A Simulation Study on the Square Bridge Piers Subjected to Vehicle Collision

By

Kilian Lau Meow Hing

15133

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Civil)

May 2014

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CERTIFICATION OF APPROVAL

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Approved by,

____
(Dr. Teo Wee)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(KILIAN LAU MEOW HING)

ABSTRACT

The number of bridge piers collapse had been major issue that results in disastrous consequences as the number collision between pier and vehicle has increased rapidly for the past few years. The current code of assessment for the bridge pier design are suggested to be not enough to be consider in a dynamic impact force. Hence, this research has been conducted to further study the impact force generated from the heavy truck vehicle to a bridge pier with different parameter studies and to reviewed the design impact force currently used. Software LS-PrePost and LS-DYNA are suggested and recommended to be used to simulate the collision between vehicle and piers in finite elements forms that can analyze the impact force based on complex scenarios. Different model of truck are used to collide with a different size of square bridge pier in scope of study. The Ford F800 Series 8-tons and HGV 16-ton heavy truck are used in this project. Different cases and parameters will be included to analyze the behavior for the impact collision.

Acknowledgement

Over the duration of this project, I feel grateful for having Dr Teo Wee as my assigned university Final Year Project Supervisor. His guidance throughout the 8-month research project has assisted me in my progress.

Also, I would like to express my gratitude to my senior, Mr Yin Hor, a Civil Engineering Master student for his continuous advice and guidance as my project advances. I am thankful for their aspiring guidance, invaluably constructive criticism and friendly advice during the project work. I am sincerely grateful to them for sharing their truthful and illuminating views on a number of issues related to the project.

Last but not least, I would like to show my token of appreciation to UTP for providing a platform for me to excel in my research and to gain my experience as well as knowledge of understanding in the field of study. UTP has offered and bought the license required for the verification of LS-DYNA software solely for our simulation project.

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CHAPTER 1

INTRODUCTION

1. Background

At the present time, the number of collision of heavy vehicles with bridge piers have increased rapidly. The occurrence in the past has sometimes result with disastrous consequences. The vehicle collisions are one of the lead causes in structural failure. The collision designed for the pier is by static analysis, but the collision force is highly dynamic practically. From the accident at Farm-to-Market (FM 2110) bridge over Interstate Highway (IH-30), Texarkana, Texas, a truck collide with a pier and caused 2 spans of the bridge to collapse. This accident not only caused human life and caused the highway to be shut down but also loss of high maintenance fee for the reconstruction. The number of collision on bridge piers had increased rapidly over the year and become a huge concern when designing for the bridge pier. Furthermore, the numbers of bridge in Malaysia are increasing and piers will be an important aspect in Malaysia.

2. Problem Statement

As the number of the collision on bridge piers subjected to vehicle accident are increasing rapidly. This has become a treat in bridge piers design as most of the piers design are designed to overcome a lower impact of collision as the current designed impacted force used is stated in the standard code. Hence, the bridge piers subjected to vehicle collision is needed to be studied to improve the current design. The natural impact force between the vehicle and pier are to be determine and analyze by using different variable of size, height, shape, support and steel reinforcement. From current studies, numerous collision research had been done on land and water. The aim of this project is to further detail study on the impact force on piers.

3. Objectives

The objective of this research is to perform a nonlinear finite element program LS-DYNA to simulate the vehicle to pier collision relating with the exact scenario and conduct parametric studies on the force imparted during the impact. The consistency of the design code used for impact design are needed to be reviewed.

4. Scope of Study

The bridge piers impacted by large vehicles are typically fail due to large shear and bending forces. The 8 tons HGV and 16 tons HGV truck are used in this model as a studied for this research. The additional loads on the truck will be applied as a factor for simulation. 2 different velocities of the impact which are 80km/hr and 110 km/hr will be analyzed using LS-DYNA software. The studies included the learning to create a square reinforced concrete bridge pier section using the software. However, elastic material will be used for the pier signifying a concrete model with steel reinforced for time saving purposes for this project. Parametric studies will be conducted after the analysis is done.

CHAPTER 2

LITERATURE REVIEW AND/OR THEORY

1. Software

LS-DYNA software is a general-purpose finite element program for simulating complex problems. It can be used in automobile, construction, manufacturing, etc. This software is applicable in a wide range of any physical events that involves in different combination of features. For this project, LS-DYNA will be able to determine a car's behavior in a collision and the effects of the bridge pier. The stresses, deformations or energy experienced by the collision can be accurately be calculated. Its capabilities include 2D and 3D of static or dynamic and linear or non-linear analysis. Hence, LS-DYNA is suitable software to be used as a analysis for this project.

2. Strength of Bridge Piers

The bridge piers subjected by vehicle collision are generally duel with large shear and bending forces that result in collapse. Based on some of the findings, the diameter of the pier does not have huge effect on the impacted force exerted by the truck (Joshi & Gupta, 2012). The maximum speed used in this research is 96km/h and 30-tons of truck with diameter of 1m of circular pier by using MATLAB software. The arrangement and tying of steel reinforcement inside the pier and meshing of the pier are essential when doing the simulation whereby the strength and stiffness helps to overwhelm the impact of the force.

3. Action live load

According to Eurocode 1- Part 1.7 of Accidental actions, it is stated in table 4.1 that the highest horizontal impact force is 1000kN for motorways and country national roads for the supporting structures. Therefore, the aim for this studies are to study whether the impact force stated in the code is comparable with the simulation we do. The collision force F may be applied at h=0.50m above the level of the road.

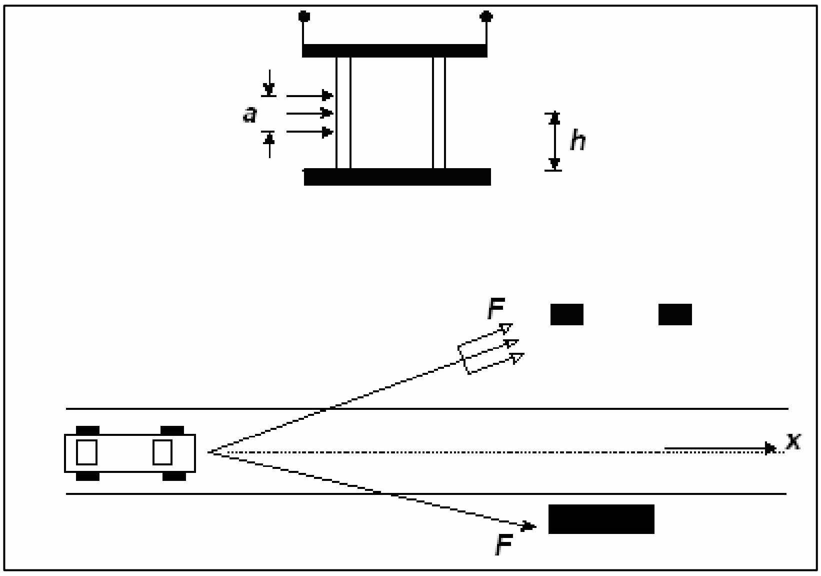


Figure 1: Vehicle collision at road

a is the height of the recommended force application area. Range from 0.25m (cars) to 0.50m (lorries)

h is the location of the resulting collision force F. The height above the level of the carriageway, range from 0.50m (cars) to 1.50m (lorries)

x is the centre of the lane.

4. Engineering structures

From “Laboratory tests and numerical simulations of barge impact on circular reinforced concrete piers” (Sha, Hao, 2013), the pier column height effect is minor to the peak impact force as the impact energy is the same for different height and the peak impact force occurs at the instance of collision. However, the impact duration corresponding to higher height is longer due to the prolongs of the impact time duration. For the effect of pier diameter, the impact force increases with the increase with the diameter. It is stated that the square pier impact cases is different which the peak impact force strongly depends on the pier dimension. The result show that the larger diameter is stiffer which reduce the impact displacement. The soil foundation pier interaction will have minimum influence on the impact forces as it affect the free vibration response. For this project, the support for the bridge pier is fixed supported on both top and bottom as it is predicted to have the highest impact force on collision between the vehicle and pier.

The model is generally made up of many parts that represent all major structural components and nonstructural components in a finite element models (Arbor, n.d.). The steel bars will be represented as beam elements and some specific point can use hinge type connection to release the moment and shear. The main bar and shear link maybe steel bar but both has its own purpose which indicate different joint connection. The geometric properties of the pier of the concrete and steel had to be govern to resemble the real situation of the impact.

5. Simulation study

The collision of time is small and large variation in the force with respect to time is needed to be study. The main study is the pier subjected to collision and not the colliding vehicle (Joshi & Gupta, 2012). Hence, by using LS-DYNA, the modeling part is essential as it define the contact part whether the vehicle or the pier to be master or slave in the analysis. The manual calculation for the force can be calculated using equation (British Standards Institution 1998) and compare with the impact force from the simulation from LS-DYNA.

$$a = \frac{(v\ sin\theta)^2}{2[c\ sin\ \theta + b(cos\theta - 1) + z]} \quad (1)$$

$$Mean\ impact\ force, F(kN) = ma$$

$$= \frac{m(v\ sin\theta)^2}{2000\ [c\ sin\ \theta + b(cos\theta - 1) + z]} \quad (2)$$

m is the mass (kg)

b is half the width of the vehicle under consideration

c is the distance of the center of gravity, which largely depends on the good being transported, considered to be located at half the distance of the truck

v is the velocity

z is the crumpling measured perpendicular to the barrier (m)

According to (T. Ambati, K. Srikanth & P. Veeraraju, n.d.) for the frontal crash test, most of the energy of the impact is absorbed by the bumper, radiator, engine and the rails for the Chevrolet C15000 model. It stated that numerous instrumental tests show that most energy transfers in a head-on or frontal vehicle within 0.2 seconds.

6. Elastic and concrete material

The elastic material is known as mat_001 in lsdyna. This hypoelastic material may not be stable for finite (large) strains. A hyper elastic material model should be used if strains are too large. The axial damping factor(DA) and bending damping factor(DB) are used for Belytschko-Schwer beam (Type 2 only). Therefore, for this pier DA and DB are specifying as 0. This material will enable this research to be assigned as a concrete material by adjusting the mass density and Young's modulus similar to concrete behavior.

The concrete mat known as mat_159 has erosion which may be caused in high speed collision. The default concrete concrete strength with unconfined compression strength in between 28 and 58 MPa. Concrete displays soft behavior in tensile and low to moderate compressive regimes. It has brittle and ductile properties causing the simulation to be more difficult.

7. 8 tons & 16 tons truck

From "Impact Analysis of a 16t Truck against different Road Safety Restraint Systems" (Mongiardidni, n.d.), the parts of the 16 tons truck are considered relevant for the impact dynamics which are model in detail. It had been concluded that the 16 tons model are proved to be reliable. The parts such as air tanks, fuel and battery box are modeled for the realistic motion at the front axle.

