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Abstract

Analysis and design optimisation have been carried out to find the best suitable design of the collapsible sign post which can minimize the possibility of injuring the passenger in the car during crash impact. The post also needs to be strong enough to withstand the wind load and self-weight. Many different design configurations were analysed and parametrical study was carried out. A couple of designs have been identified to be better in terms of minimizing the acceleration of the car during crash impact. This report discusses the modelling aspects of the finite element analysis and presents the results.

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CANCES **LEAP**

ATSB

REPORT

Crash Simulation and Design Optimization of Collapsible Signpost

Funded by: Australian Transport Safety Bureau

Prepared by: Dr Jindong Yang
Technical Director
Leap Pty Ltd,

Date: 15 May 2001

EXECUTIVE SUMMARY

The objective of the project was to investigate the viability (strength, ability to support the signs, performance in the event of crash) of the thin walled collapsible sign post as a replacement to the existing rigid structure. Specifically:

- To predict the behaviour of the alternative signposts using Finite Element Analysis software, under wind load and self-weight and in the event of crash.
- To optimize the design of the post to achieve better performance under both wind load and crash impact.

These objectives have been achieved by the work of this report. A range of collapsible post designs have been evaluated and optimized. The computer simulation and analysis results indicated that the collapsible post could reduce the acceleration of an impacting car or vehicle significantly when the design parameters are optimized. The work done in this report also demonstrated that computer simulation could be a very useful tool for design and optimizing the roadside furniture such as signpost. It could save many expansive physical crash tests and speed up the product development process.

The below is a summary of the findings:

1) There are two main design requirements for the collapsible post. One is withstanding the wind load and the self-weight. The other is to collapse easily during a crash impact so it is safer for the car occupants. These two requirements are contradictory to each other. A compromise has to be made to satisfy both requirements.

2) In the first stage of the analysis double cylinder post was investigated. The minimum thickness and the strength of the lower part of the post has be the sufficient to withstand the wind load. In the double cylinder post design, the high stress occurs on the outer cylinder shell, the inner cylinder does relieve much of the bending load from the outer cylinder. While in the crash impact, the inner post adds significant stiffness and mass to the post. The acceleration of the car is relatively higher. The double cylinder post configuration is not the most efficient use of material, The manufacturing cost is also relatively higher. It does not offer any advantage over a single cylinder design. The single cylinder post design was adopted in the second stage of the project.

3) For tall signpost (7.5 m to the centre of the sign face), the bending moment on the post due to the wind load is high, and a larger diameter post and (or) a thicker wall shell is required. The simulation result indicated that it is very difficult to achieve the impact acceleration below 20g with a small car impact on the post at 70KPH under the current design constraints (no base shear off, the wind load rating and steel material and cost considerations). However with a small car 19.0g acceleration was achieved for a shorter post (3.5 m to the centre of the sign board) with optimized design parameters.

4) It is possible that the collapsible post will be sheared off when a larger car or truck crashes into the post at 70 kph or higher. A steel cable can be placed inside the post to prevent the post being completely sheared off. The cable should not be pretensioned. A slack cable would have no effect when a small car impacts into the post, but would help to restrain the post when impacted by a larger vehicle.

5) A couple of oval shape posts were analysed, one with long axis perpendicular to the traveling direction. The other analysis with the long axis parallel the car traveling direction. The diameter dimensions of the post were the same for the two posts: Da=350 (long axis), Db=250 (short axis). The analysis results indicated that the oval posts do not have significant advantages over the simple circle cylinder post. The manufacturing cost was relative higher for the oval post, therefore it is not recommended.

6) For taller signposts, split base design and other innovative post designs may be more appropriate. The split base post allows the post base to break off in the event of crash impact. The car or vehicle can still travel forward after the impact. The impact acceleration of the car can be relatively smaller and the passenger's risk is reduced. Material other than steel (e.g. aluminium, plastics, and foams) is also worth considering. These materials can be more ductile, the post can deform more during the crash impact. More energy can be absorbed. Further investigation is recommended.

ACKNOWLEDGEMENTS

This project was funded by Australian Transport Safety Bureau (ATSB). The author would like to thank ATSB for the support.

Hadi Alrawi and Harry Gopalani of RTA Road Technology Branch have worked closely with Engineers at LEAP on this project. They kindly provided original design concept and drawings, as well as offering valuable suggestions and recommendations. The author would like to thank them for their assistance and contribution to this project.

Contents

1. INTRODUCTION

Most sign structures on NSW roads are supported by thick wall posts. These posts do not yield when hit by a vehicle at high speed, thus the risk of serious injuries and deaths is high. To reduce this hazard, the use of thin wall posts that would collapse in a controlled manner when hit by a vehicle is proposed by the Roads and Traffic Authority (RTA) of New South Wales.

The objective of the project was to investigate the viability (strength, ability to support the signs, performance in the event of crash) of the thin walled collapsible sign post as a replacement to the existing rigid structure. Specifically:

- To predict the behaviour of the alternative sign posts using Finite Element Analysis software, under wind load and self-weight and in the event of crash.
- To optimize the design of the post to achieve better performance under both windload and crash impact.

There were two options for the collapsible post design:

1) A composite post made of two thin walled tubes, one inside the other.
2) A single thin walled tube post with steel cables inside to prevent the post completely shearing off.

CANCES ATP and LEAP Pty Ltd undertook the task of assessing the post strength, ability to support the sign face, and impact performance using computer simulation. The primary goal of this project is to reduce the acceleration of the car during the impact to below 20g and preferably 15g, at the same time to be strong enough to withstand wind load and self-weight. The following analyses were conducted:

1) Crash simulation of the collapsible signpost hit by a vehicle. Passenger cars and pick-up truck models were used to crash into the post to determine the impact performance of the post during the car crash impact.
2) Static analysis of the collapsible signpost subject to wind load and self-weight.
3) Linear buckling analysis of the collapsible signpost to evaluate the capacity of resisting buckling.

Ford Festiva (small size car 820 kg), Ford Taurus (medium size car 1500Kg) and C2500 pickup truck (2000Kg) were used for crash simulations. The FE models of the posts were created and analysed for static loading conditions using ANSYS FEA software. The crash simulations were carried out using LS-DYNA, the most widely used explicit dynamic simulation software.

2. FINITE ELEMENT MODEL

The conceptual design of the composite post (Drawing SK 491, attached in Appendix D) was supplied by RTA Road Technology Branch. The lower part of the post consists of two steel cylinders, one inside the other. The sign face centre is 7.5 metre above the ground. The diameter of the outer cylinder is in the range of 360-450 mm. The diameter of the inner cylinder is in the range of 200-300 mm. The thickness of the post shell was specified between 2 to 3 mm. The Finite Element (FE) models of signpost were created using ANSYS FEA software. Models with various post dimensions were created and analysed for parametrical study.

A Taurus sedan car was selected as the colliding vehicle. The Taurus car model was a public domain finite element model generated by The FHWA/NHTSA National Crash Analysis Center at The George Washington University. The major dimensions of this car were:

Length of car = 4.6 m
Width of car = 1.8 m
Height of the car = 1.4 m
Total mass = 1560 Kg

Figures 1 and 2 show a Finite Element (FE) model of the car and the signpost used for the simulation.

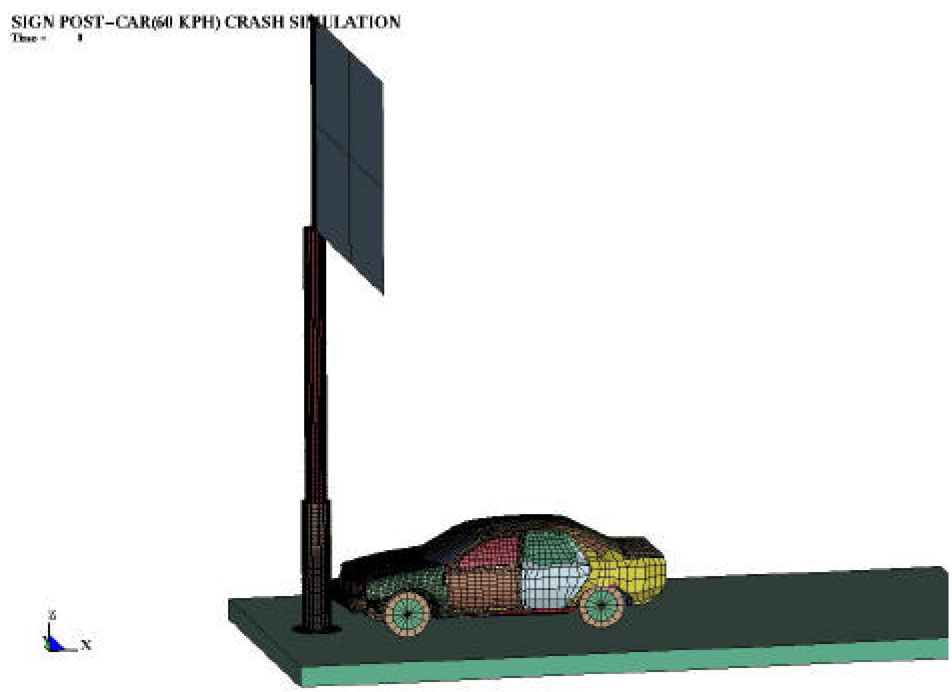

Figure 1 The finite element model of the signpost and the colliding car

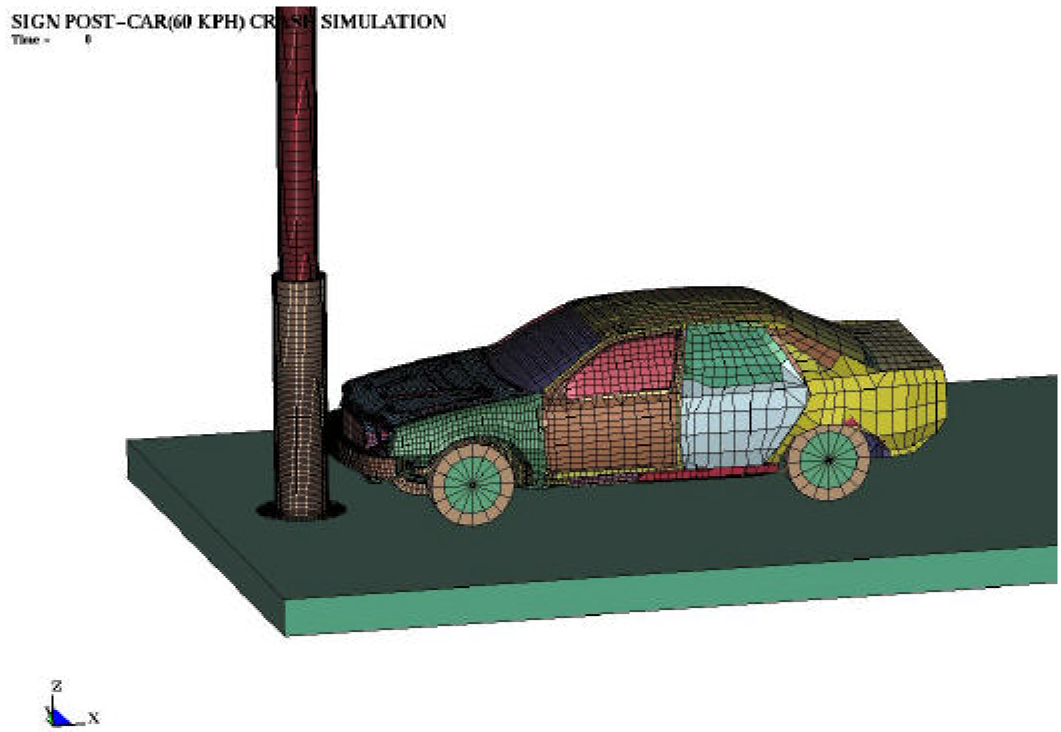

Figure 2 The FE model of the signpost and the colliding car (zoomed in)

