of ore on the car, which in reality is a static load that varies from car to car. It was approximated to 1000 kg per car and was applied as a pressure distributed on a portion of the tub of the car. The second load was a horizontal load on the rear handle (while the front handle was restrained) to create tension in the car as if the car in front was pulling on it. This load was unknown, so it was assumed to be 16,000 lbf.

Finally, the final load was the tire contact force and shear force of the side panel, which was the one of most interest. For the normal contact force, the information given was that the value was constant at 12,000 lbf. Effectively, this normal force is calibrated with a custom press to obtain 12,000 lbf of force when pushing out the tires with the same displacement as the width of the car will do passing through the drive station. This calibration is done when they adjust the position of each tires and fix them in place.

The combination of normal and shear force was applied in the FE Model using a simplistic representation of the tire that is pushed towards the car with an imposed displacement to create the required normal force of 12,000 lbf. To represent the tire in the FE Model, a simple linear elastic material was defined. Several analyses were required to adjust the material stiffness of the tire and the imposed displacement to create the right normal force and a realistic contact area on the side plate. Values obtained were not real, they just created a good approximation of the load created by the tire on the side plates. As a second step, a torque was applied to the tire to generate the shear force that propels the car forward. The shear force value was not known at the time, so it was assumed to be the maximum friction force possible with a friction coefficient of 0.65.

To realize a fatigue analysis of the car passing through a drive station using static analyses, the forces of the tire on the car needed to be applied at several position along the length of the car from the front to the rear. In total, fourteen (14) equally distant positions were used, creating the same number of static analyses (Figure 5) to run.

Applied boundary conditions were simply the symmetry, the vertical displacement restraint at the wheel (not explicitly represented) and the longitudinal restraint at the rea handle to counterbalance the loading on the front handle.

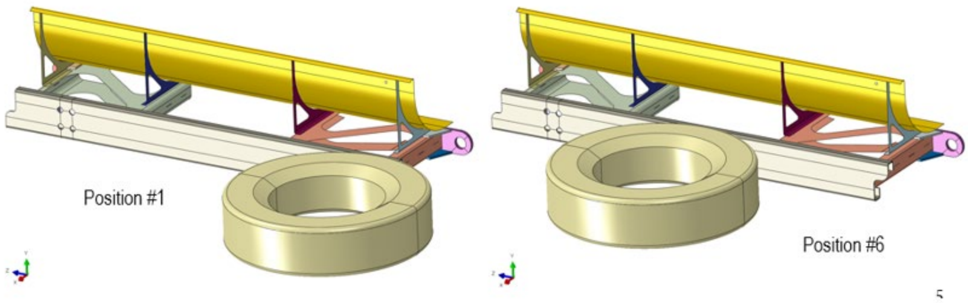

Figure 5: Sstatic FE Model with two (2) different tire positions

Static analysis Results

In addition to the analysis of the handle and payload cases, fourteen (14) static analyses were realized using ABAQUS 2017 for the contact for the tire load on the side plates. Results showed that the tire loading is the one creating the most stresses on the side rail, as expected. What the results showed was local bending being created on the side rail at several locations, more specifically, at both ends of the car and at junction points with the internal structure cross members. It was highlighted that the drastic change of lateral stiffness of the car structure at those locations is responsible for the local bending areas. Both ends and the centre portion of the car were found to be significantly more flexible than the rest of the structure in the lateral direction (the one of the loading). Figure 6 shows the Von Mises stresses for different tire position to illustrate some high stressed areas. Stresses that were calculated at positions 1 and 14 are slightly overpredicted since in reality, another car is present in front and behind the car to take a portion of the tire loading. It was decided that this simplification was acceptable.