CHAPTER 3

METHODOLOGY/ PROJECT WORK

1. Project Flow Chart

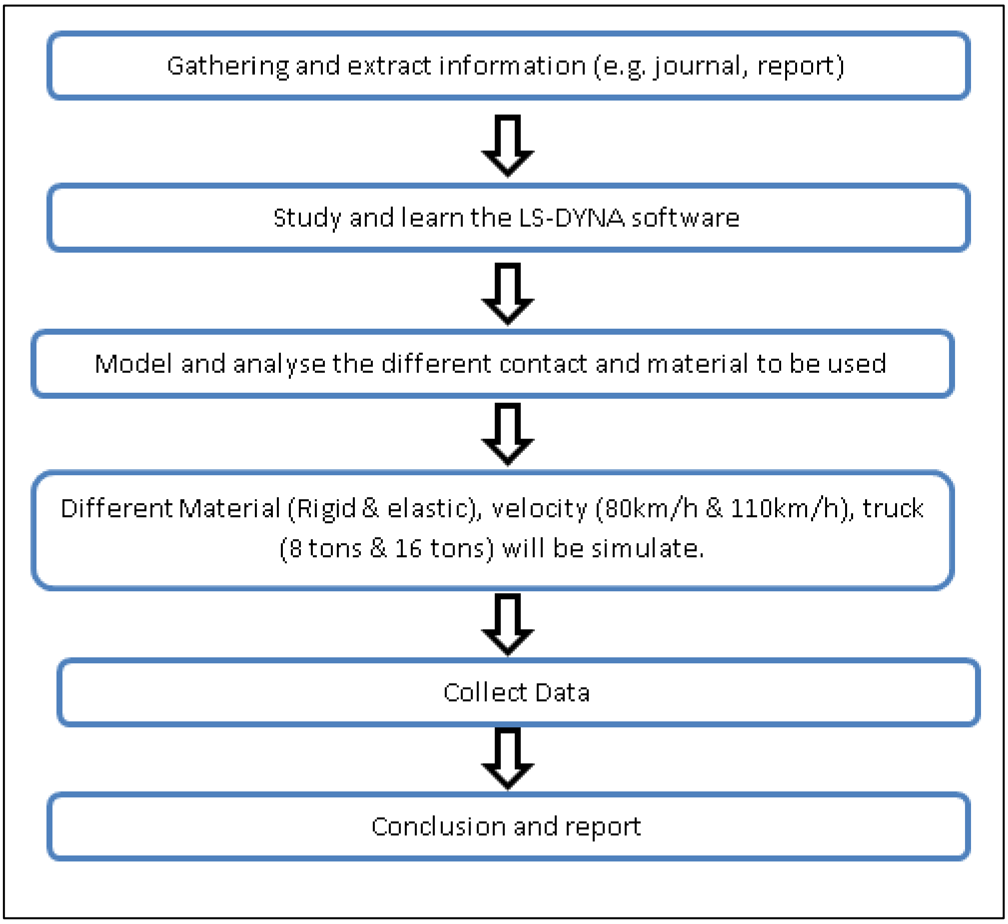


Figure 2: Project Flow Chart

2. <u>Gantt chart and key milestone</u>

FYP 1															
No.	**Activity**	**W1**	**W2**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**	**W9**	**W10**	**W11**	**W12**	**W13**	**W14**
1	Selection of Project Topic														
2	Preleminary Research Work														
3	Submission of Extended Proposal Defense														
4	Proposal Defense														
5	Project work continues														
6	Submission of interim Draft Report														
7	Submission of Interim Report														
FYP 2															
8	Project work continues														
9	Submission of progress report														
10	Project work continues														
11	Pre-SEDEX														
12	Submission of draft report														
13	Submission of dissertation report (soft bound)														
14	Submission of technical paper														
15	Oral presentation														
16	Submission of dissertation report (hard bound)														

3.

Figure 3: Gantt chart and key milestone for FYP

From the Gantt chart, the preliminary research work takes a significant amount of time for the understanding of this whole project from the existing studies on the related topic from journal and books. This is due to the time taken to understand the concept and theory of the vehicle collision and study the LS-DYNA software. The concept and theory include the consideration on analyze of the collision. In this case, only 1 size of square bridge pier with diameter of 1.0m and height of 7m are used. The fixed variable for this simulation is the collision vehicle used which is 16 tons HGV truck and 8 tons truck. However, additional loads are needed to be added as a factor for the analysis.

The scenario is then modeled using LS-DYNA software for the simulation to study on the collision. The 16 tons model of truck will be provided and the bridge pier is needed to be design and modeled. The range of collision time for the analysis will be around 0.5s to 1.5s. The velocity used will be according to the Design Code had stated.

The simulation is conducted and data is collected. This data will determine the severity of the collision and provide a clear understanding on the impact of it. With this, result and discussions can be determined. This project can be concluded and prepared for the report for the project.

4. Model Development

Units used in LS-DYNA for this model:

Length unit	**millimeter,mm**
Time unit	**second**
Mass unit	**tonne**
Force unit	**Newton**
Stress unit	**Mpa**
Energy	**N-mm**
Density	**7.83E-09**
Young's	**2.07E+05**
Velocity	**2.22E+04**
Gravity	**9.81E+03**

Table 1: Units used

Vehicle

The model of the 8 tons truck and 16 tons truck is checked with different parameter studies before it is agreed that the model is accurate. The vehicles model are checked to be exactly 8 tons and 16 tons by using d3hsp file. The different parts of the vehicle are model in different materials and sections. The crucial parts which is the 2 mounts for fixing the brake onto the front axle, passenger side are model in solid section types and a rigid behavior that had the highest stiffness that holds the vehicles. The other part will be the frame of the vehicle which is known as fishbone that holds the vehicle at the bottom from front to back. The engine are model in elastic behavior and the rest of the parts are plastic. The vehicle are assigned to be 80 km/h in velocities for current progress, velocity of 110km/h will be assigned for parametric studies. The addition load for this project will not be added to represent load carried on truck and passenger sitting in the front sit. Hence, the main application will be the collision between the pier and truck.