Number of elements and nodes in the car and post model were as follows:

	Number of elements:	Number of Nodes:
Car	28386	26729
Signpost	7707	9639
Total	36093	36368

Total mass of the car is 1560 Kg.

There were eight bolts on the base plate of the pole that fix it to the ground. Eight corresponding nodes on the plate were fixed in the FE model. It was assumed that the bolts are strong enough and will not fail. It was also assumed that the welded connection between the posts and base plate is strong enough and will not fail during the impact.

Grade 200, Grade 250 and Grade 350 hot rolled steel are available for selection. The material properties were obtained from BHP CPD Port Kembla technical services. The steel product specification is attached. The non-linear stress-strain curves were not readily available for these materials. However BHP CPD Port Kembla technical services kindly conducted a number of tensile tests to determine the non-linear behaviour of the material. A failure strain (plastic strain to fracture) is required to model the fracture of the metal under loads. The failure strain was determined from the material test (see the Appendix C material properties test).

The material properties used in the analysis are listed below:

Grade 200 HR steel

Young modulus: E= 2.0 E5 MPa
Poisson Ratio : γ = 0.29
Yield Stress : σ_y=245 MPa
Failure strain ε_f =70%.

The non-linear stress-strain curve:

True plastic strain	True stress(MPA)
0.0000	245.0
0.0488	294.0
0.0953	357.0
0.140	396.7
0.1823	430.0
0.2623	481.0
0.3364	518.0
0.405	540.0

Grade 250 HR steel

Young modulus: E= 2.0 E5 MPa
Poisson Ratio : γ = 0.29
Yield Stress : σ_y=260 MPa
Failure strain ε_f = 40%.

The non-linear stress-strain curve:

True plastic strain	True stress(MPA)
0.0000	260.0
0.039	315.0

0.077	371.0
0.113	406.5
0.148	427.0
0.1823	448.0
0.400	470.0

Grade 350 HR steel

Young modulus: E= 2.0 E5 MPa
Poisson Ratio : $\gamma = 0.29$
Yield Stress : σ_y=415 MPa

Failure strain ε_f=40%.
The non-linear stress-strain curve:

True plastic strain	True stress(MPA)
0.0000	415.0
0.0169	453.9
0.0363	488.8
0.0554	538.5
0.0834	572.3
0.1106	593.6
0.1371	598.0
0.4500	600.0

The units used in the FE model are:

Quantity	Units
Length (L)	mm
Force (F)	N
Modulus of elasticity (E)	N/mm^2 (MPa)
Mass (m)	Tonne
Density (ρ)	$Tonne/mm^3$
Time (t)	s
Acceleration (a)	mm/s^2

3. STAGE 1: ANALYSIS OF DOUBLE CYLINDER POST IMPACTED BY A FORD TAURUS SEDAN CAR (MEDIUM CAR)

3.1 Frontal Impact simulation using a Taurus sedan car of 60kph

A number of crash impact simulations were carried out with the various post dimensions. The double cylinder posts were made of 2 mm thickness plate of hot rolled grade 250 steel for both inner and outer cylinders.

Table 1 below is a summary of the peak acceleration results from simulations for different combinations of diameters of the post cylinders. The accelerations at the driver side (node 10404), Centre of Gravity (CG, node 10888) and passenger side (node 11226) were extracted. The acceleration was filtered using 180Hz SAE filter and the value listed below was averaged over 10 ms.

Table 1 The acceleration of the car during impact.

		Driver accel(g)		
		Outer D		
		400	**420**	**450**
inner D	**200**	20.0	22.9	20.0
	250	21.0	22.4	20.3
	300	21.2	24.3	22.0
		CG accel(g)		
		Outer D		
		400	**420**	**450**
inner D	**200**	21.0	22.0	20.8
	250	21.0	21.4	20.0
	300	22.4	24.3	22.4
		Passenger accel(g)		
		Outer D		
		400	**420**	**450**
inner D	**200**	22.0	22.9	23.3
	250	23.3	21.6	22.1
	300	23.8	24.0	23.2

The above table shows that the best combinations of cylinder diameters are 400-200,450-200 and 450-250 because the average accelerations over the three points were the lowest. The acceleration is about 20g for the driver side and CG. The acceleration at the passenger side is higher than that at the driver side and CG in all cases. This may be caused by asymmetrical stiffness of the car. The engine is also off-centered in the bonnet. Another possibility is that the buckling of the post became asymmetrical, which resulted in acceleration being slightly different between left and right.

Figures 3 to 7 are the results for post diameter combinations 400-200 (a typical set of results). Figure 3 shows the car and the post deformed shape after the impact (150 ms). Figure 4 shows the plastic strain contour of the post. There is slight shearing of the outer cylinder at the base of the post, however the car was stopped, therefore no further shearing will occur.

Figures 5 to 7 illustrate displacement v. time graph plot, velocity v. time graph plot and acceleration v. time graph plot respectively, at CG of the car (node10888) and the left and right safety belt anchor points (node 12266 and 10404) for the car speed of 60 kph. The unit for displacement is metre, velocity is m/s and acceleration is g ($9.8m/s^2$). Time unit is millisecond in the plots. The acceleration was filtered using 180Hz SAE filter. The peak acceleration (averaged over 10 ms) of the car during the impact is shown in table 1.

A few observations of the simulation results:

1) The car stopped in about 150 ms (milliseconds) and traveled about 1.2 metres after the impact.
2) The post has collapsed with slight shear failure at the base of the post. It only occurred in a very small area in the front part.
3) Because the post is quite tall, the inertial effect of the mass of the sign is quite significant. It did not move very much in the direction of the impact. Therefore the collapsed post still limits the distance the car can travel. The scope to further reduce the acceleration is limited.

Two animation files (carpost400-200.avi, post400-200-pstrain.avi) were created to show the deformation history of the car and the post. They can be found in the accompanying CD.