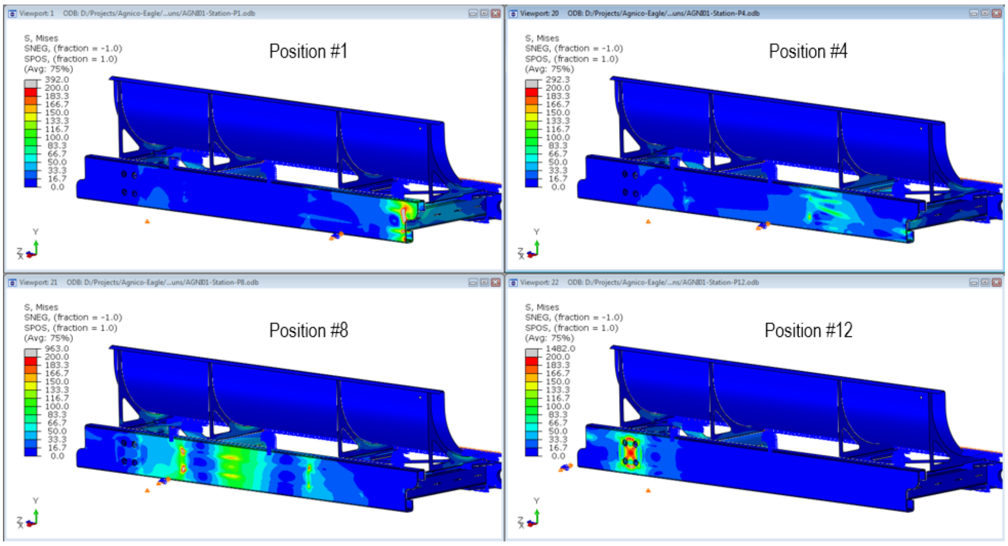

Figure 6: Von Mises stress (MPa) for tire loading at four (4) different positions along the car length

Using a displacement control loading on the tire allowed us to replicate more closely the real loading. We were then able to extract the reaction force of the tire in the FE analysis to verify if the 12,000 lbf (53 KN) of normal force applied is constant. This normal force was calibrated in the FE Model at position one, which is at the front end of the car (right on Figure 7). As it is apparent in Figure 7, the reaction force is varying with each position of the tire along its length. In fact, position 1 and 14 are the most flexible, along with the central section of the car. The reaction force is a reflection of the unequal lateral stiffness of the car structure.

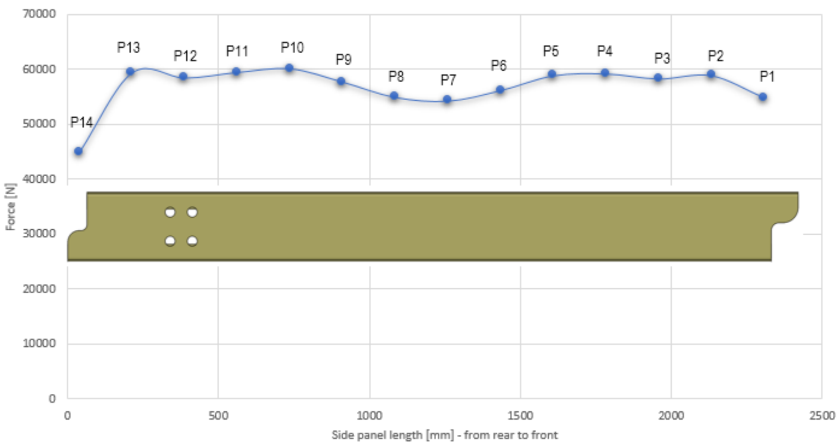

Figure 7: Tire reaction force for all fourteen (14) positions along the car length

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Fatigue analysis results

Using the 14 static stress results, a sequence was defined in Fe-SAFE from position 1 to position 14 to create a duty cycle representing the car moving forward into the drive station. This sequence was repeated 182 times representing going through 2 times 91 drive station (approximately 2 times going up).

Material used for the car is A572 Gr50, which didn't exist in the Fe-SAFE database, so it was created from a Baumer-seeger approximation. Figure 8 shows the strain life curve of the material.

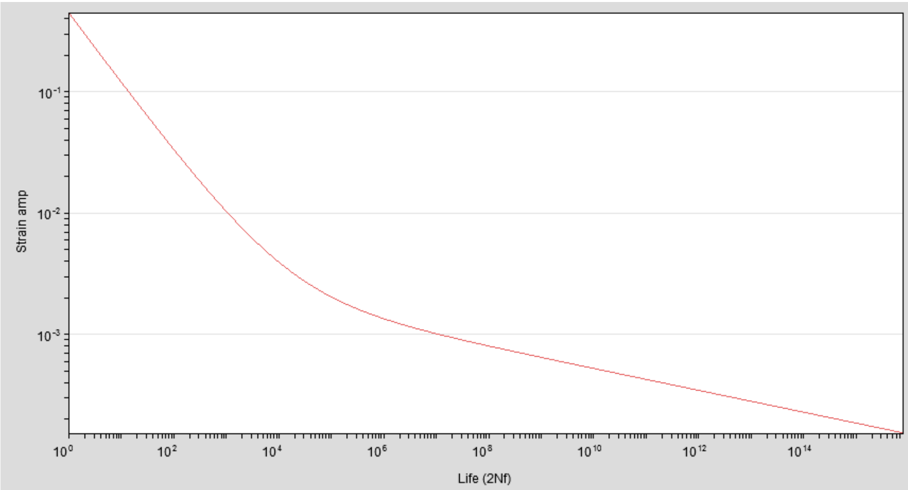

Figure 8: A572 Gr 50 strain life curve

Results of fatigue life (Figure 9) show low life in areas of high stress already highlighted in the static analysis, which are the front and rear end as well as junction areas of the side plate with internal structure cross members. All regions of minimum life correlated well with the location of cracks. The number of cycles was on the order of magnitude with observations in the field. Overall the simplified fatigue analysis was highlighting the problematic areas very well.