8 tons truck model

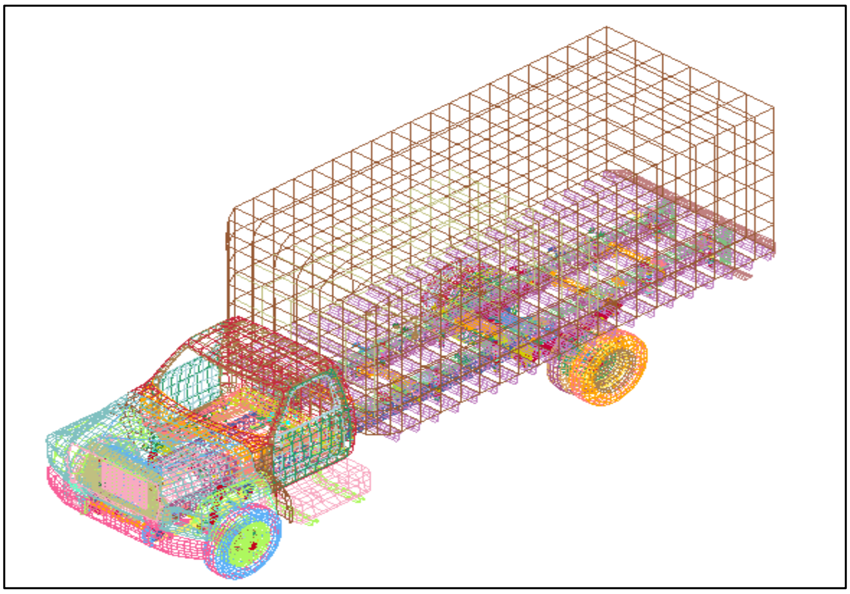


Figure 4: Isometric view of the detail model of the 8 tons HGV

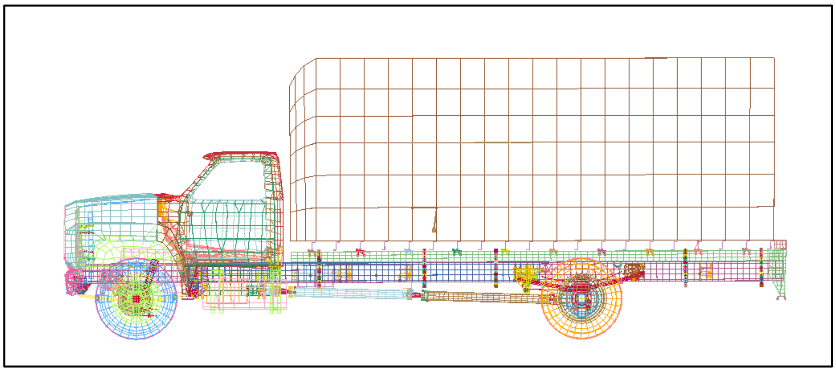


Figure 5: Side view of the detail model of the 8 tons HGV

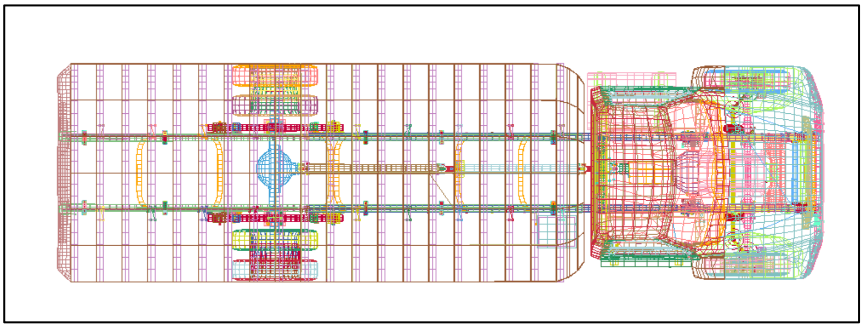


Figure 6: Top view of the detail model of the 8 tons HGV

16 tons truck model

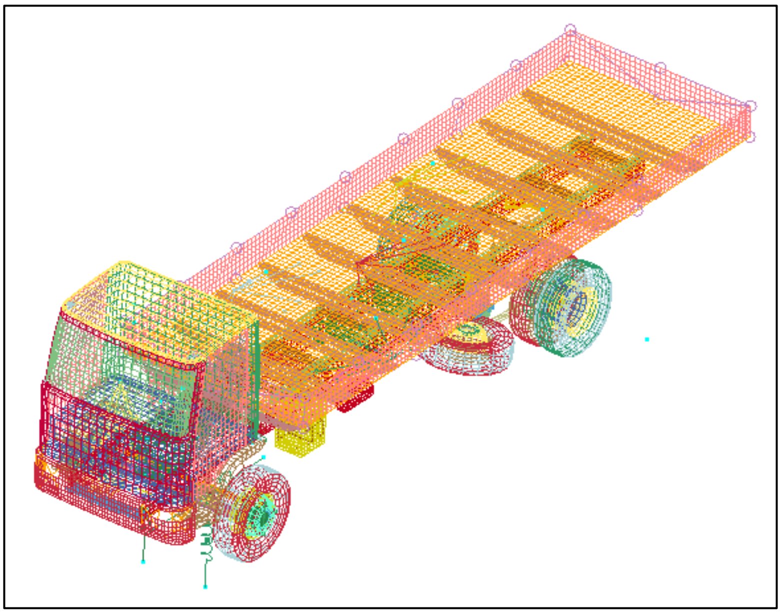


Figure 7: Isometric view of the detail model of the 16 tons HGV

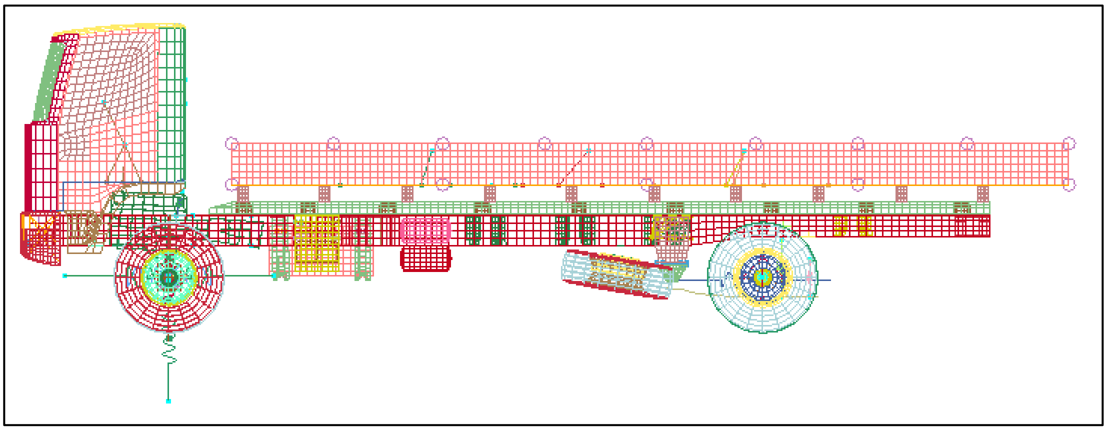


Figure 8: Side view of the detail model of the 16 tons HGV

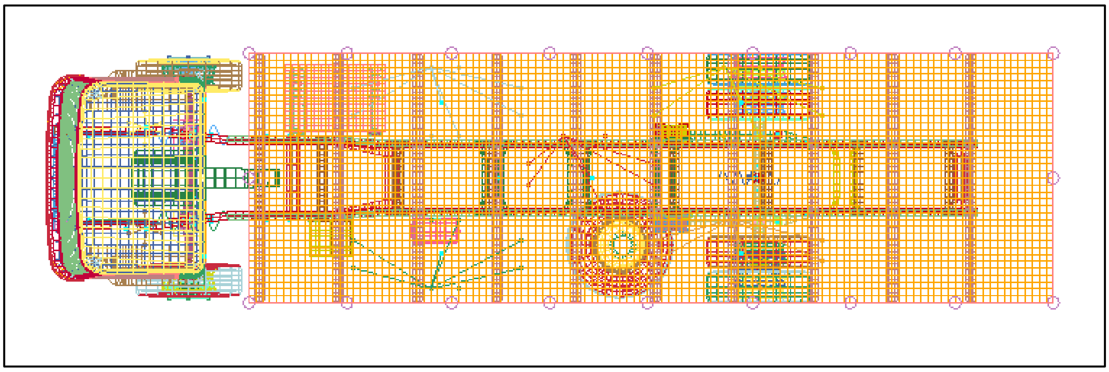


Figure 9: Top view of the detail model of the 16 tons HGV

Pier

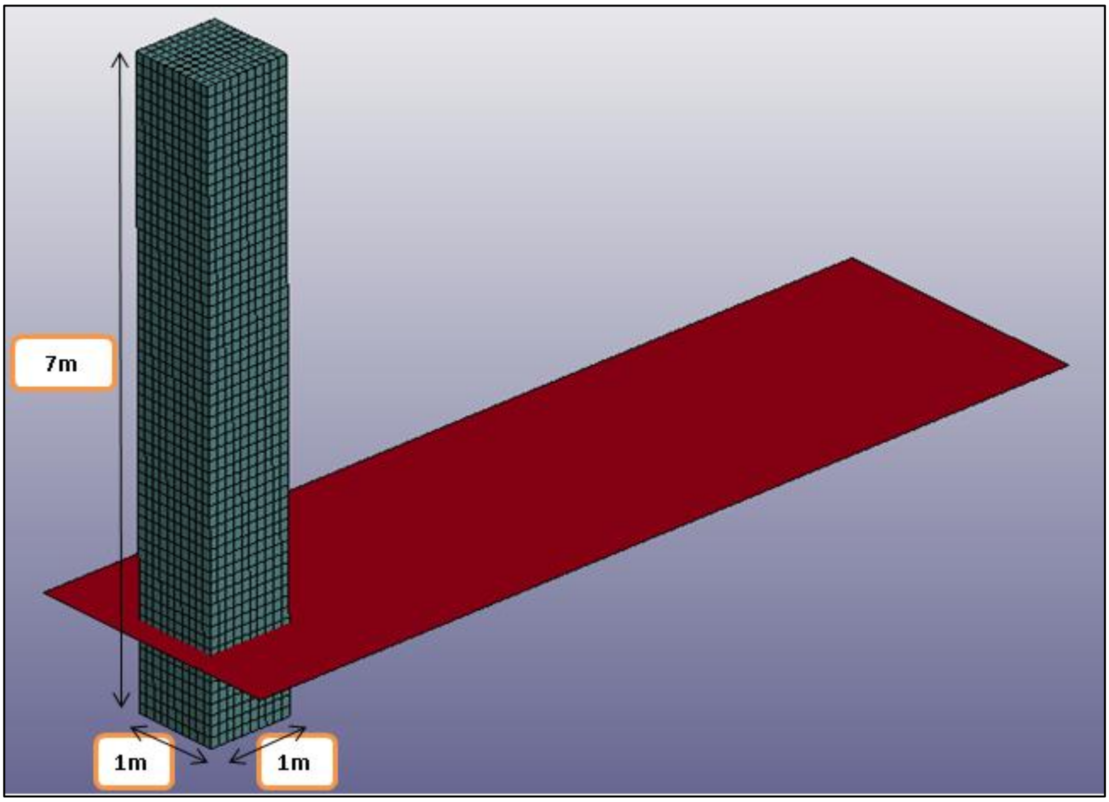


Figure 10: Rigid pier and road

2 type of materials for the pier will be used to analyze for this project. For the progress so far, the pier are model in rigid behavior with material of 21 x 10^4 of Young's Modulus, mass density of 7.85 x 10^{-9}. The rigid pier column are fixed at both end in the model. The pier used in this research will be square in shape. The rigid pier is model in 7m high for the testing and a rigid wall is model as a road using rigidwall_planar keyword. The rigid pier is placed right in front of the truck model to reduce the time of processing.

The second material used will be elastic behavior with mass density of 2.5 x 10^{-9} and Young's Modulus of 3.1 x 10^4. The contact used will be automatic_surface_to_surface.

Different cases

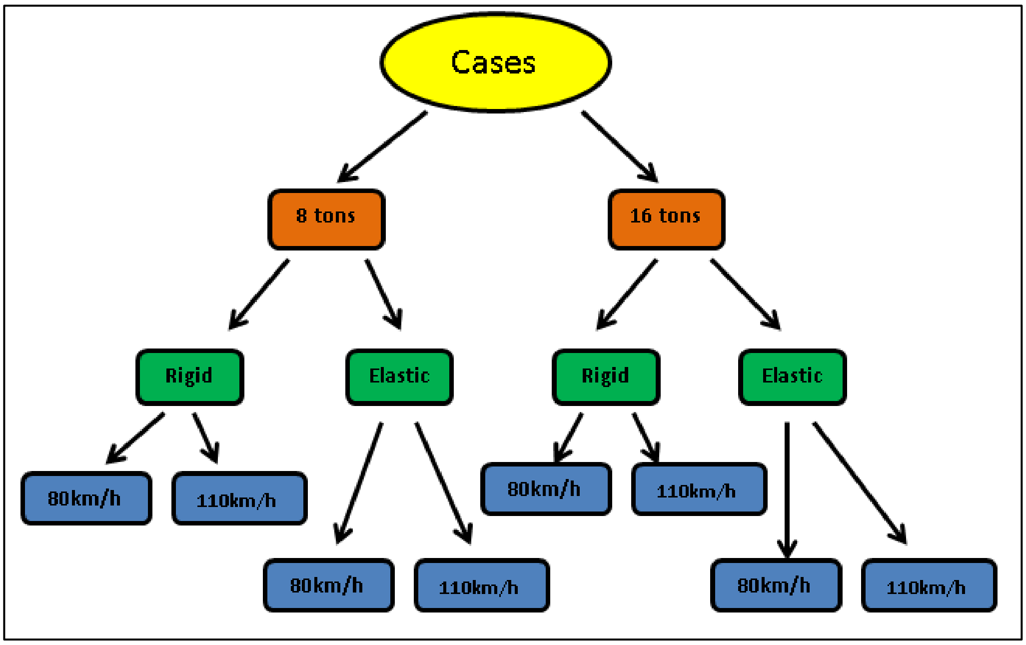


Figure 11: Different cases

Progress Table

Cases	8 tons	16 tons	Rigid	Elastic	velocity= 80km/h	velocity= 110km/h	Completed
Case A	√		√		√		C
Case B	√		√			√	C
Case C	√			√	√		C
Case D	√			√		√	C
Case E		√	√		√		HC
Case F		√	√			√	HC
Case G		√		√	√		C
Case H		√		√		√	HC

C	Completed
HC	Haven't completed

Table 2: Progress Table

The material of mat_159 of CSCM_CONCRETE and mat_072R3 of CONCRETE_DAMAGE_REL3 had been tried so far. However, due to time constraint, the elastic material will be used to represent a reinforcement concrete behavior for the pier. Further time are needed to study the modeling for reinforcement in the mat_159 by using different contact to merge the stirrup and main rebar together to behave like a real reinforcement concrete pier. For the time being, rigid and elastic material will be used for this project.

As for the contact, automatic_single_surface and automatic_general had been tried but automatic_surface_to_surface had been used for this project. Compare with both the contact, automatic_surface_to_surface are easier and safer to be used as it does not need to verify any master and slave or force transducer for post processing. Due to the limited availability of resources, easier contact and material had to be used which will ultimately cause inaccuracies of the result.

CHAPTER 4

RESULT AND DISCUSSION

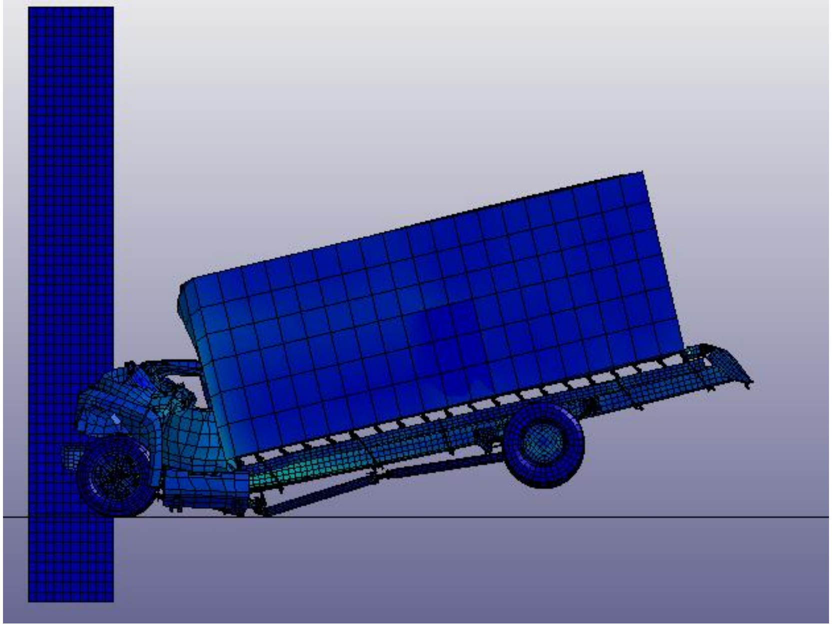


Figure 12: Crashing of truck onto the rigid pier

The F800 Series Truck is used for the simulation on a rigid pier for the progress so far. Rigid Pier which is not yieldable are used only to test on the deformation and damage on the truck. It is shown in Figure 4 that the pier does not bend or crack due to its rigid behavior. Hence, the energy and force acquire in this stage may not be accurate. From the simulation result, it has shown that the crashing of the truck appears to be realistic and equitable which the vehicle crash in and lift up and then falls back down. The truck had lifted around 0.8m high due the center of gravity that cause the moment.