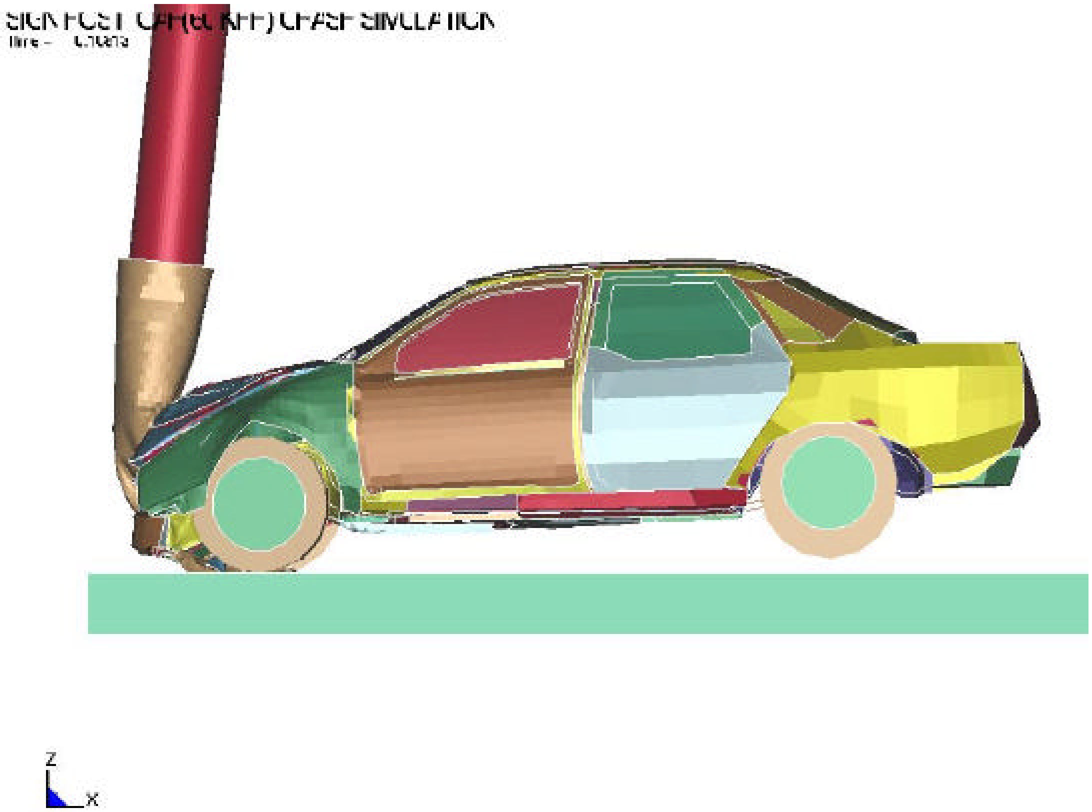

Figure 3 The deformed shape of the post and the car

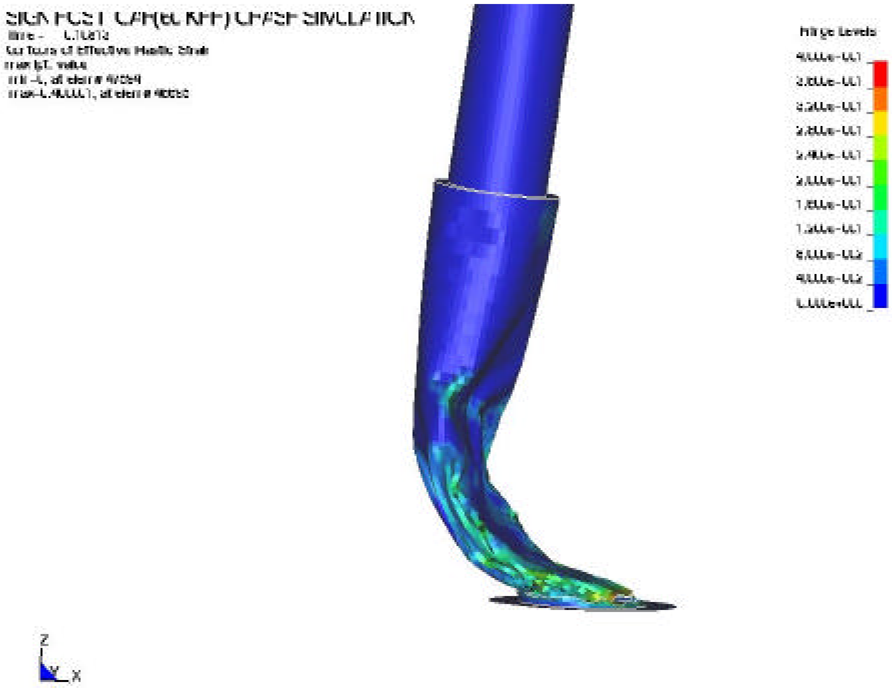

Figure 4 The plastic strain and the deformed shape of the post after impact

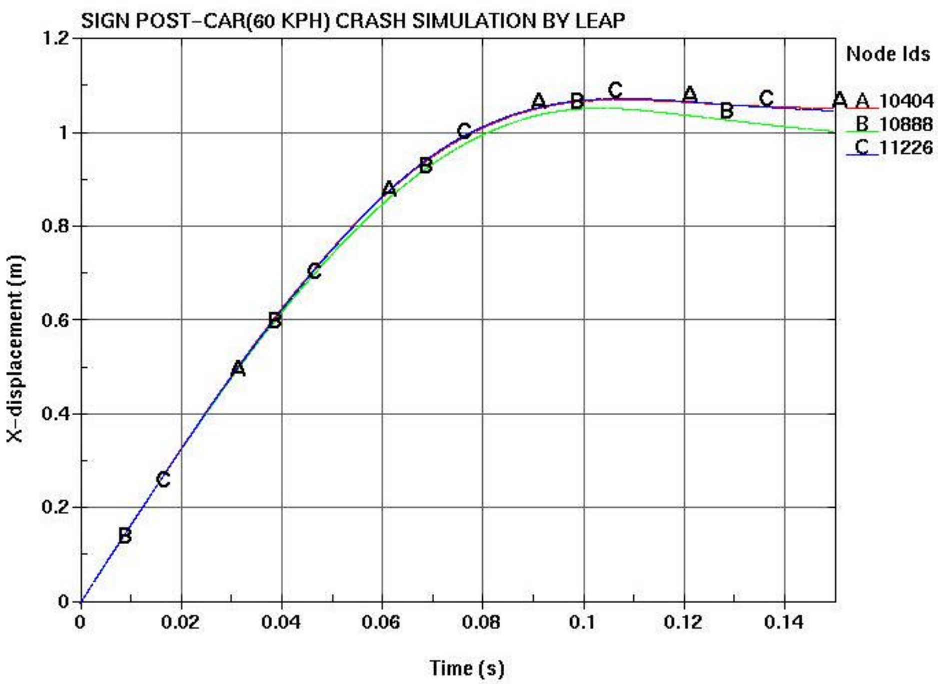

Figure 5 The displacement history at the nodes monitored

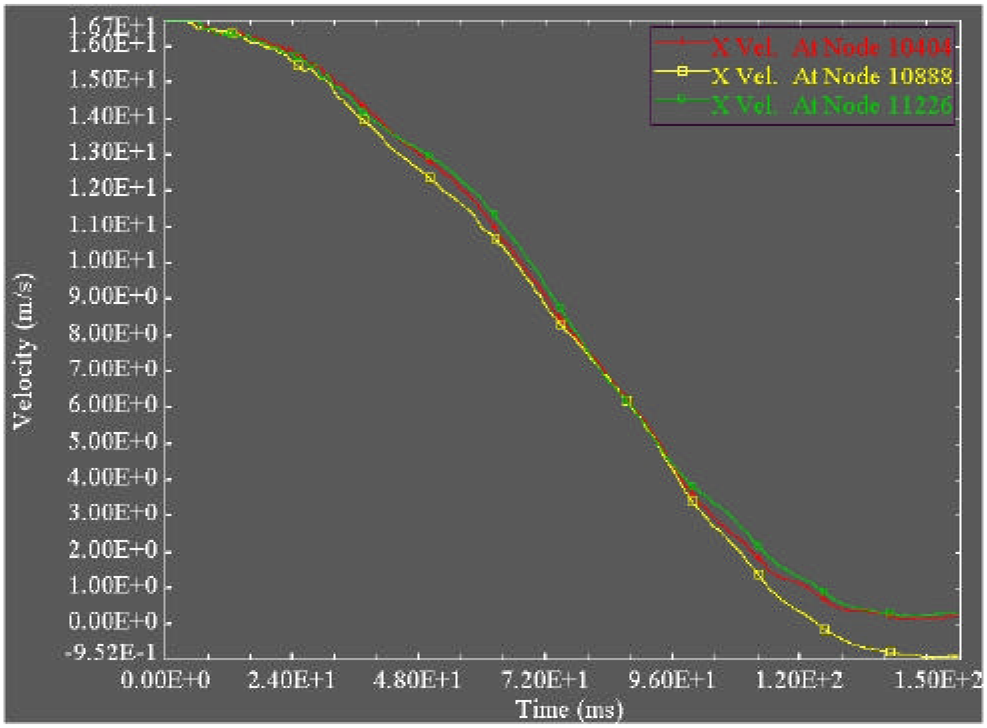

Figure 6 The velocity history at the nodes monitored

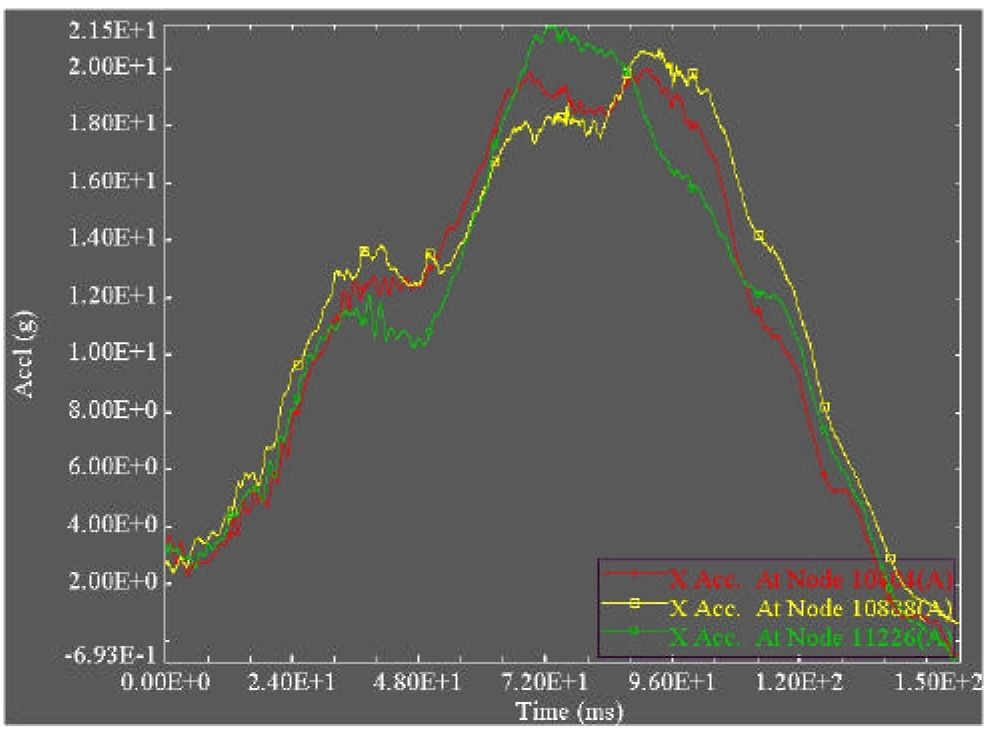

Figure 7 The acceleration history at the nodes monitored

The simulations of the posts with higher grade steel were also conducted. These simulations were:

1) post 450-250 with grade 350 steel for the outer post and grade 250 steel for the inner post.
2) post 400-200 with grade 350 steel for both inner and outer post.

The analysis results are summarised in the following form along with the previous results for the Grade 250 steel:

	Impact Acceleration (g)		
Post	Driver side	CG	Passenger side
Outer D450-Grade 350 Inner D250-Grade 250	25.0	23.5	27.5
Outer D400-Grade 350 Inner D200-Grade 350	23.5	24.0	26.5
Outer D450-grade 250 Inner D250-Grade 250	20.0	21.0	22.0
Outer D400-Grade 250 Inner D200-Grade 250	20.3	20.0	22.1

Figures 8 to 12 are the results for post 450-250 with grade 350 steel for the outer post and grade 250 steel for the inner post.

Figure 8 shows the car and the post deformed shape after the impact (150 ms). Figure 9 shows the plastic strain contour of the post. There is no shearing of the post at the base.