It was concluded that the displacement driven loading of the side tire was important as it was creating peaks of stresses due to local bending in some specific areas where the lateral stiffness of the car structure was drastically changing. While the preliminary fatigue analysis showed realistic results, the loading from the tire as well as the one at the handles were still not known with accuracy. It was then decided to obtain a better evaluation of those loads.

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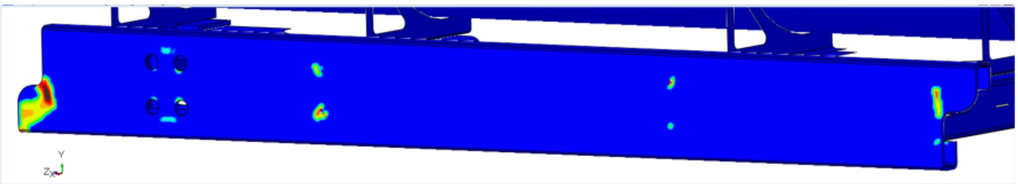

Figure 9: Log of Fatigue life for the 182 repeats of a drive station passage

5. True-Load Analysis

Each car of a train goes through the drive stations going up on a rail that has a path far from being uniform. The train sees multiple turns and the rail slope is varying significantly (Figure 1). Agnico Eagle was interested in evaluating loads on a car for the whole distance as it goes through all the drive stations, loads from the tires as well as the dynamic loads at the handle attaching one car to another.

With that in mind, it was decided to use True-Load software to dynamically calculate real loads on one car while in operation. True-Load is a unique solution leveraging a FE Model to back calculate loads histories from strain histories measured in nominal (linear) areas of a structure. The True-Load methodology is always the same, first build a FE Model of a structure, then decompose the real loads into unit load cases, and solve each load uniquely to get a strain response per load. The True-Load software calculates and optimizes strain gauges locations to use on the structure. When strain gauges installation is done on real equipment, measurements are realized in the field and strain histories and imported back in True-Load which then calculates scaling functions of the unit loads to obtain a correlation between virtual (simulated) strains and real strains. In this application, the structure is going through the drive station. The loads from the drive station are moving along the structure. A unique feature within the True-Load software called 'Moving Loads' was used to produce the time and spatially varying loads on the structure.

Unit loads definition

Loads that were considered for the True-Load study were the tire normal and shear forces, the rear handle vertical and longitudinal loads and the payload vertical and longitudinal loads (representing the friction force of the ore in the tub as it goes up or down on a slope). The tire loads on the side of the car was created 14 times along the length of the car as it was done in the preliminary analysis. Instead of having a simplified representation of a tire applying the normal and shear loads, concentrated forces were used with flexible couplings to distribute each force on an 8 inches wide region (Figure 10). These side loads were combined as a moving load in True-Load for load reconstruction.

These loads were separately applied with unit value to the existing ABAQUS FE Model in static linear analyses to obtain stress and strain results.

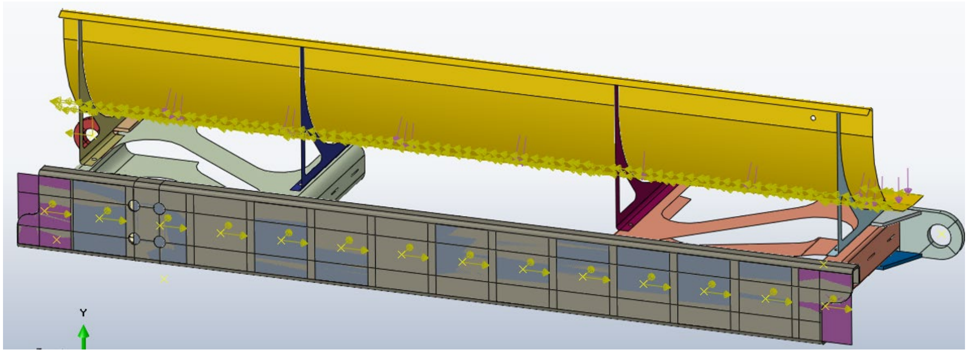

Figure 10: Unit loads definition for True-Load showing 14 concentrated force on the side rail