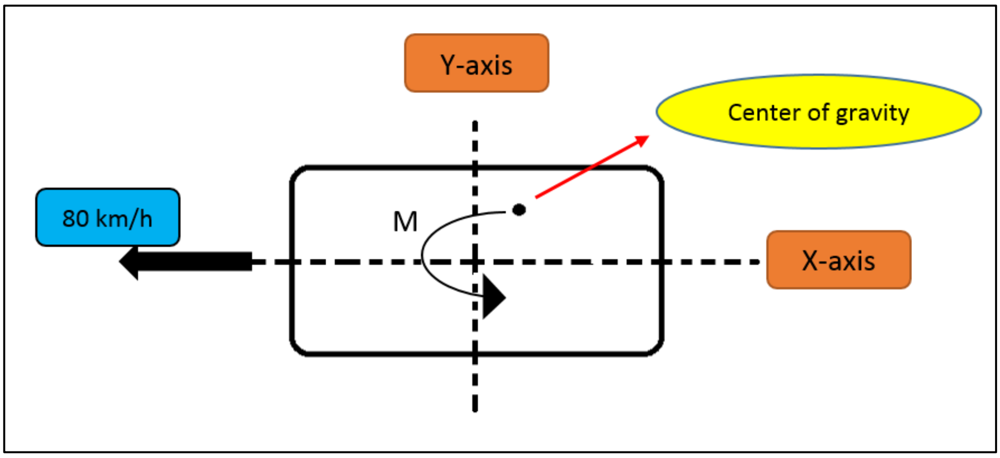


Figure 13: The moment causing the vehicle to lift up

By testing the truck, different contact are used to resemble the exact scenario collision:

Contact_Automatic_Surface_To_Surface

This contact is a 2-way treatment of contact where slave and master is needed to be defined for the vehicle and pier. It is recommended contact type since the orientation of parts relative to each other cannot always be anticipated model undergoes large deformations.

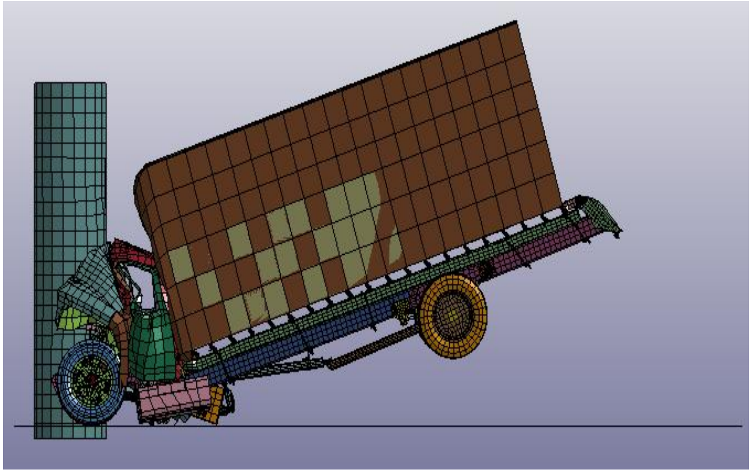


Figure 14: Automatic surface to surface collision

From the contact used, it has shown that the contact of crashing truck appear to be realistic and logical. However, based on the current result, the collision of contacts are still not be able to be determine which one to use due to lack of uncertainty result. Further findings, researches and simulation are still needed to study to resolve this uncertainty.

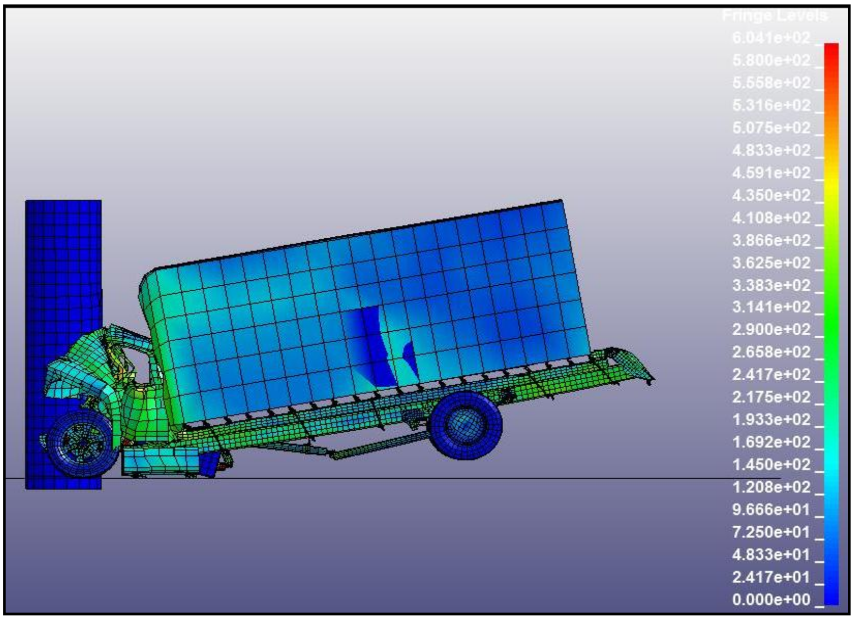


Figure 15: Von Mises Stress Analysis of the Truck

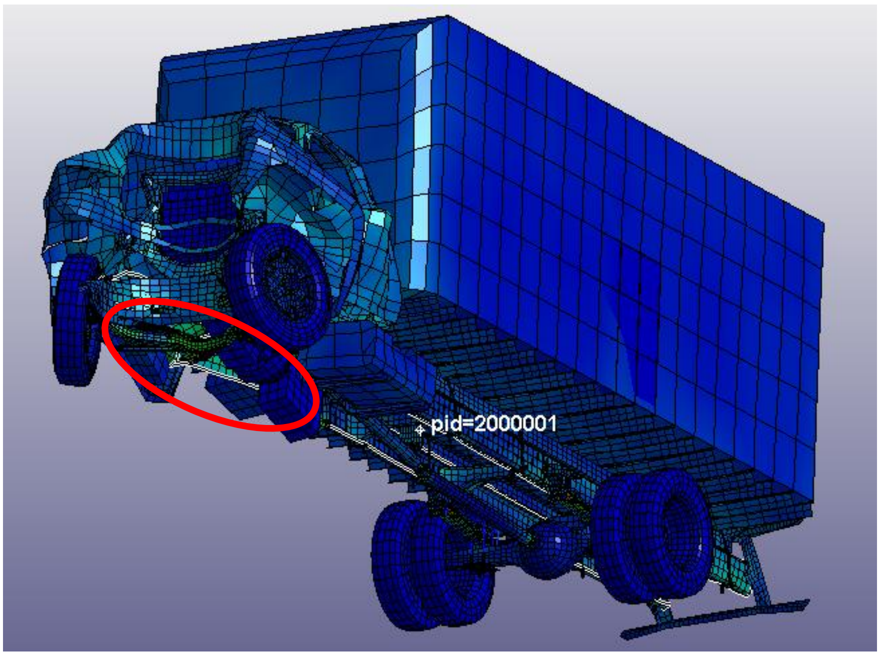


Figure 16: The frame of the truck

Based on the result, the frame experienced the highest stress due to material property which is 385 MPa in this model. Part ID 2000001= frame (Figure 9) is the major part that collide with pier and helps transfer most of energy to the back part of the truck. The energy are covert from kinetic energy to heat energy and sound energy but most to internal energy.

Rigid

1. Energy

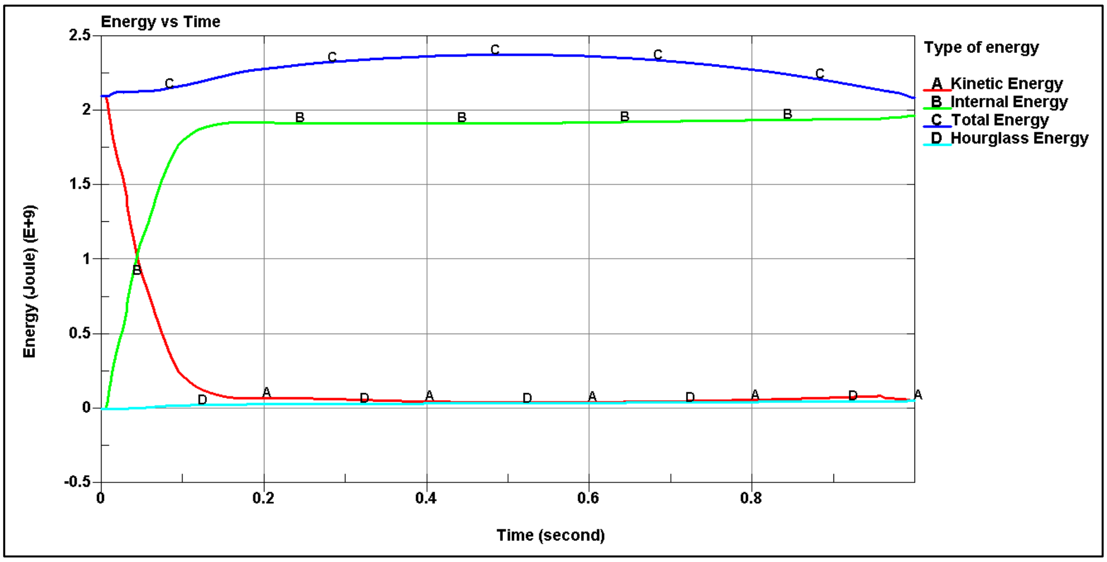


Figure 17: Energy vs time in Rigid Pier

The kinetic energy is slowly changing to internal energy after the collision. However, due to the rigid pier, the truck are bounce back without transferring the energy to the pier.