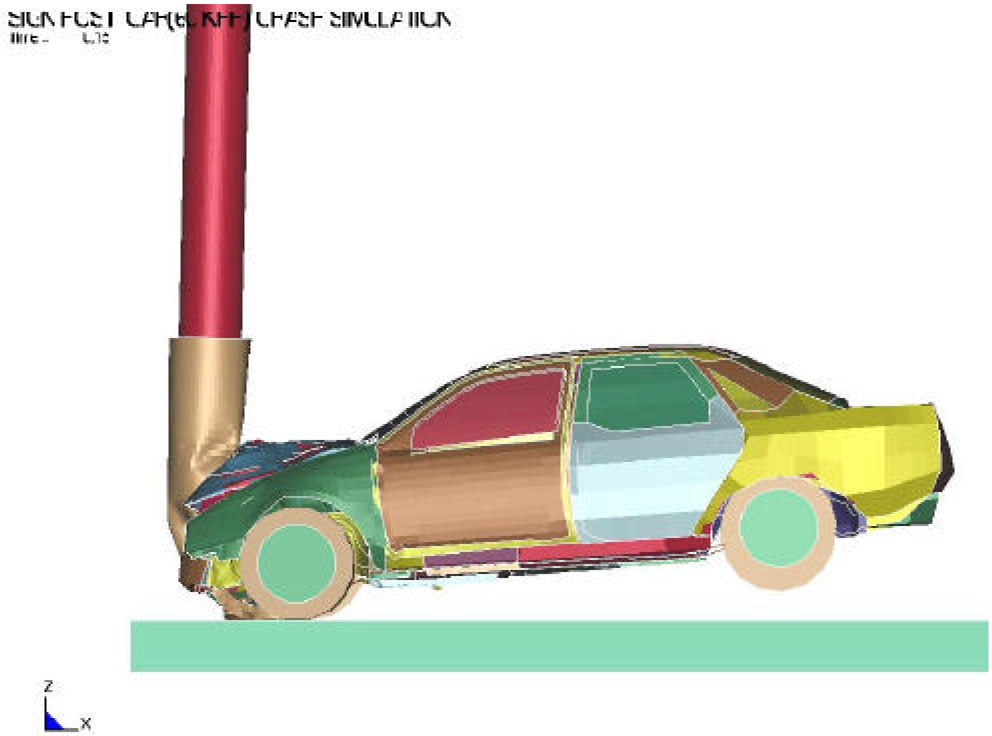

Figure 8 The deformed shape of the post 450-250-g350 and the car

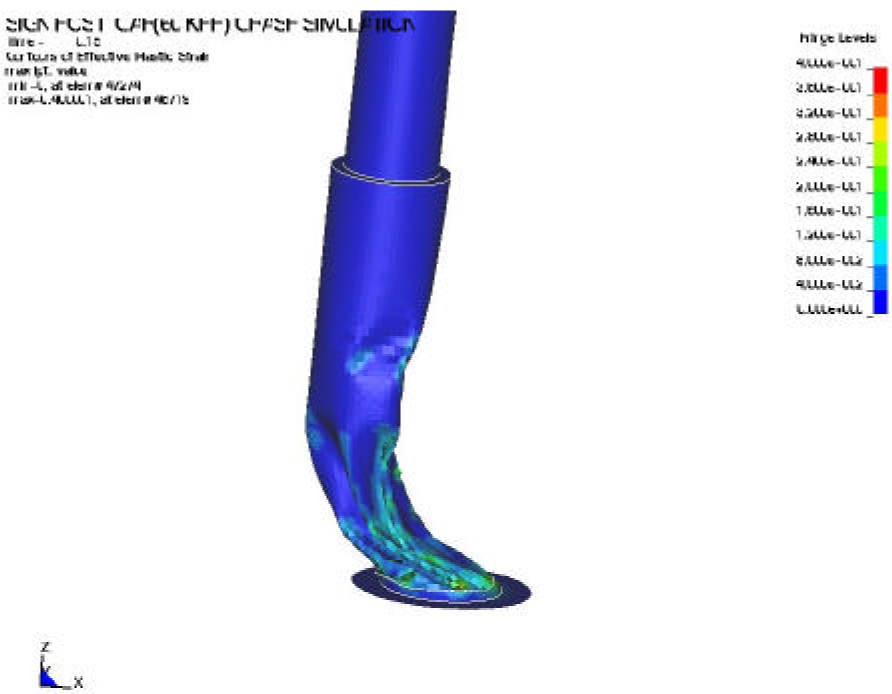

Figure 9 The plastic strain of the post 450-250-g350 after impact

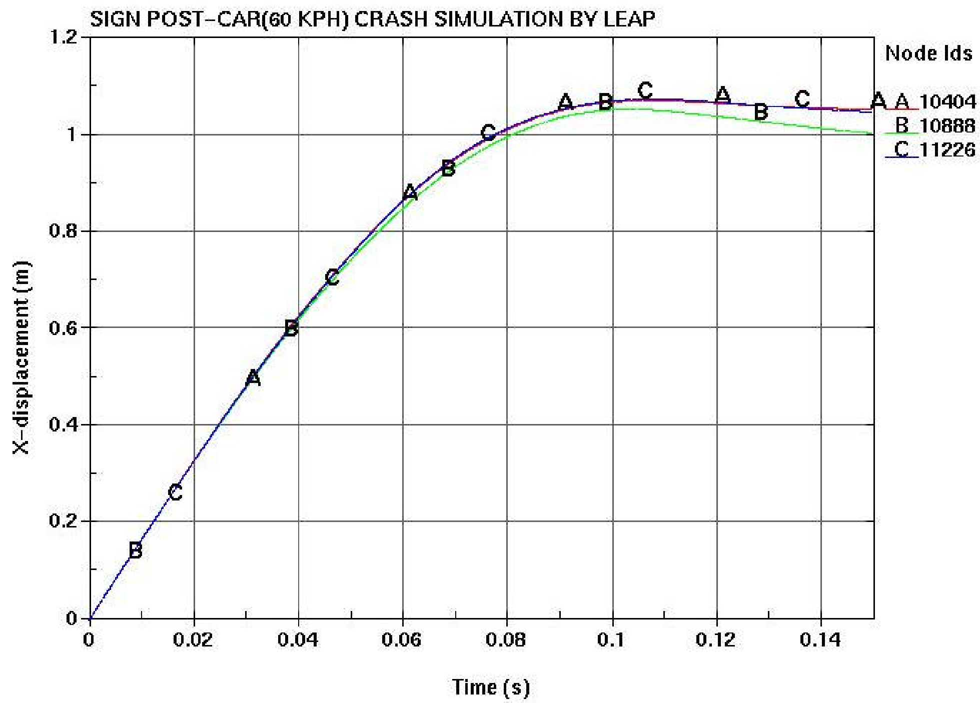

Figure 10 The displacement history at the nodes monitored

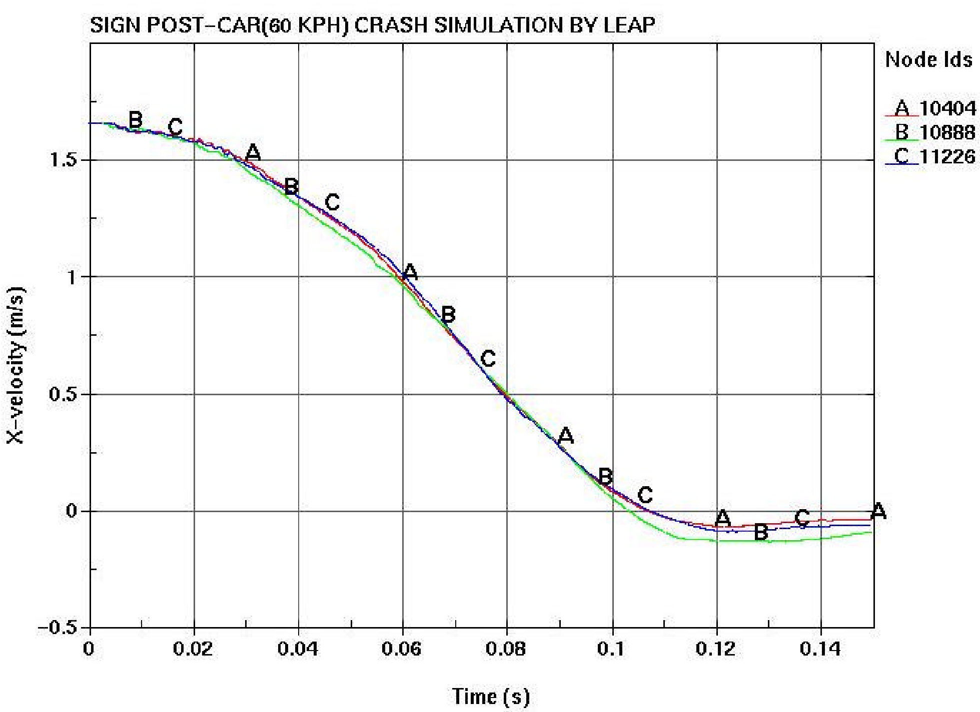

Figure 11 The velocity history at the nodes monitored

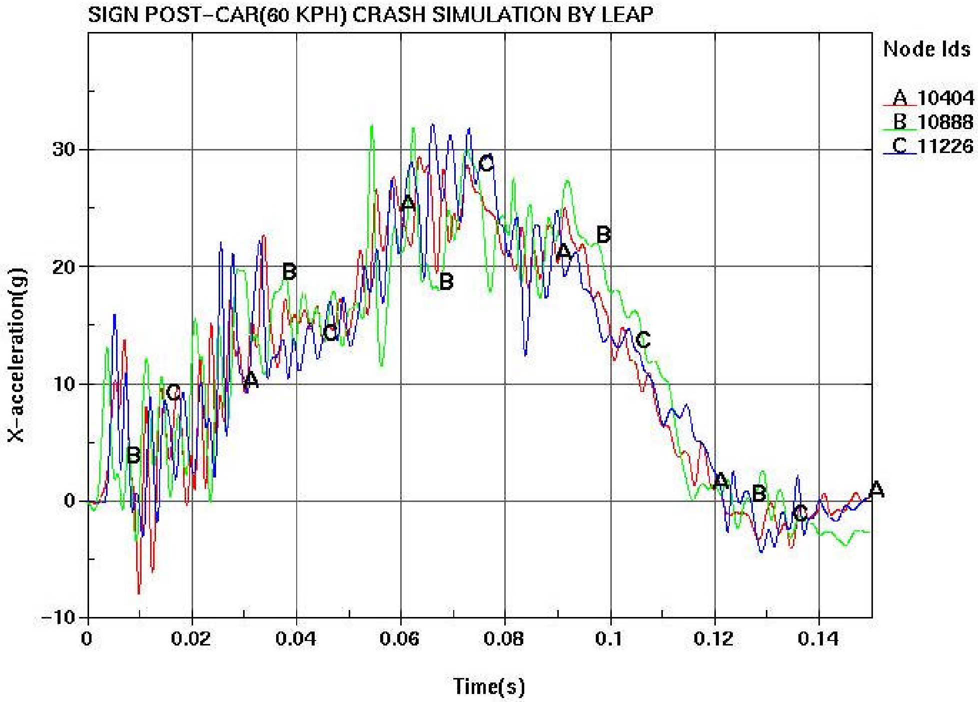

Figure 12 The acceleration history at the nodes monitored

Figures 10 to 12 illustrate displacement v. time graph plot, velocity V. time graph plot and acceleration v. time graph plot respectively, at CG of the car (node10888) and the left and right safety belt anchor points (node 12266 and 10404). The unit for displacement is metre, velocity is m/s and acceleration is g (9.8m/s^2). Time unit is ms in the plots. The acceleration was filtered by 180 Hz SAE filter.