Strain gauges

Strain results from those analyses were used by True-Load to calculate and optimize strain gauges locations on the structure. The True-Load technology requires that the number of strain gauges should be at least 1.5 times the number of unit load cases. With the usage of moving loads in this application, it was decided that 16 strain gauges were sufficient. The moving load technology analyses the individual spatially varying (drive station) loads along with the stationary (payload and hitch) loads for each position. By using this approach, the number of loads active any one time are 6 and thus great efficiency of strain gauges may be used (e.g. 16). If the moving load technology was not used 32 loads would need to be considered which would require at least 48 gauges. For the same reason as the preliminary fatigue analysis, the symmetry was used for True-Load analysis and the 16 strain gauges were positioned on one side of the car only. Since more channels were available on the acquisition equipment, 4 extra strain gauges were position in a mirror fashion on the other side for validation purposes. Figure 11 shows location of strain gauges as positioned by True-Load while Figure 12 shows images of some of the real strain gauges on the car.

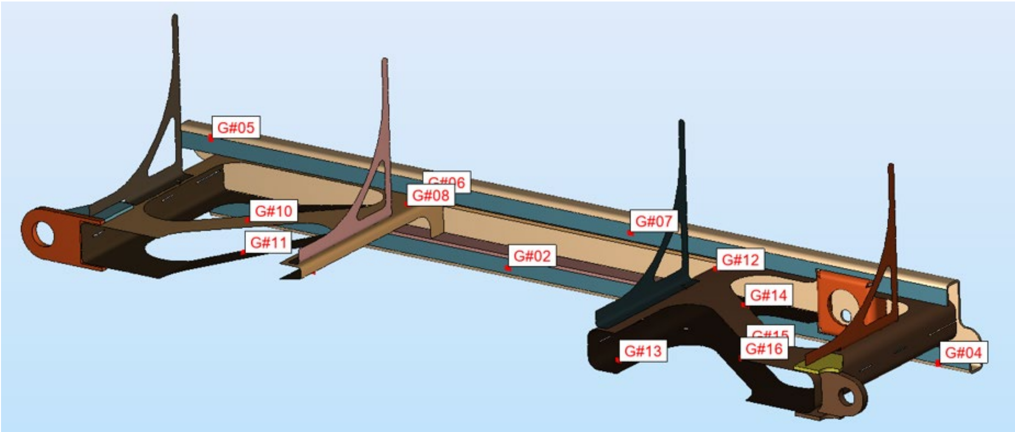

Figure 11: Strain gauges location as optimized by True-Load

Figure 12: Strain gauges installation

Experimental testing

Experimental measurements at the mine was then conducted. A first measurement was done with the train going up full of ore, from 1200 m deep to the top of the rail at 730 m deep. Then a second recording of strains was realized with the train going down empty. Recordings were each of about 20 minutes.

In total there are 91 drive stations on the rail, but during the experimental test, the train went through 75 drive stations when going up, and 60 drive stations going down. When going down, the train skips some drive stations while moving on a side rail to let another train coming up pass. Drives stations at the very top and bottom of the rail were excluded for accessibility reasons.

In order to reduce the data to be processed, selected drives stations were chosen to be analysed with True-Load based on their location and on the velocity profile of the car at drive stations. For each selected drive station, strain histories were post processed for all strain gauges for a time long enough to capture entry and exit of drive stations. Several python scripts were created and used to extract the data from the two long recorded signals. Using the signal from the strain gauges closest to each end of the car (front and rear), average velocity of the car was computed at every drive station, for the case of the train going up (Figure 13) and for the train going down (Figure 14). Drive stations selected for load reconstruction analysis are identified on the same images.