2. Resultant forces

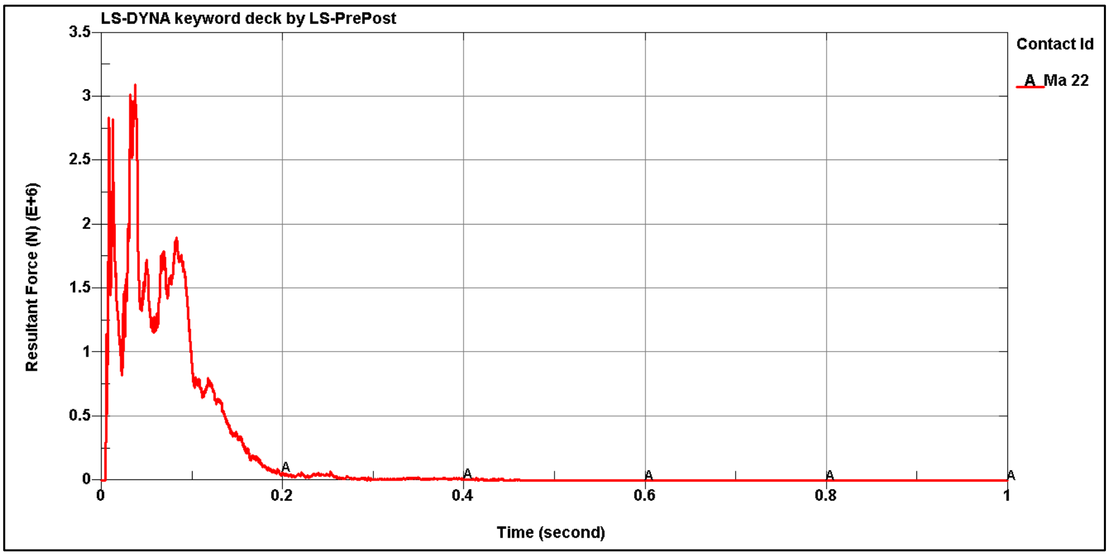


Figure 18: Resultant Forces in 1 second

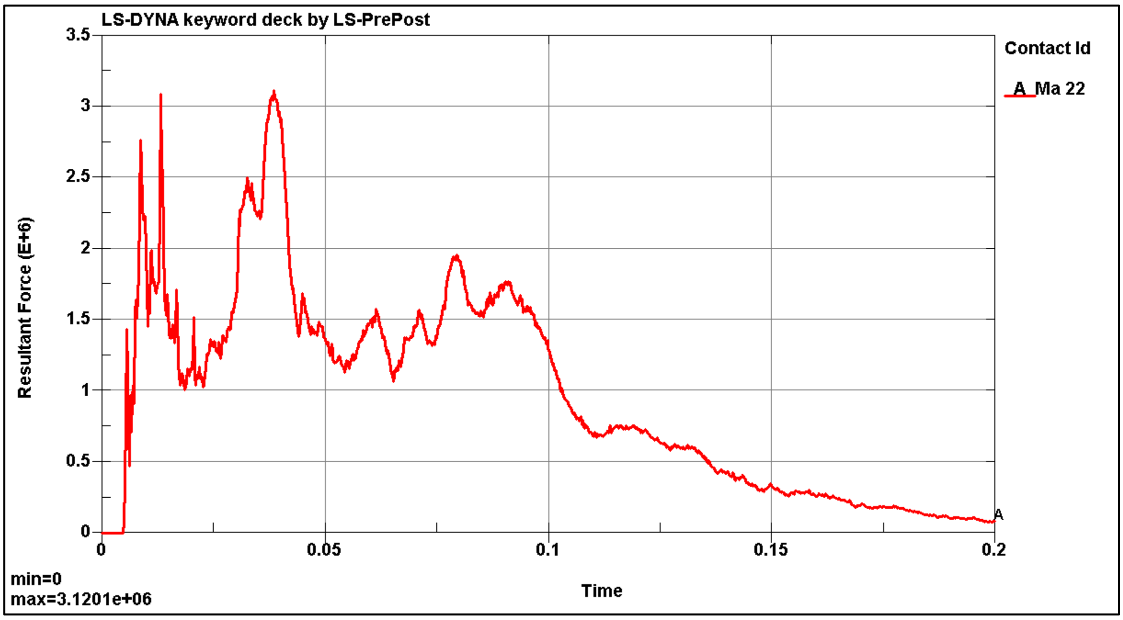


Figure 19: Resultant Forces in 0.2 second

The graph shows the total force impacted on the rigid pier with velocity of 80km/h. The maximum force impacted are 3.12 x 10^6N. It can be clearly seen that 2 peaks of force within 0.05 second with the 1^{st} collision of contact between head and pier, and 2^{nd} collision from behind the truck.

3. Displacement

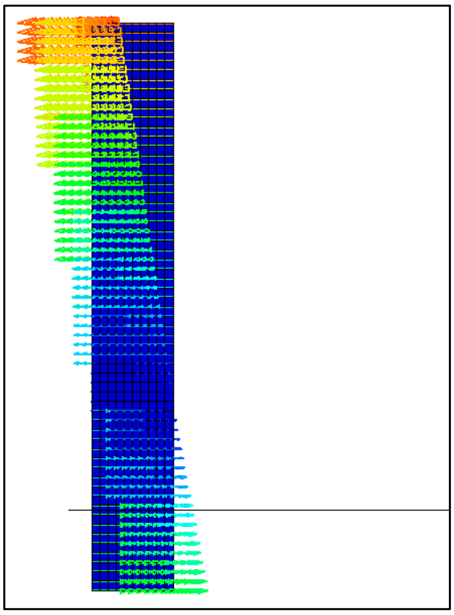


Figure 20: The vector plot of displacement for rigid pier

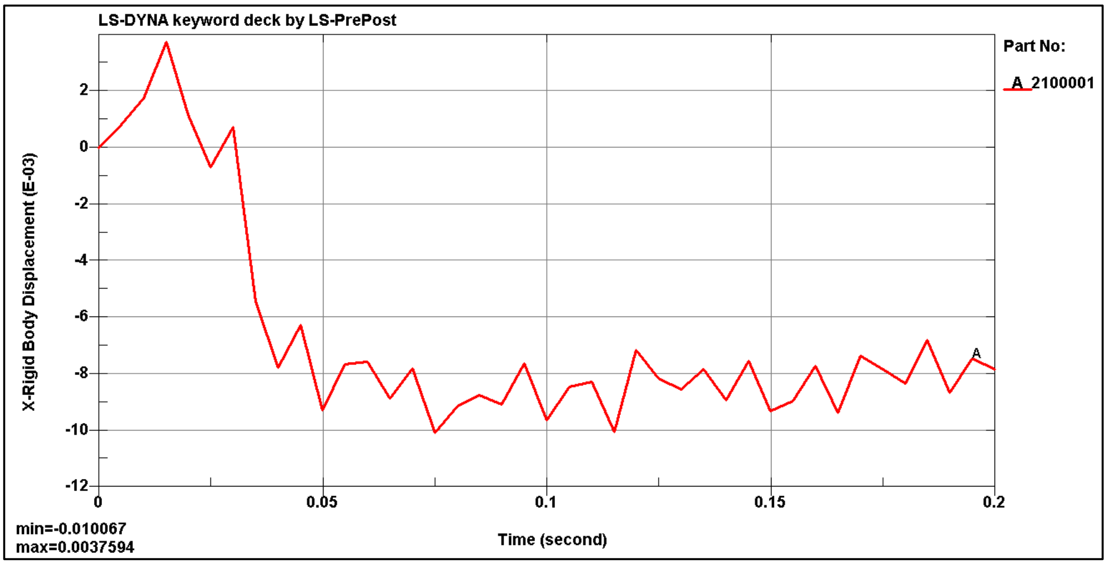


Figure 21: The displacement vs time

The graph shows that the maximum deflection is 0.01mm. The pier material used is rigid which prevent the pier to deflect greatly. From the vector plot of displacement, the highest deflection are located at the top of the pier.

Elastic

1. Energy

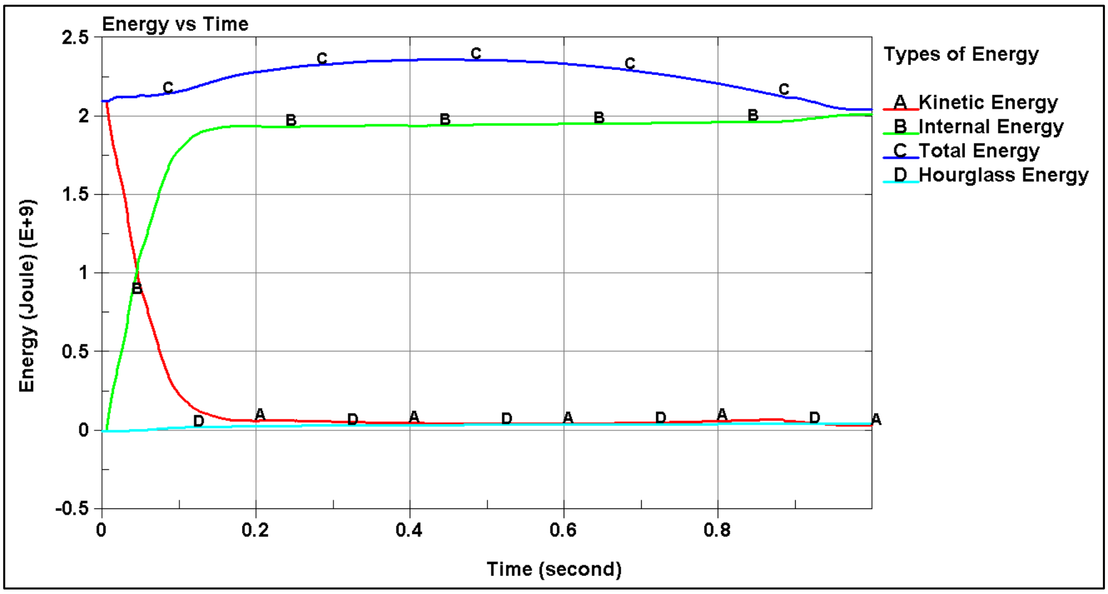
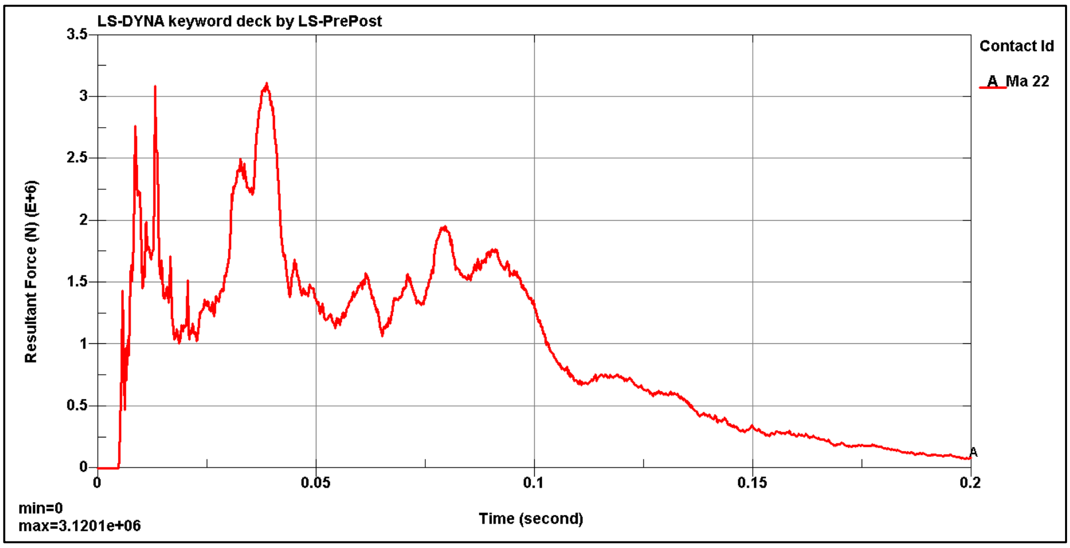


Figure 22: Energy vs time for elastic pier

It can be seen clearly that the hourglass energy is less than 10% of the total energy. The graph for the energy of elastic pier are almost similar compared to the rigid pier. The kinetic energy are transfer to internal energy after the collision.