Two animation files (carpost450.avi, post450-pstrain.avi) were created to show the deformation history of the car and the post. They can be found in the accompanying CD.

3.2 Static analysis

The specified static load is 9,600N wind load and self weight of the post (post extension 150kg and sign board 200kg). The following table is a summary of the static analysis results:

Table 2. The Von-Mises stress of the post shell under static load.

7 metre	Inner post	Outer post	Yield stress required for	Yield stress of grade 350

post	stress(Mpa)	stress(Mpa)	safety factor of 1/0.6	Steel
400-200	200	280	466	415
450-250	162	220	366	415

Figures 13 and 14 show the static stress for the post 400-200 and post 450-250. The static analysis result indicates that the grade 250 steel will not satisfy the requirement that the safety factor to be larger than 1.66 (1/0.6). The Grade 350 steel may be required for the post.

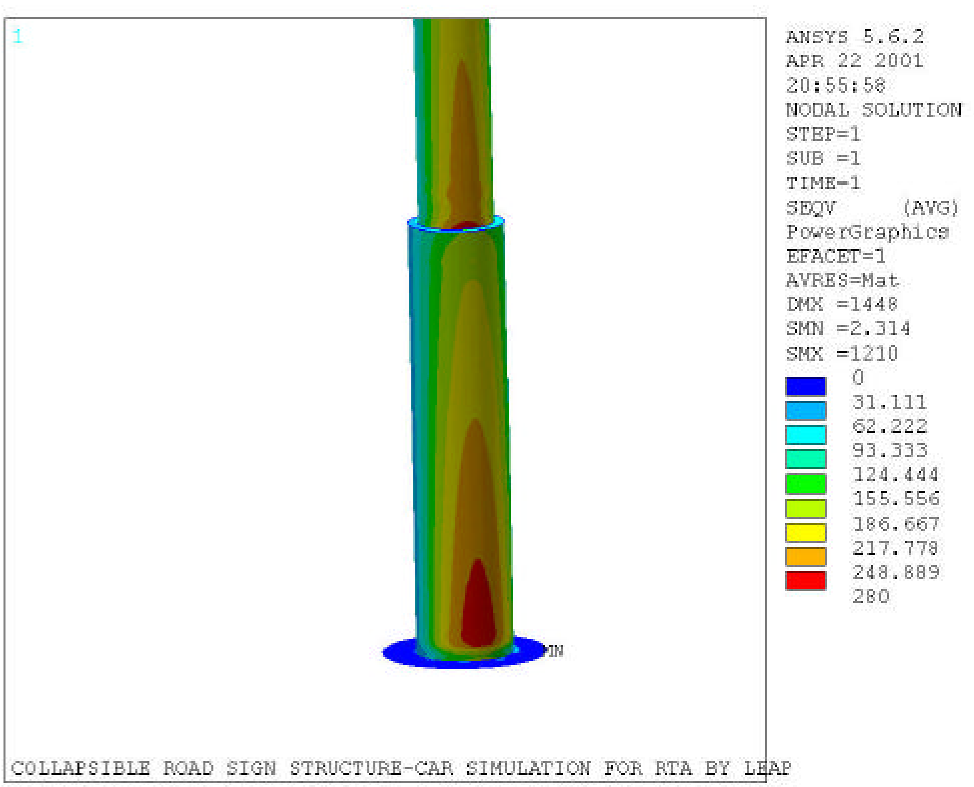

Figure 13   Von Mises stress on the 400-200 post

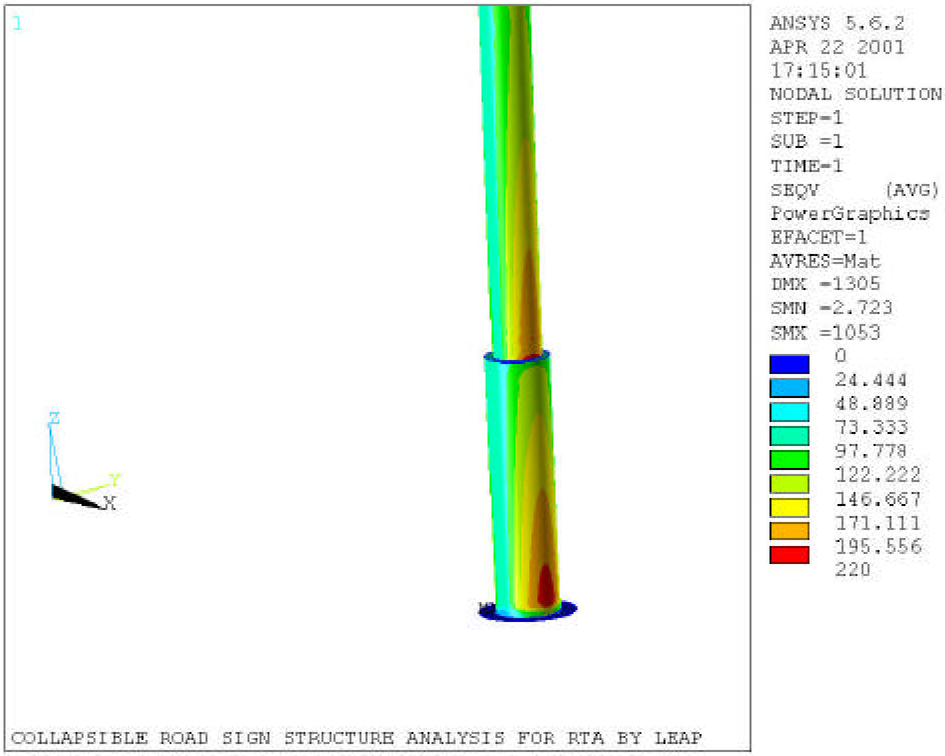

Figure 14 Von Mises stress on the 450-250 post

3.3 Buckling analysis

The buckling load factors from Eigen buckling analysis for the post 400-200 and 450-250 post are 3.29 and 3.38 respectively. The value of the buckling load factor represents the safety factor of the structure against buckling. Buckling failure is not likely to occur if there is no pre-existing imperfection.

Figures 15 and 16 show the buckling mode shapes for the post 400-200 and post 450-250.

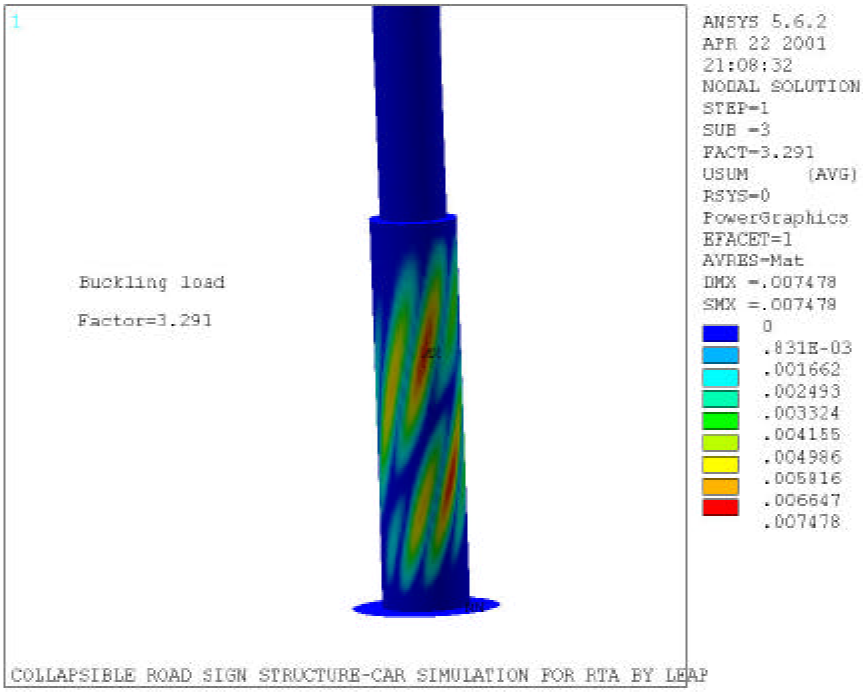

Figure 15 The first buckling mode of the signpost 400-200

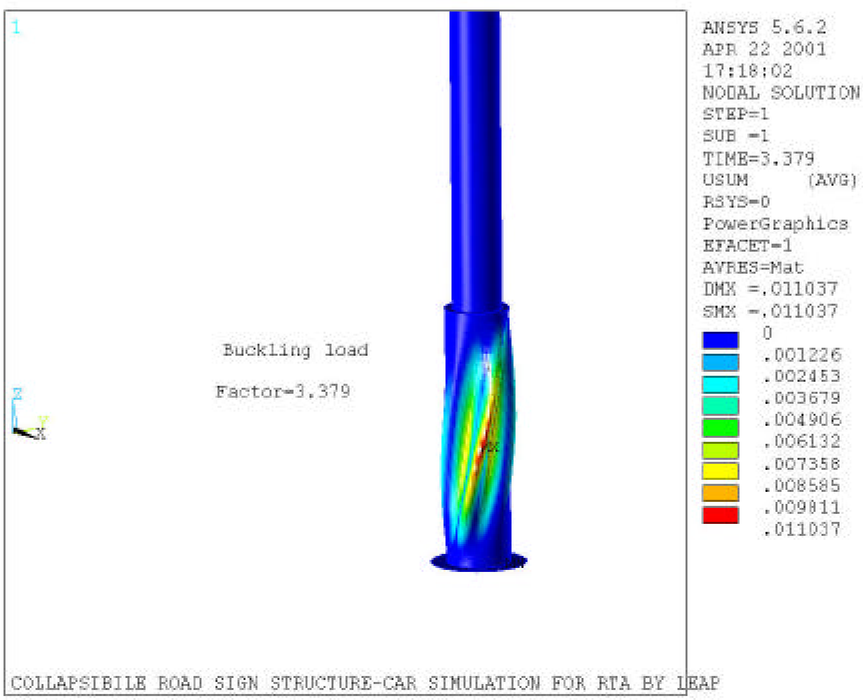

Figure 16 The first buckling mode of the signpost 450-250

3.4 Discussion

A few observations can be drawn from the above analysis result:

1) The static stress (280 Mpa for the post 400-200 and 220 Mpa for Post 450-250) is too high for the grade 250 steel material (Yield stress 260 MPA). There is no safety factor for the wind load. The post 450-250 with grade 350 steel for the outer cylinder would satisfy the static stress requirement, but the post would be deformed less during impact. The acceleration would be above 20 G.