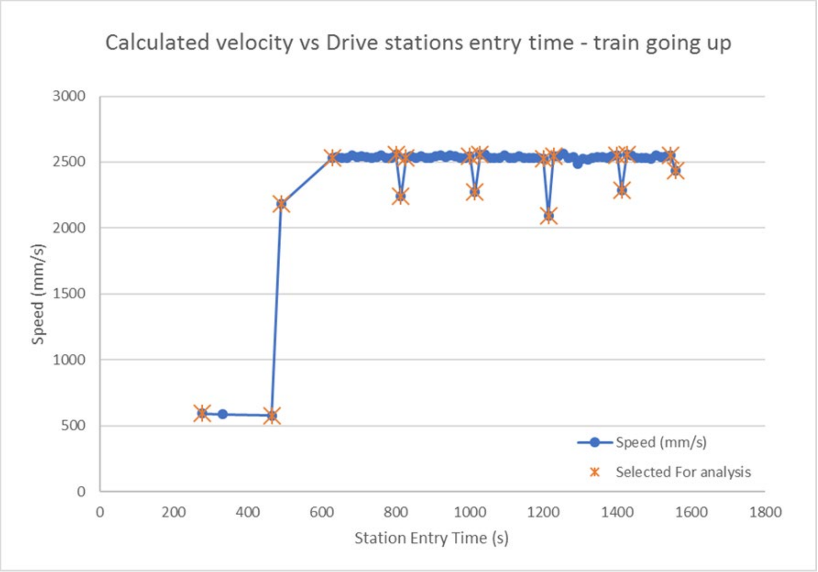

Figure 13: Average car velocity at each drive station (blue dot) while going up

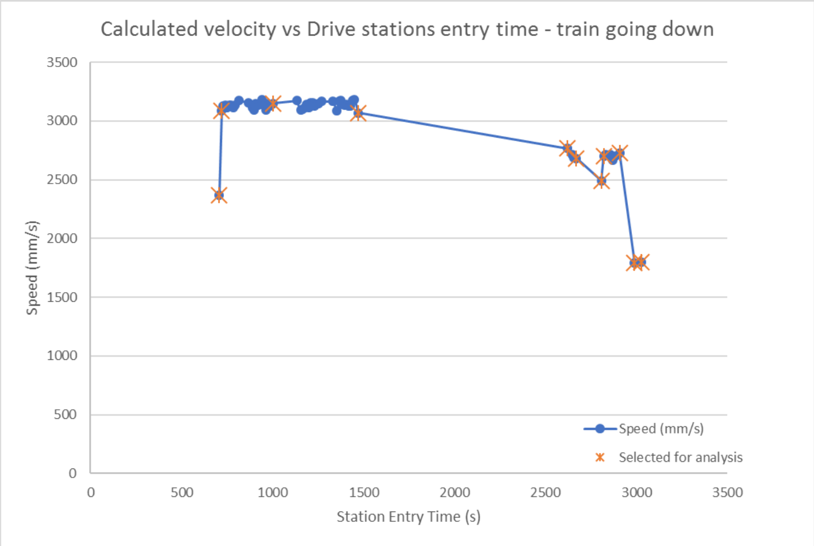

Figure 14: Average car velocity at each drive station (blue dot) while going down

Load reconstruction and results correlation

True-Load/Post-test capabilities were used to calculate the loads from the strain histories. Loads calculated were the normal and shear forces coming from the tire (applied on the side of the car), and the vertical and longitudinal forces at the rear handle.

For every drive station analysed, and both for the train going up and going down, forces vs time plots were generated for the duration it took the car to completely pass through a drive station. A sample of forces plots is presented at Figure 15 for drive station 5 while the train is going down (so going backwards, rear first). The important curve is the brown one, showing the average force as the tire sees it. The other colour curves are individual loads used in the moving load technology of True-Load that were summed up to make the purple curve, that was then integrated over a width of 8 in contact area to obtain the brown curve. The technique used here is to have a stationary static FE Model of the car with the loads from the tire moving along the car. With this approach, True-Load can capture the real behaviour of the moving loads as a dynamic event. By placing an image of the car just below the graph and scaling it at the same width, it is possible to link the location where forces are peaking on the car, since the total time of the graph is the time the tire takes to move from the rear to the front of the car.

The graph shows that the average normal force varies significantly along the length of the car. In the middle of the car and close to both ends, the normal force is constant at about 8,000 lbf while it peaks at around 50,000 lbf and

22,000 lbf temporarily at the intersection of the structure's cross members. At these locations, the lateral stiffness of the structure is much higher than in the middle of the car. This was already observed in the preliminary FEA analysis. The True-Load results show a significantly more important variation of the normal force than expected. The way the system was designed, the normal force was intended to be constant at 12,000 lbs.

In the preliminary FEA analysis discussed at the beginning, it was found that a variation of the normal tire force would be around 10% (Figure 7) along the car. True-Load shows a variation of up to 500% at the peak, which is much higher. This variation of force could be caused by many things, one of which is the tire itself. Our preliminary FE analyses used a soft linear material for the tire, but in reality, the tire is filled with foam and has an unknown stiffness which may well be strain rate and temperature dependent. Looking at results at the selected drive station it seems that a trend present itself where the faster the train goes, the lower the peak of the normal force, and vice versa. For example, Figure 16 shows the force plots for drive station 33 where the train as accelerated to its maximum speed. There is the same pattern of normal force curve, but with lower peaks. The low lateral stiffness of the car structure explains a portion of this normal force variation, but more work would be required to find the other reasons for it.

The shear forces created by the rotating tire also varies with a similar pattern as the normal force, which makes sense since the shear force comes from the friction force that the tire can generate on the side rail. A varying normal force creates a varying shear force.