2. Resultant forces



Figures 23: Resultant force vs time in elastic pier

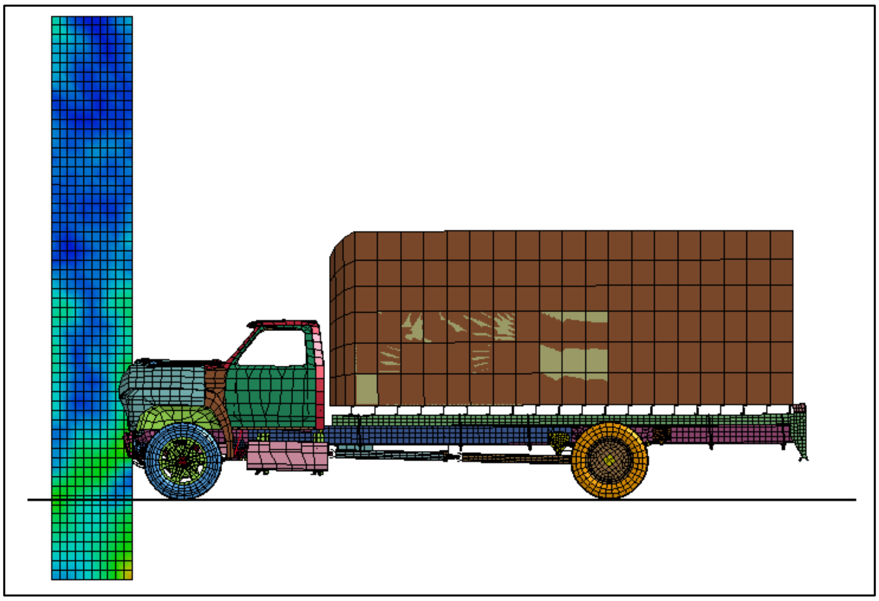


Figure 24: 0.013s (1st peak)

The 1st peak is at 0.013second which has 3.09x 10^6N. This peak of the force are the first collision between the pier and F800 truck with velocity of 80km/h. The figure shows the highest stress comes at the bottom of the pier.

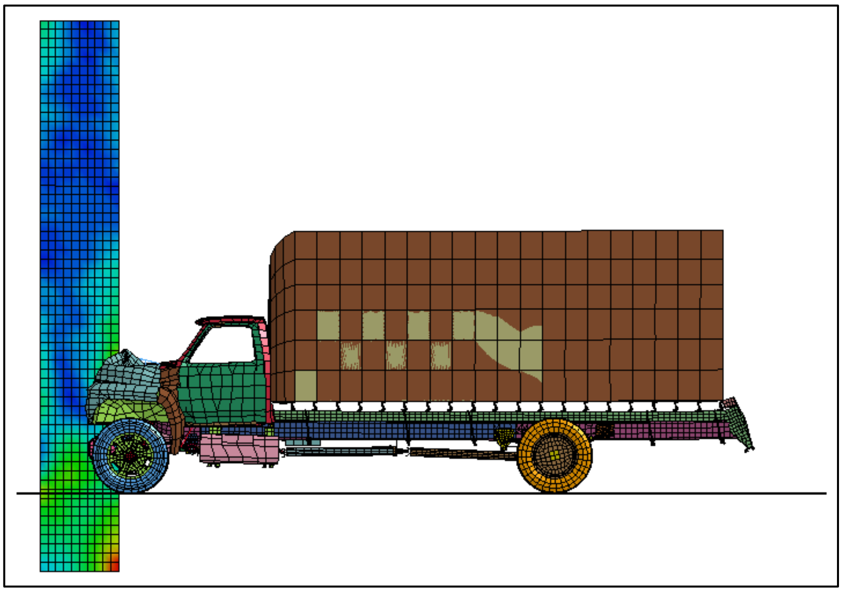


Figure 25: 0.038s (2nd peak)

The 2nd peak time is 0.038s which has 3.12x 10^6 N. This point is where the truck began to overturn causing the back of the truck to uplift. The second peak of the force is caused by the back of the truck which the force transfers late to the pier. It can be seen clearly that the highest stress is located at the bottom of pier.

3. Displacement

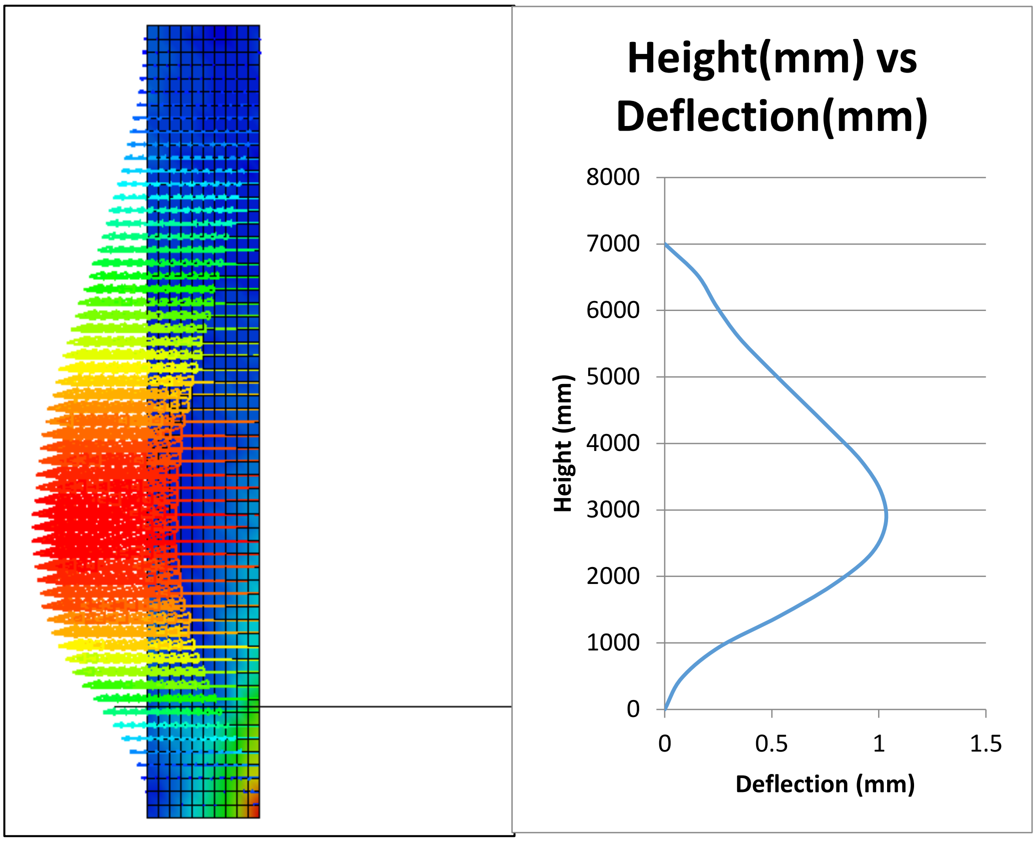


Figure 26: The deflection of piers

These figures show the deflection by using the vector plot for the displacement. The graph shows that the highest deflection is 1.0322mm around 2m above the road surface at the point the truck collide. From the vector plot of displacement, the red colour shows the highest deflection on the pier. Due to elastic behaviour, the deflection will return to its original position after the collision.

The whole result

	Case A	Case B	Case C	Case D	Case E	Case F	Case G	Case H
Force (N)	3.29x 10^6	10.43x 10^6	3.67x 10^6	8.71x 10^6	/	/	7.67x 10^6	/
Kinetic Energy (J)	2.10x 10^9	5.24x 10^9	2.10x 10^9	3.89x 10^9	/	/	4.00 10^9	/
Internal Energy (J)	2.04x 10^9	7.12x 10^9	1.97x 10^9	3.67x 10^9	/	/	3.05x 10^9	/
Total Energy (J)	2.37x 10^9	4.49x 10^9	2.38x 10^9	4.45x 10^9	/	/	4.11x 10^9	/
Hourglass Energy (J)	4.79x 10^7	7.74x 10^7	4.05x 10^7	10.45x 10^7	/	/	33.23x 10^7	/
Hourglass Energy/ Total Energy	2.0%	1.7%	1.7%	2.3%	/	/	7.5%	/
Deflection (mm)	0.020	0.300	1.032	3.500	/	/	3.693	/

Table 3: Comparison between different cases

For the progress now, only case A and B are completed. For this both cases, the value for the force and energy are around the same. However, for the 8 tons truck, case D show a higher force of 8.71x 10^6N which has the material of elastic with velocity of 110km/h. Case A shows the smallest impact force of 3.29x 10^6N due to its rigid material. Further studies and analysis will be done to recheck the value. Hence, the results for this table are not yet finalized and further changes might happen. However, comparing with the design impact forces of 1000kN, the smallest result obtained are 3 times higher than the design code.

From the result obtained, the highest hourglass energy/ total energy is 7.5% which is lower than 15% which the result are consider relatively accurate. The highest deflection obtained 3.693mm from case G which is 16tons with elastic material and truck velocity of 80km/h.

The graphical results obtained so far showed that the test models behavior were similar to the journal. The 16 tons files which are case E, F and G are still running due to its large file and dealing with some server errors.

Challenges and Problem faced

The major problem faced is the mechanical terms and software languages which is very fundamental knowledge that is needed to understand the whole simulation. Dynamic force and finite elements are not major focus to be deal in civil engineering. Hence, terms such as contact, elements, sections or timesteps are difficult to agree with, and be used as a simulation. Forces that deal with time are challenging as it involves different velocities and materials which in dynamic forms.

Time for the simulation to analysis takes around 2 days which is a huge problem for time lag. With additional of internet and server problems had impact on simulation time. However, it is believe that the simulation still can be done completely on time.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

As a conclusion, this project is important as it deals with unintentional incident in everyday lives. Action load is believed to be one of the most critical considerations when designing for bridge piers to encounter the vehicle collision. The simulation on this bridge piers subjected to vehicle collision using LS-DYNA is to improve the understanding on the action load specified in the code. From the result obtain so far, the minimum forces acquire are 3290kN which are 3 times higher than the design impact forces of 1000kN. The minimum force is acquired from case A with the pier of rigid material and the velocity of the truck are 80km/h. Although the result are incomplete and are not perfectly verified, the result so far had shown that design codes of the impact force are needed to be reevaluated.

The different parameter of velocity, material and vehicle are been run at the current progress. However, more resources are needed to be acquired to support this data. For current progress, the graphical results obtained showed that the test models behavior were similar to the journal and realistic.

The time frame for this project is feasible and able to be completed within the time allocated. With the guidance from the supervisor, this project is believed to be able to finish within capability of a final year student. It is recommended that additional load can be applied to represent the driver and load carried on the truck. For more accurate results, the computer resources required for the simulations would have been much higher. Further studies on the material on concrete mat_159 or the different contact for the collision can be done.