2) The best acceleration result achieved is about 20G for the post 400-200 and post 450-250 with grade 250 steel. With Grade 350 steel for the outer cylinder shell, the post 450-250 achieved 23.5g at the CG. This acceleration result does not meet the target. Further reduce acceleration would require some major change of the design or reduce the static load of the post.

3) The posts are acceptable for buckling assessment because the buckling load factors are much larger than 1.

4) A shorter post would reduce the bending moment on the post. A smaller size post would be sufficient to withstand the wind load. A smaller post size and lower yield stress steel material may make the post collapse more easily, therefore reducing the acceleration of the car during crash impact.

5) It was found that the outer cylinder takes the majority of the static load and the inner cylinder does not relieve much of the load in the static loading condition. The stress in the outer post only increases about 10%, if the inner cylinder is removed. While in the crash impact, the inner post adds significant stiffness and mass to the post. The acceleration of the car is relatively higher. The double cylinder post configuration is not the most efficient use of material, The manufacturing cost is also relatively higher. It does not offer any advantage over a single cylinder design. Therefore for the shorter post, a single cylinder post is preferred.

7) In the first stage of the analysis double cylinder post was investigated. The minimum thickness and the strength of the lower part of the post has be the sufficient to withstand the wind load. In the double cylinder post design, the high stress occurs on the outer cylinder shell, the inner cylinder does relieve much of the bending load from the outer cylinder. While in the crash impact, the inner post adds significant stiffness and mass to the post. The acceleration of the car is relatively higher. The double cylinder post configuration is not the most efficient use of material, The manufacturing cost is also relatively higher. It does not offer any advantage over a single cylinder design. The single cylinder post design was adopted in the second stage of the project.

4. STAGE 2: ANALYSIS OF SINGLE CYLINDER SHORTER POST

A couple of shorter posts (3.5 m to the centre of the signboard) were analysed to investigate the possibilities of further reduction of the acceleration. The initial design of the post geometry was supplied by RTA (Drawing SK 494, attached in Appendix C). The wind load was reduced to 8500N and the mass of the signboard was reduced to 150kg.

The previous study found that the outer cylinder takes the majority of the static bending load on the post. The inner cylinder does not relieve much of the bending load of the static loading condition. The stress in the outer post only increases about 10% if the inner cylinder is removed. Therefore for the shorter post, a single cylinder post is preferred and used in the subsequent analysis.

The configurations of two shorter single cylinder posts are

Post 1) Post diameter = 360, Shell thickness=2 mm. Material grade 250 Hot rolled steel. Yields stress 260 Mpa.

Post 2) Post diameter = 400, Shell thickness=2 mm. Material grade 200 Hot rolled steel. Yields stress 245 Mpa.

The following is a result summary for the shorter post under various load cases: (Impact, Static load–wind load and signboard self-weight, Eigen Buckling):

Impact Acceleration (g)				Static load		Eigen Buckling
3.5 metre single cylinder post	Driver side	CG	Passenger side	post Von-Mises stress(Mpa)	Yield stress required for safety factor of 1/0.6	load factor
360	17.3	18.0	16.5	165.0	275.	3.69
400	17.2	17.5	17.2	135.5	225.	4.14

It can be seen that the acceleration of the car was further reduced by using a single cylinder shorter post. The material selection of Grade 200 for shorter post 400 and Grade 250 for shorter post 360 is adequate.

Figure 17 shows the FE model of the shorter post. Figures 18 and 19 are the static stresses on the shorter post 360 and shorter post 400.

Figures 20 to 21 are the acceleration v. time graph plots for shorter post 360 and shorter post 400 respectively, at CG of the car (node10888) and the left and right safety belt anchor points (node 12266 and 10404) for the car speed of 60 kph. The detailed location of these nodal points is given in the Appendix A. The unit for acceleration is g (9.8m/s^2). Time unit is ms in the plots. The acceleration was averaged over 10 ms.

The deformed shape of the car and the post are shown in Figure 22 for the shorter post 400 (a typical set of results). Figure 23 shows the plastic strain contour of the post 400. There was a very slight shearing of the post at the base, however the car was brought to a complete stop.

Figures 24 and 25 show the buckling mode shapes for the shorter post 360 and post 400.

Two animation files for the shorter post of 400 diameter (carlowpost400.avi, lowpost400-pstrain.avi) were created to show the deformation history of the car and the post. They can be found in the accompanying CD.