Results of horizontal forces at the handle are showing significant variations as well, sometimes even changing direction. Figure 17 shows handle force results at same drive station 5 while the train is going down. These force results show some push and pull type of variation and peaks appear somewhat at same location (time) as the normal and shear forces from the tire, which also makes sense. Forces at the rear handle show a dynamic variation going from largely negative to slightly positive as the tire is working to push the train down and puts the car structure in compression pushing against the other cars in front. The horizontal handle forces are working together with the tire shear forces on the side rail. The handle horizontal force is reacting to the varying shear force of the tire on the car, plus the movement and forces coming from the other cars of the train. Focus of this study was on the cracking problems off the side rail of the car, but the varying forces at the handle should certainly be studied to validate the design of the mechanical connection between cars. A loose fit at the handle attachment could eventually create a hammering and fatigue problem.

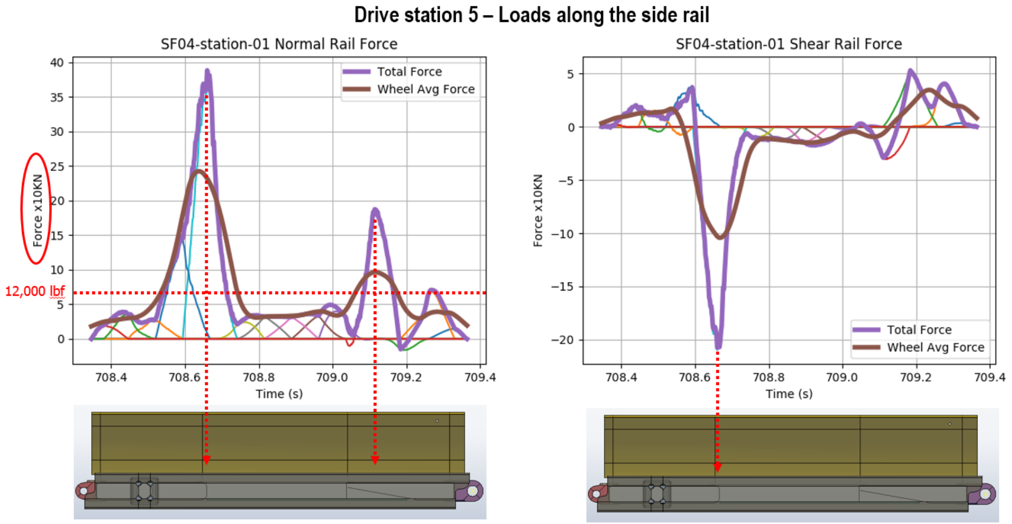

Figure 15: Normal and shear forces from the tire vs time at drive station 5 - Train going down

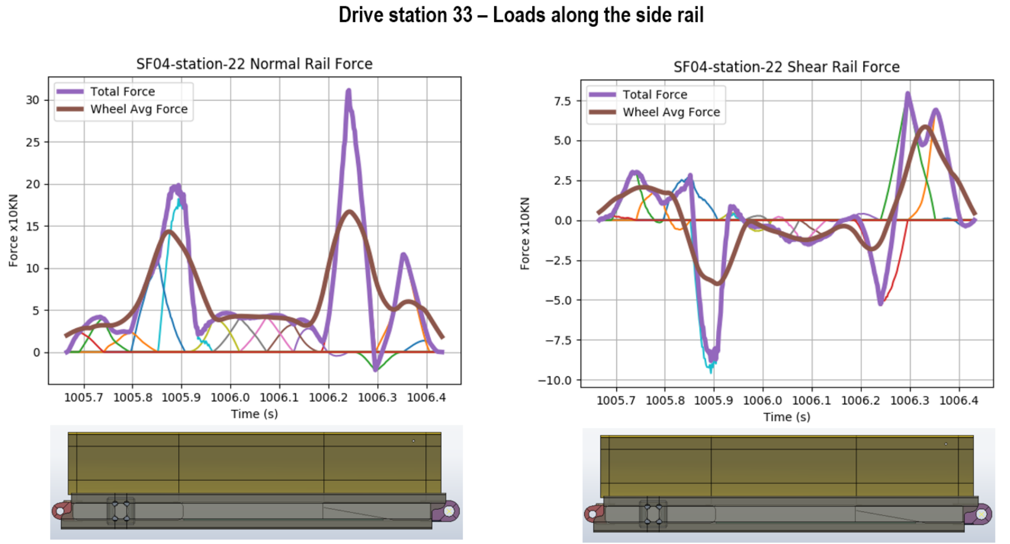

Figure 16: Normal and shear forces from the tire vs Time at drive station 33 - Train going down