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APPENDICES

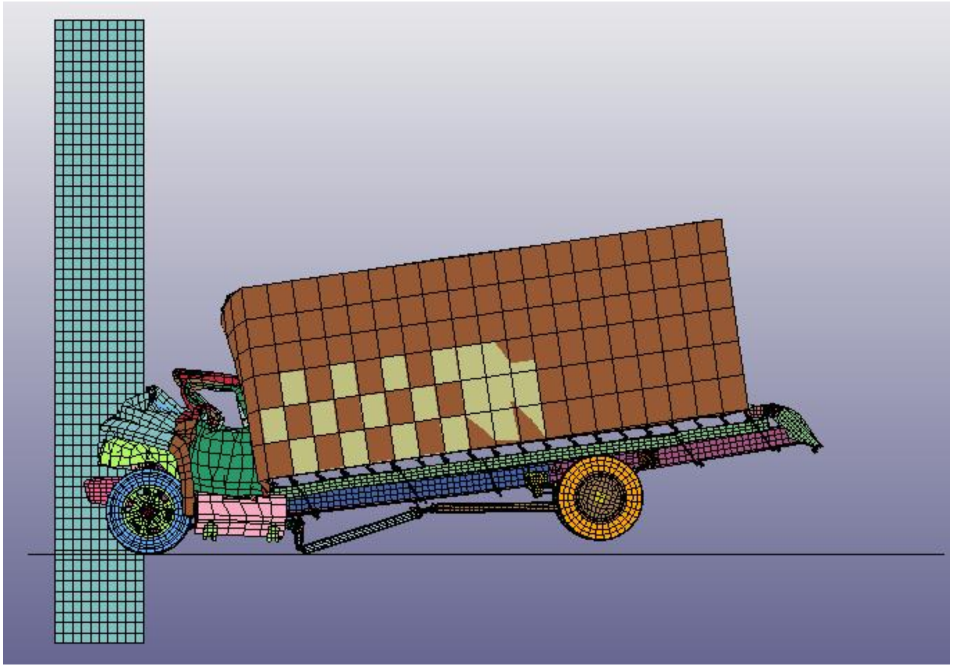


Figure 27: Bridge Pier subjected to vehicle collision using LS-DYNA

Table C.1 - Indicative data for probabilistic collision force calculation

Variable	Designation	Probability distribution	Mean value	Standard deviation
v_o	vehicle velocity			
	-highway	Lognormal	80 km/h	10 km/h
	-urban area	Lognormal	40 km/h	8 km/h
	-courtyard	Lognormal	15 km/h	5 km/h
	-parking garage	Lognormal	5 km/h	5 km/h
a	Deceleration	Lognormal	4,0 m/s^2	1,3 m/s^2
m	Vehicle mass – lorry	Normal	20 000 kg	12 000 kg
m	Vehicle mass – car	----	1 500 kg	--
k	Vehicle stiffness	Deterministic	300 kN/m	--
φ	Angle	Raleigh	10°	10°

Table 4: Designation velocity

Table 4.1 : Indicative equivalent static design forces due to vehicular impact on members supporting structures over or adjacent to roadways.

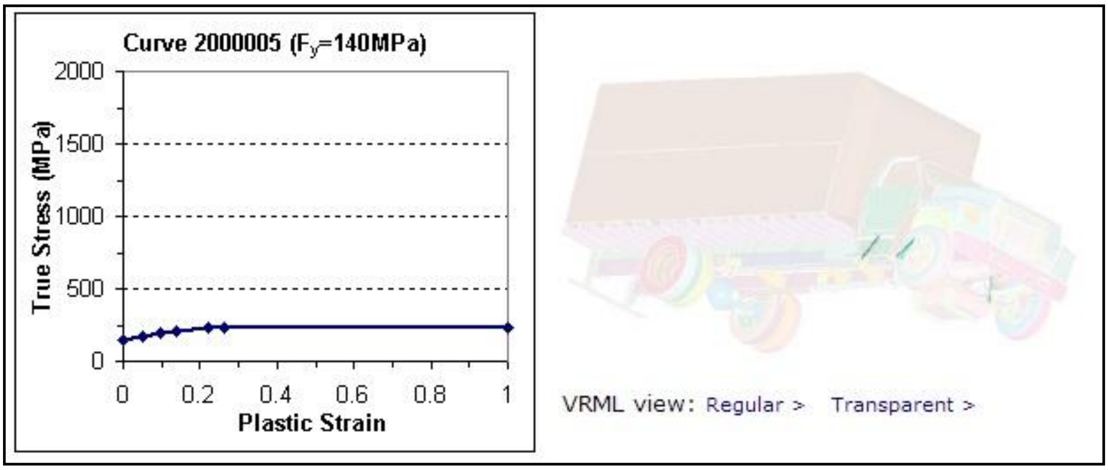
Category of traffic	Force F_{dx} [a] [kN]	Force F_{dy} [a] [kN]
Motorways and country national roads	1000	500
Country Roads in rural area	750	375
Roads in Urban area	500	250
Court yards and parking garages with access to:		
- Cars	50	25
- Lorries [b]	150	75

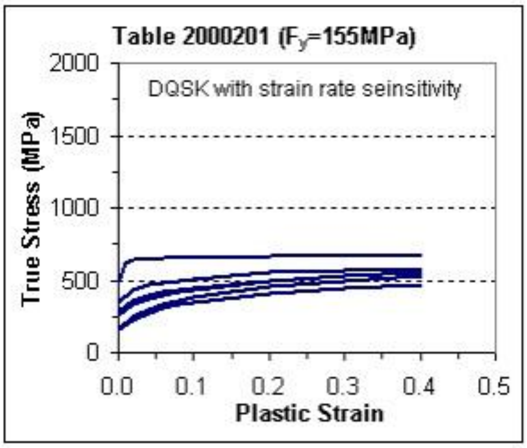
[a] x = direction of normal travel, y = perpendicular to the direction of normal travel.

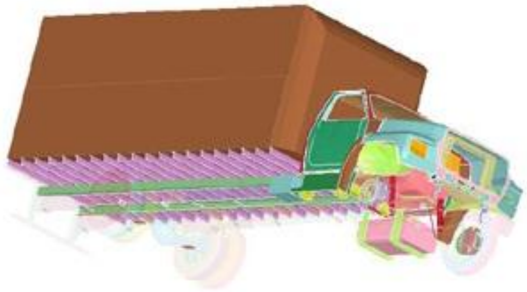
[b] The term 'lorry' refers to vehicles with maximum gross weight greater than 3,5 ton.

Table 5: Design forces for vehicular impact

<u>Material properties of Ford F800 Series Truck</u>







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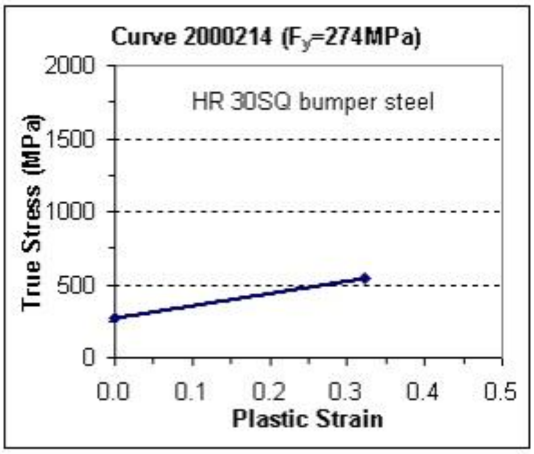

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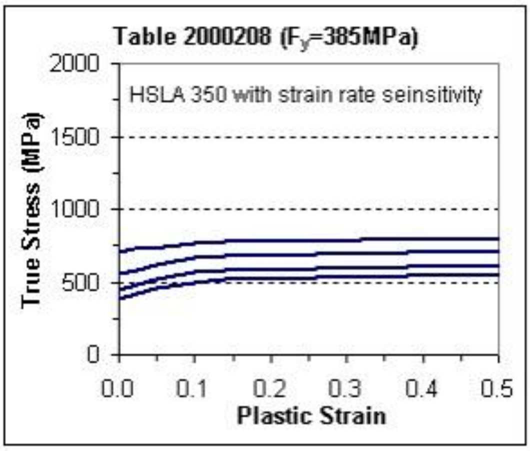

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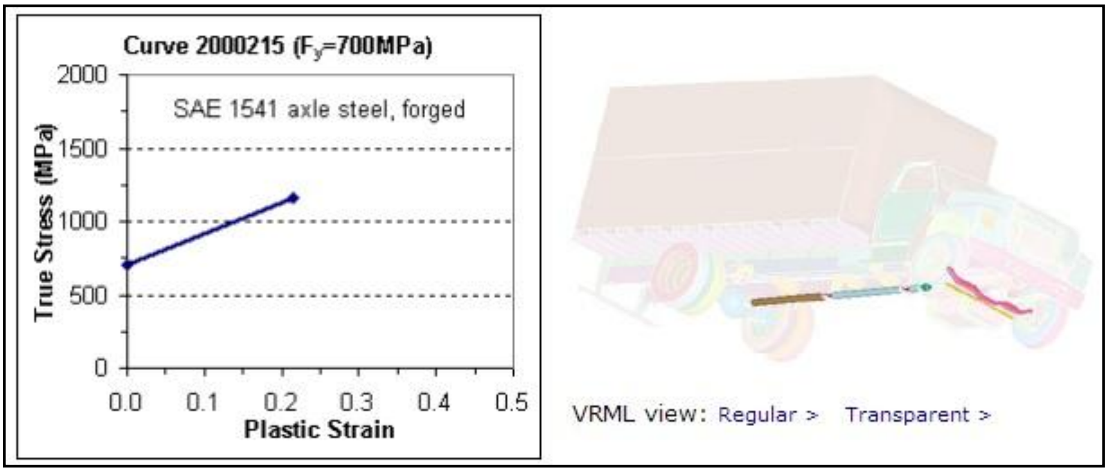
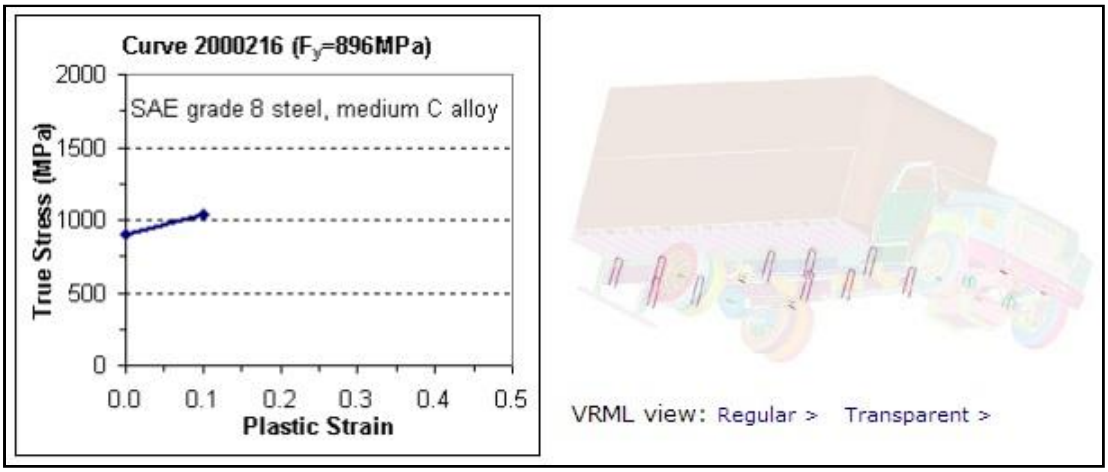