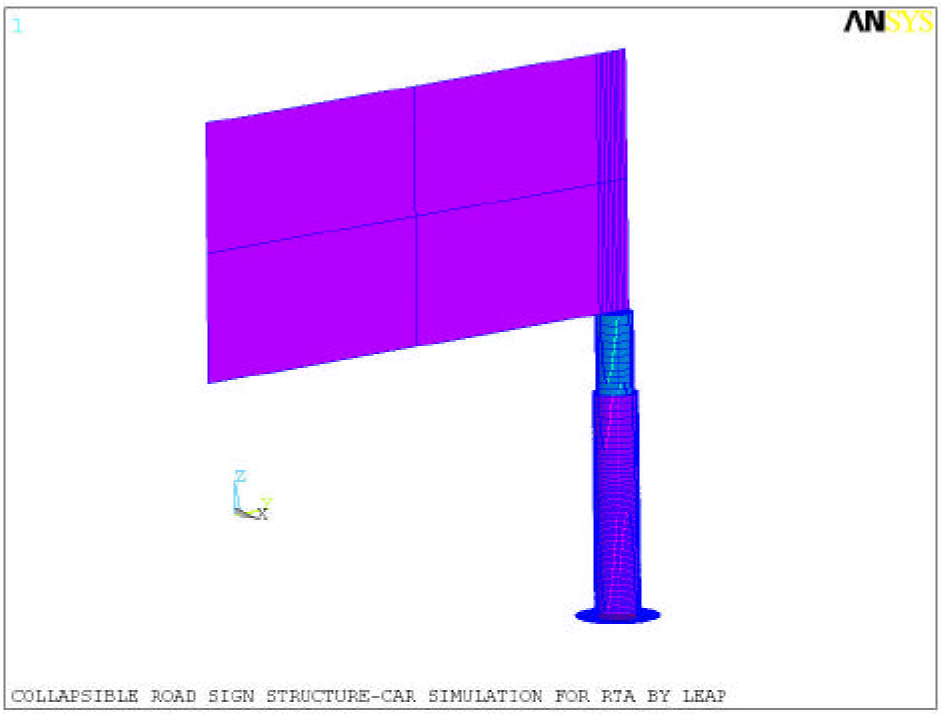

Figure 17 The FE model of the shorter post

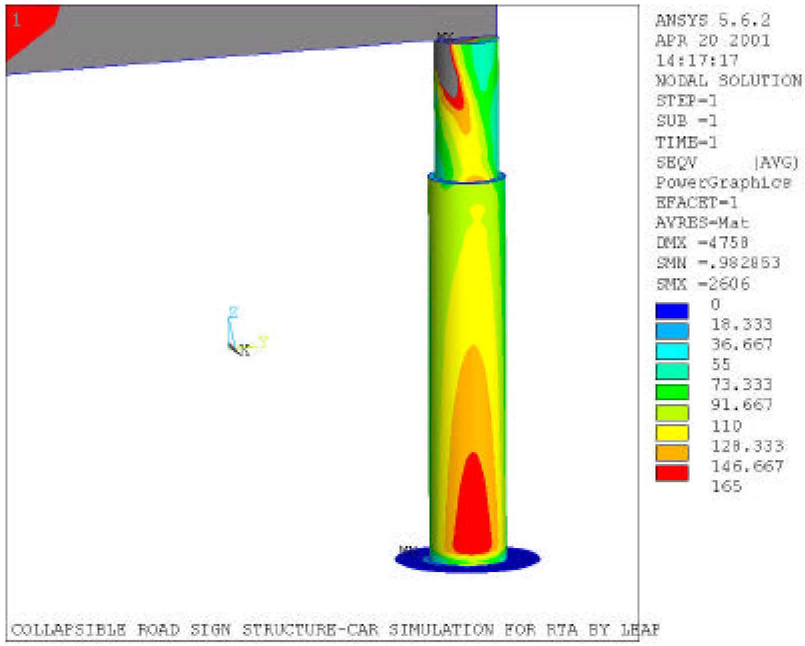

Figure 18 The Von-Mises stress on the shorter single post360

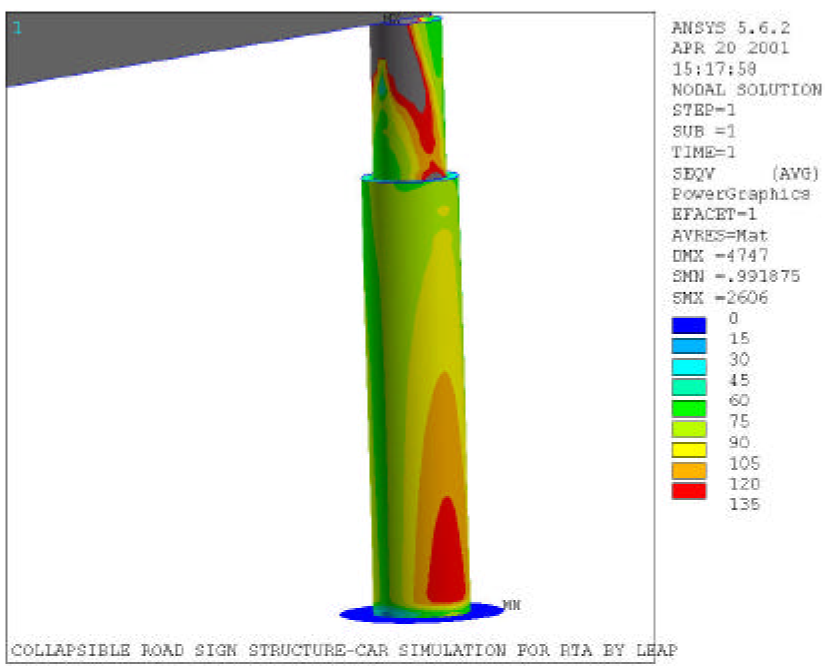

Figure 19 The Von-Mises stress on the shorter single post400

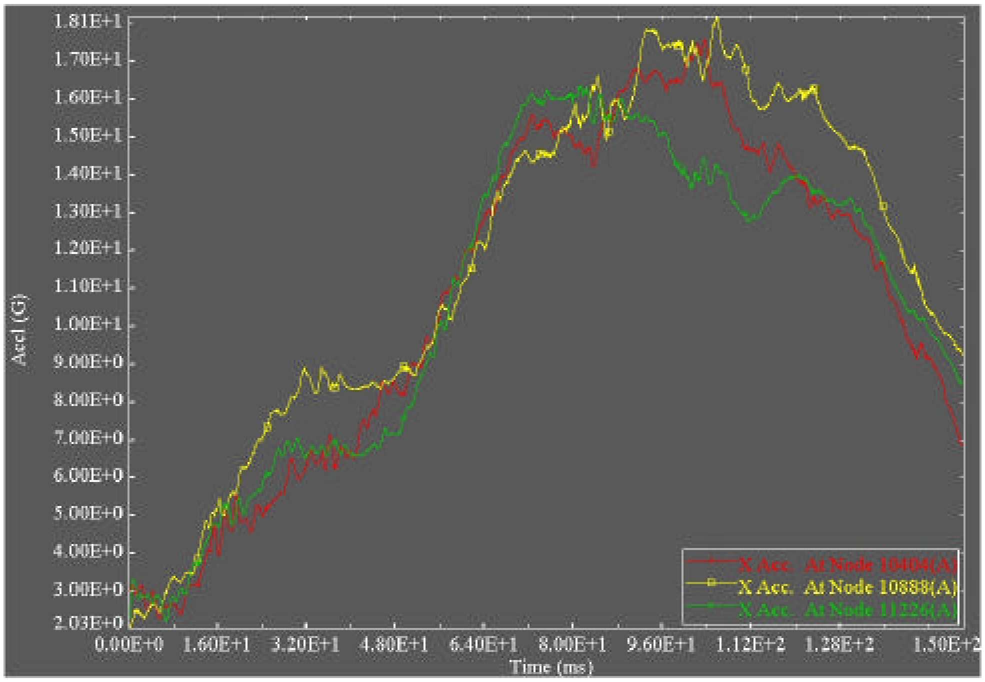

Figure 20 The acceleration of the car impact to a shorter single cylinder post360

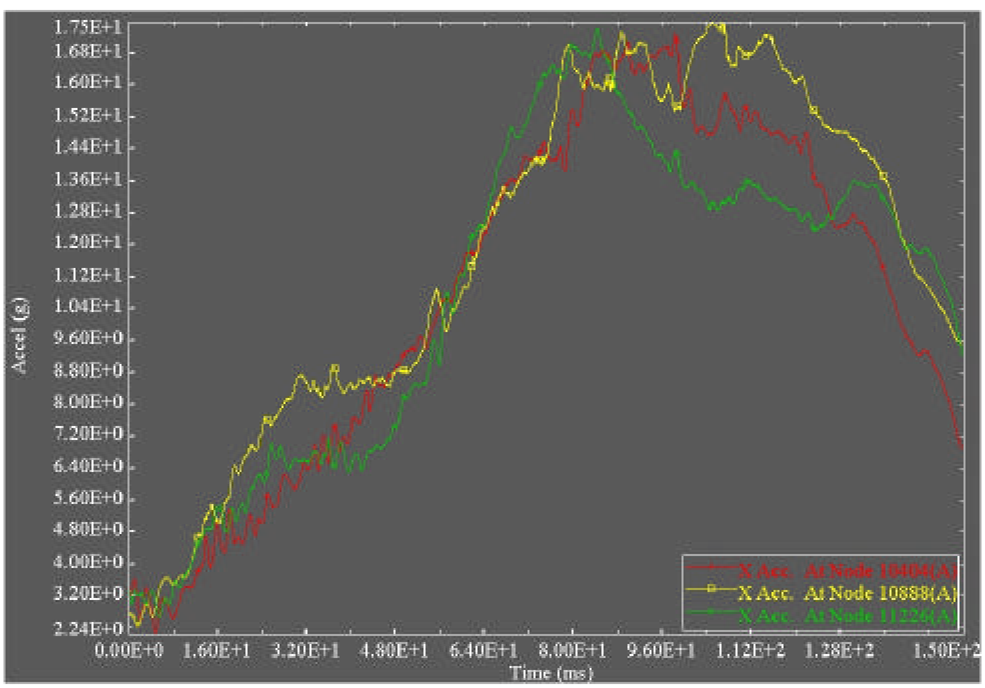

Figure 21 The acceleration of the car impact to a shorter single cylinder post400

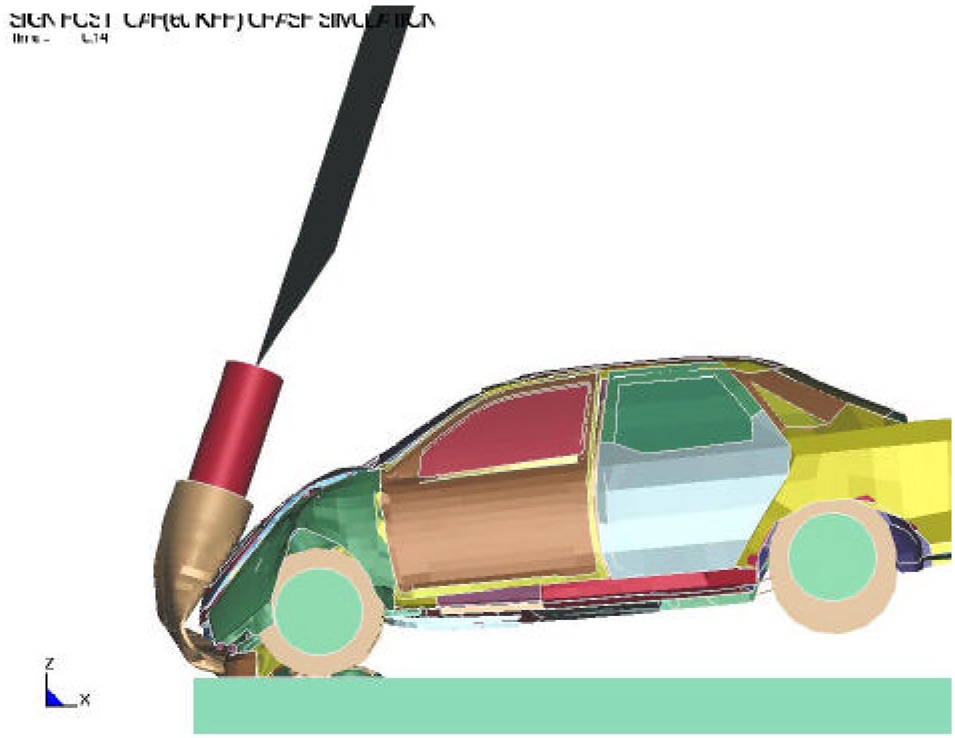

Figure 22 The deformed shape of the car and the post (shorter post400)

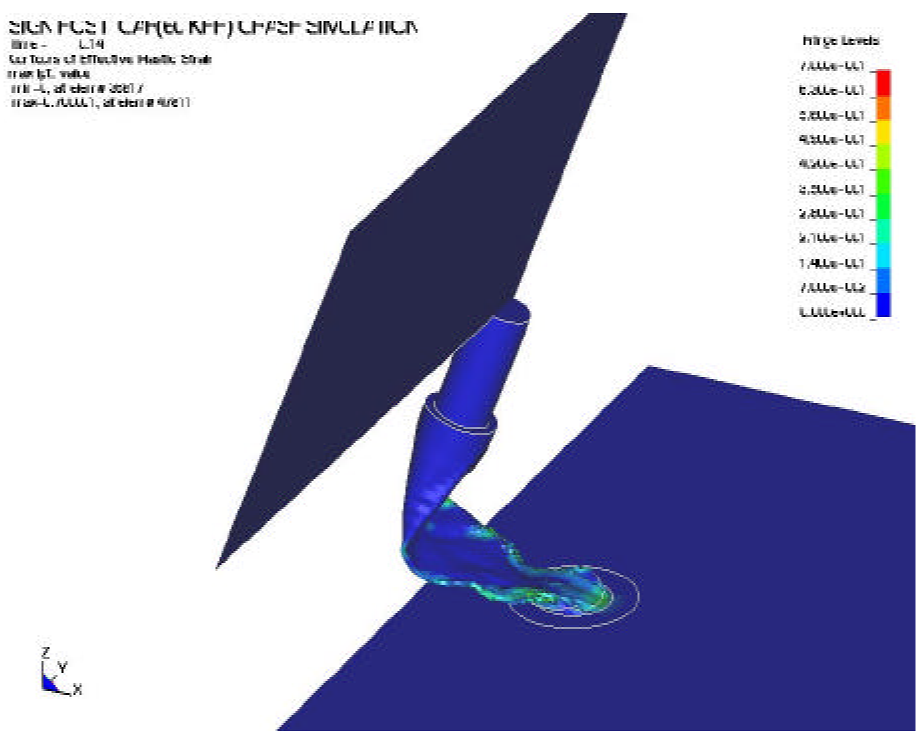

Figure 23 The plastic strain and the deformed shape of the post (shorter post400)