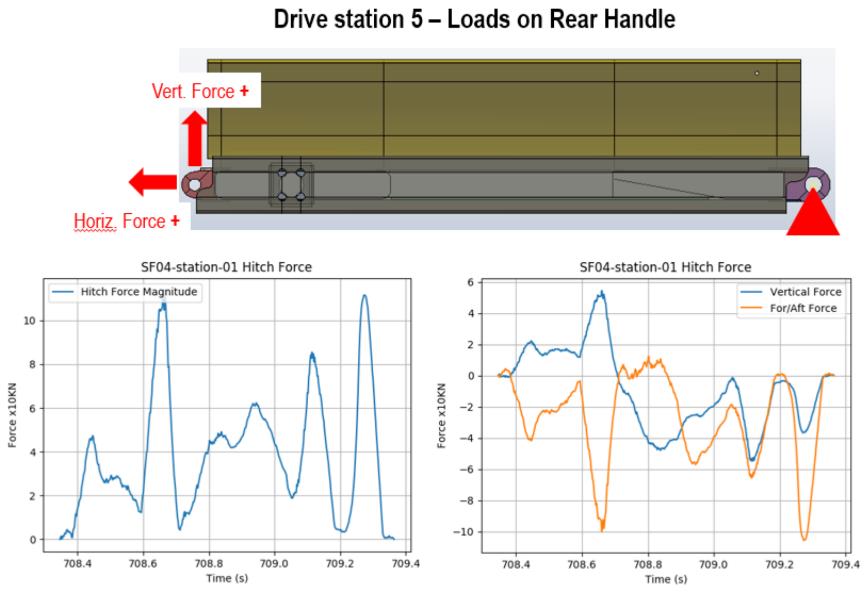

Figure 17: Horizontal and vertical forces on the rear handle at station 5 – Train going down

It is possible to bring back the load functions calculated by True-Load to the ABAQUS FEA Model to generate displacement and stress results as a sequence of static analyses that create a dynamic animation of the loading event (Figure 18). Stress results were higher than in our preliminary FE analysis, since the loads were higher, but the same distribution of stress was obtained showing local bending of the side plate at intersections with cross members.

Generating this dynamic sequence allowed to validate the issue of the drastic lateral stiffness changes in the structure close to the central section and at both ends. It also highlighted an unknown structure issue with the font cross member that buckles under low loads. Effectively, during the passage in a drive station, as the tire arrives close to the front of the car, the cross member sees large deflection up or down as it becomes unstable (Figure 19). Even though this behaviour doesn't have a direct impact on the cracking of the side rail, it is a weakness in the car structure that should be corrected.

This buckling behaviour of the front cross member wasn't expected at the beginning of the project, and the usage of strain gauges for True-Load on this section of the structure is not ideal. True-Load technology is based on a linear behaviour of a structure at the location of strain gauges, which was assumed to be the case for the steel frame of the car. Such a buckling behaviour would generate large strains at strain gauges positioned on it and induce errors in load prediction. Efforts were done in post processing of True-Load results to reduce the effect of these strain gauges and to obtain good correlation between simulation and real. A lesson learned is to spend a little more time studying the structure of interest by FEA using non-linear analyses to validate the linear behaviour of the regions where strain gauges are planned to be installed. Assuming that the design is good is sometimes misleading. Nonetheless, True-Load showed how it is good at capturing design flaws as such in a structure.