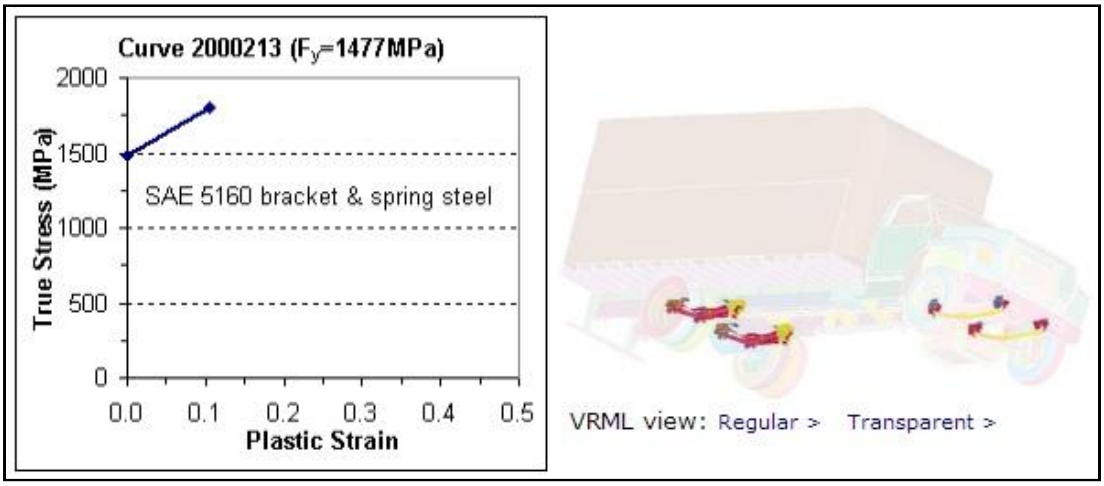
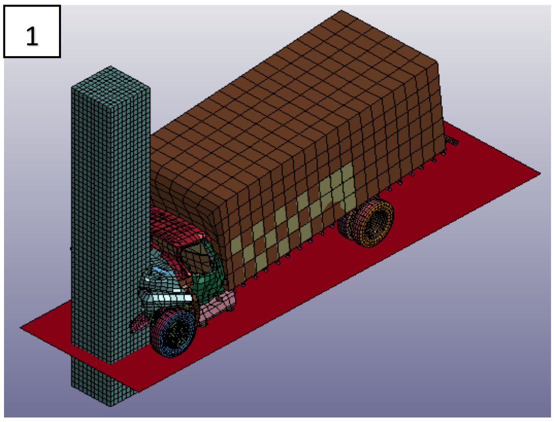


Figure 14: Plasticity behaviour

<u>Simulation process</u>

1



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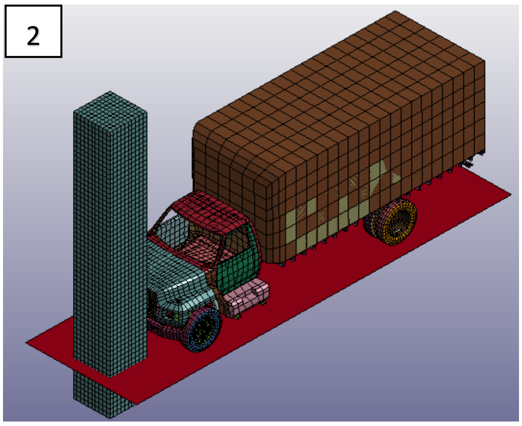

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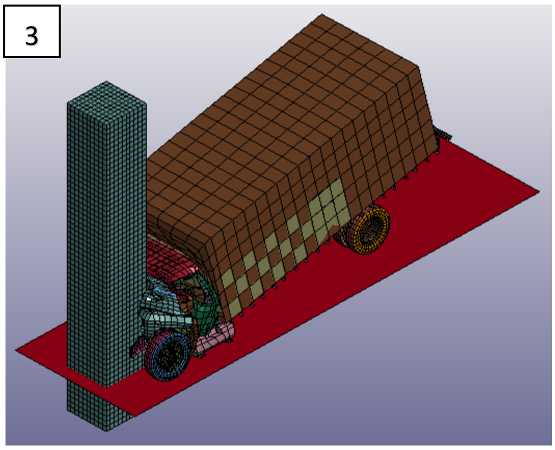

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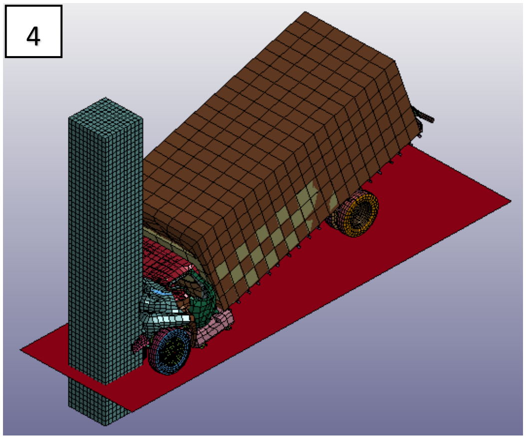

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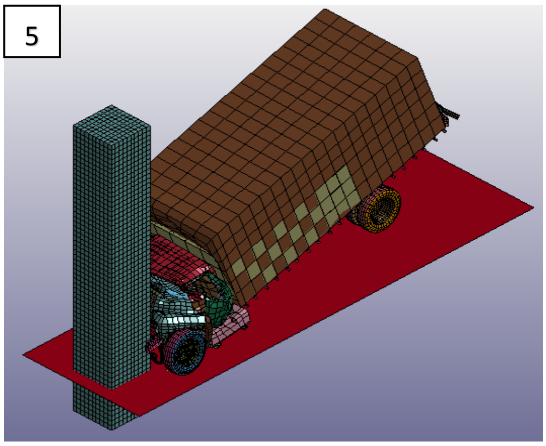

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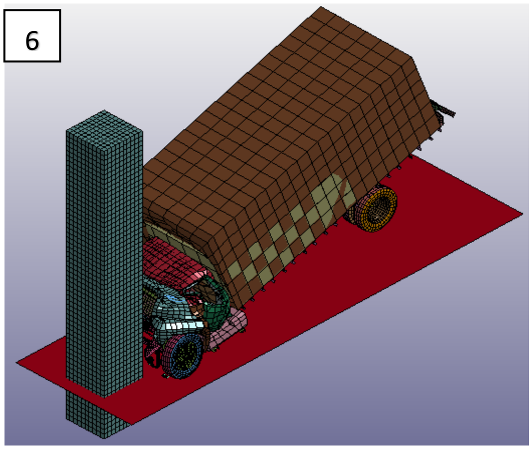

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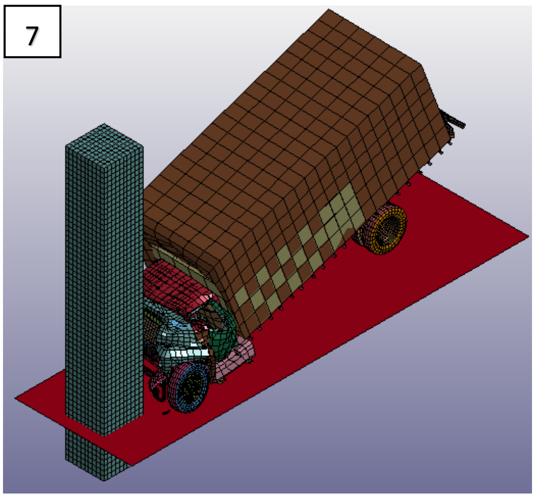

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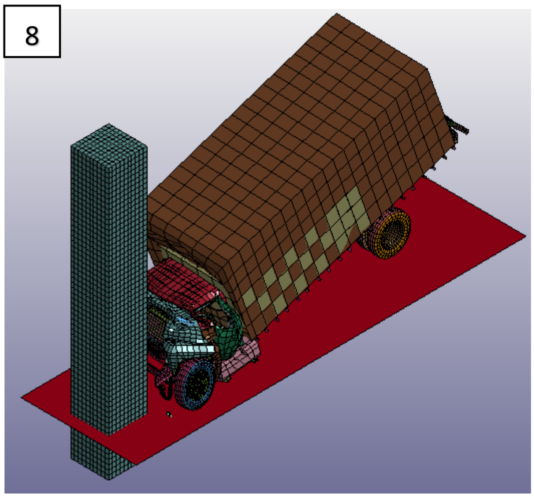

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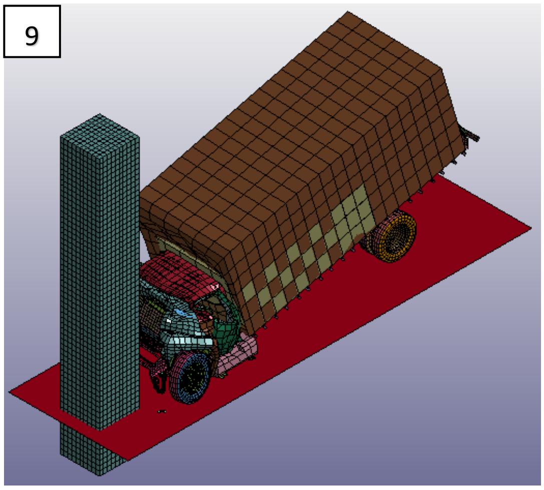

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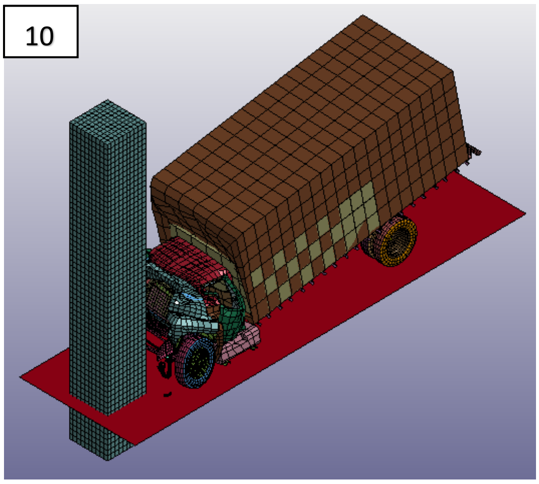

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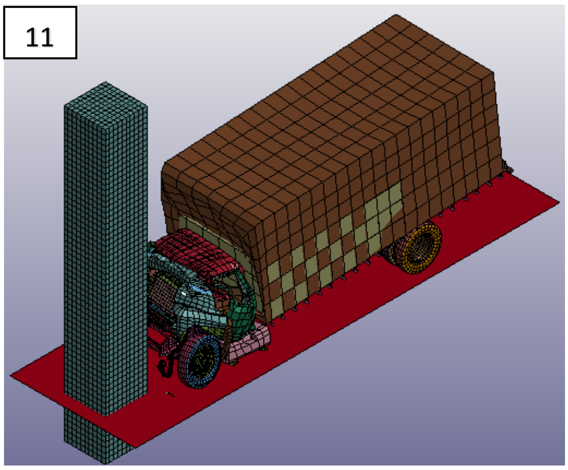

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Figure 28: Time of process