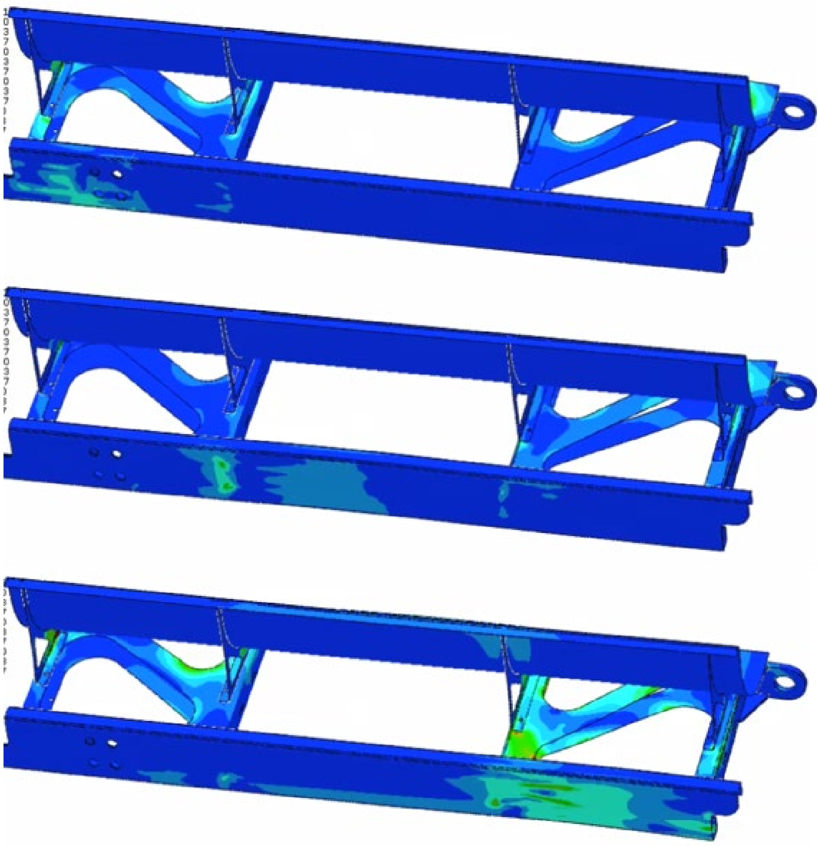

Figure 18: Snap shot of the sequence of stress results while the car goes through the drive station - using True-Load loading

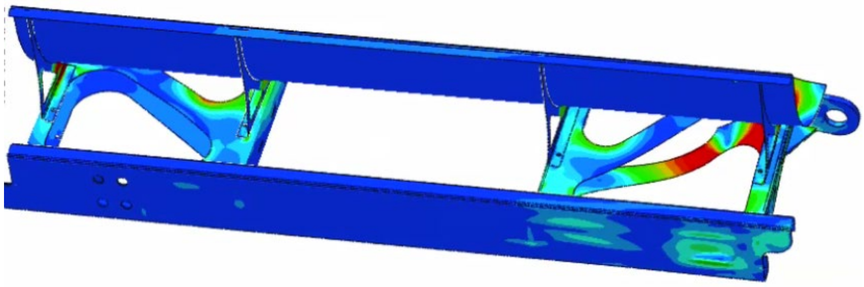

Figure 19: Stress results when tire is at the front of the car showing the front cross members buckling

6. Design Optimization

Following the True-Load results, work was started to make design modifications to the car structure to stiffen the central as well as both end regions of the side rail to obtain a more uniform lateral stiffness which will contribute to obtain a more uniform normal force from the tire. Stiffeners are also added to the cross members in the front to rigidify them and remove the unstable behaviour. This optimization work is still in progress and fatigue FE analyses will be redone to validate the impact of design changes on the fatigue life.

7. Conclusions

The goal of this project was to better understand the loads supported by a mine train car when passing through a drive station in order to understand and to fix a cracking problem of the side rails of cars. Building a FE Model of the car and using a simplified approach with assumed load values was a good assessment that showed local areas of potential cracking that correlated well with reality.

Leveraging the FE Model using True-Load technology allowed the measurement of real loads vs time while an instrumented car passed through all drive stations going up and down. Loads reconstruction calculated by True-Load showed same pattern of normal and shear forces on the side rail from station to station, but with some magnitude differences. The normal force on the side rail showed significantly more variation along the length of the car than it was predicted using the simplified FE Method. Since the driving system is displacement driven (by fixing both tires at a certain distance from each other), no control over load is possible during operation. Position of the tires are selected in a way to generate 12 000 bf of compressive force on the car using a calibration tool. Loads calculated from the True-Load technology show an average of 8000 lbf and peaks reaching up to 5 times that value. The low lateral stiffness of the car structure in the central sections and at both ends were highlighted as a reason that increases normal force variation. Regarding the surprising high value of normal peak forces, more work would be required to study the calibration process to better understand the settings used.

Using the reconstructed loads from True-Load also allowed us to learn significant information on the variation of forces and the push and pull phenomenon between cars that seems to be present all the time. These force variations may affect the handle region as the horizontal forces was even changing sign during a passage in the drive station.

Finally, creating a sequence of static FE analysis from True-Load loading functions allowed for visual animation of the deformation and stress of the car as it passes through a drive station. These results showed a structure weakness in the front cross member of the car that buckle under small loads.

For such a driving system, it would be ideal to have a constant normal force of the tire acting along the car in order to create a constant friction force to propel the car forward steadily. A force driven system, while being more complex, would be the perfect solution. With the actual displacement driven system, more studies should be done on the tire loading and calibration to understand the variation of normal force from the tire. While the car structure having a flexible central section is certainly a reason explaining the variation of force, the foam filled tire itself is probably an area to look at as well. Design improvements have focused on reducing the stiffness variation in the structure and addressing local stress concentrations.