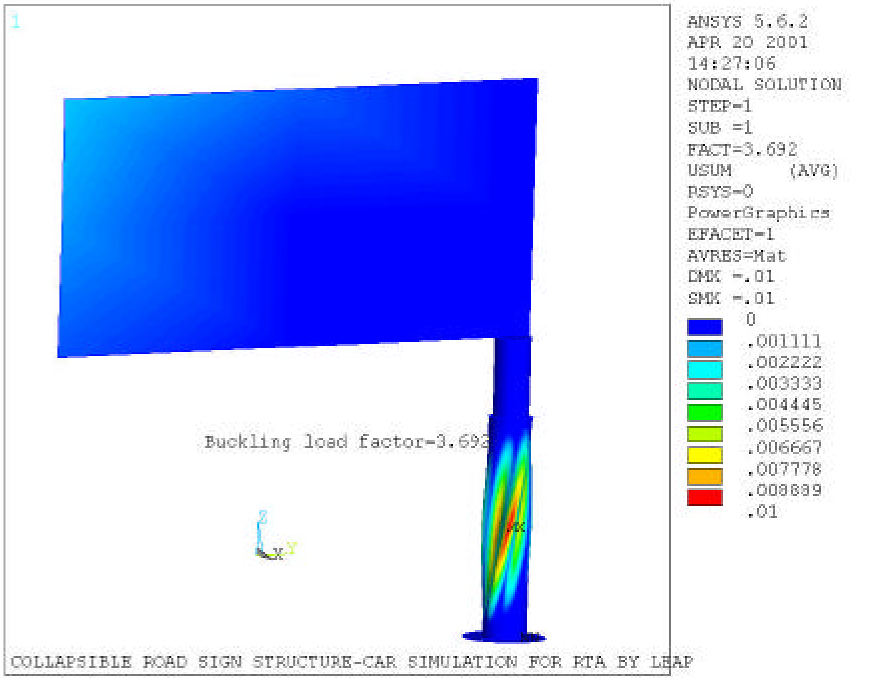

Figure 24 The buckling mode of the single cylinder post 360

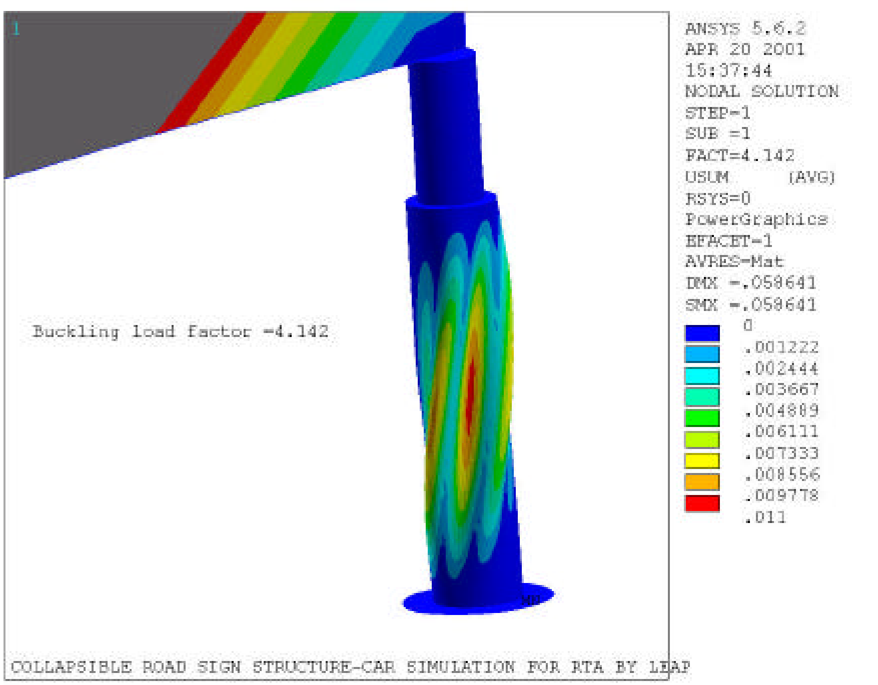

Figure 25 The buckling mode of the single cylinder post 400

5. STAGE 3: ANALYSIS OF SINGLE CYLINDER SHORTER POST IMPACTED BY A FORD FESTIVA (SMALL CAR)

It was requested by RTA to investigate the performance of the post impacted by a small car. A Ford Festiva passenger car (820kg) was used for the impact simulation. Frontal impact simulations with a car of initial velocity of 70km/hour were performed.

The conceptual design of the post (Drawing SK 495) was supplied by RTA Road Technology Branch. The lower part of the post consists a single steel cylinder. The diameter of the cylinder is in the range of 360-400 mm. The thickness of the post wall shell was specified as 2 to 3 mm. The Finite Element (FE) models of the signpost were created using ANSYS FEA software. Models with various post dimensions were created and analysed for parametrical study.

A Festiva car was selected as the colliding vehicle. The Festiva car model is a public domain finite element model generated by The FHWA/NHTSA National Crash Analysis Center at The George Washington University. The major dimensions of this car are:

Length of car = 3.60 m
Width of car = 1.65m
Height of the car = 1.40 m
Total mass = 820 Kg

Figure 26 shows a Finite Element (FE) model of the car and the signpost used for the simulation. Number of elements and nodes in the car and post model are as follows:

	Number of elements:	Number of Nodes:
Car	4014	5305
Signpost	7707	9639
Total	11721	14944

The units used in the FE model are:

Quantity	Units
Length (L)	mm

Force (F)	KN
Modulus of elasticity (E)	KN/mm^2(Gpa)
Mass (m)	kg
Density (ρ)	kg/mm^3
Time (t)	ms
Acceleration (a)	mm/ms^2

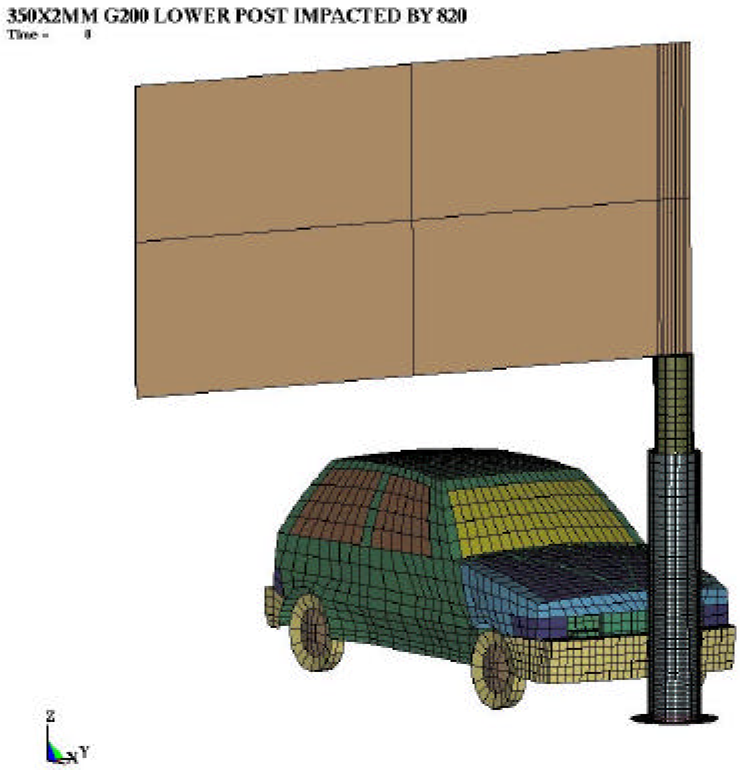

Figure 26 The finite element model of the signpost and the colliding car

5.1 Frontal Impact Simulation Using a Car of 70kph

A number of crash impact simulations were carried out for various design configurations: two post diameters (360mm and 400mm), one plate thickness (2mm), and three materials (grade 200, grade 250 and grade 350 Steel).

Below is a summary of peak acceleration results from simulations for different combinations of the design configurations. The acceleration extracted is at the Centre of Gravity (CG, node 4319). The acceleration data were filtered using SAE 180 filter and then averaged over 10ms period.

Table 2 The acceleration of the car during impact.

SAE 180 filter averaged over 10ms		
Wall Thickness	2mm	2mm
Post Diameter	360 mm	400mm
Steel Material		
Grade 200	21g	23g
Grade 250	23g	23g
Grade 350	24g	25g

Figures 27 to 31 are the results for post 360x2mm with grade 200 steel (a typical set of results). Figure 27 shows the car and the post deformed shape after the impact (150 ms). Figure 28 shows the plastic strain contour of the post. There was a slight shearing of the cylinder at the base of the post, however the car was brought to a standstill.

Figure 29 shows the acceleration v. time graph for the CG of the car. Figures 30 and 31 are the velocity and displacement graph of the passenger relative to the car (integrated from the acceleration data). The occupant impact velocity (the occupant velocity relative to the car at the time the occupant moves 0.6m in the car during the crash impact) was extracted and listed in table 3 below:

Table 3 The occupant impact velocity

V_t velocity at t*		
Wall Thickness	2mm	2mm
Post Diameter	360 mm	400mm
Steel Material		
Grade 200	12.2m/s	11.0m/s
Grade 250	10.8m/s	11.3m/s
Grade 350	12.5m/s	11.7m/s

Three animation files for the shorter post of 360 dameter (360x2mm-g200-front.avi, 360x2mm-g200-side.avi, 360x2mm-g250-post.avi) were created to show the deformation history of the car and the post. They can be found in the accompanying CD.

The following are a few observations of the simulation results:

1) The car stopped at about 165 ms and traveled about 1.6 metre after the impact.

2) The post has collapsed with a slight shear failure at the base of the post for the grade 200 material but was torn quite badly for grade 250 steel for which failure strain is lower (0.4). Figures 32 and 33 show the torn front base of the post. However the car appears to have stopped (see the animation 360x2mm-g250-post.avi) at the end of the simulation. The post will not be sheared off completely. It shows that the shear failure is very sensitive to the failure strength or the failure

strain of the material. An accurate simulation result is very much dependent on the accuracy of the material data.

3) The occupant impact velocity is close to or below the allowed level by Report 350 (Reference 1) which is 12 m/s.

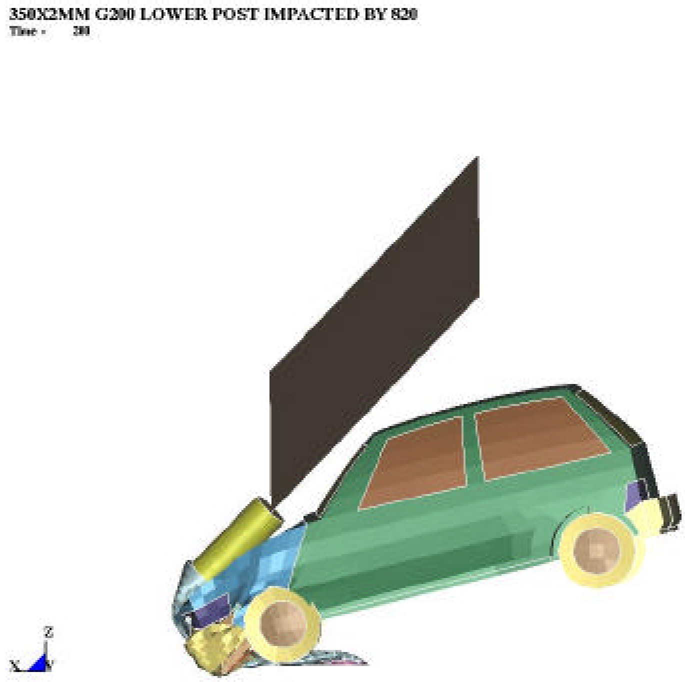

Figure 27 The deformed shape of the post and the car

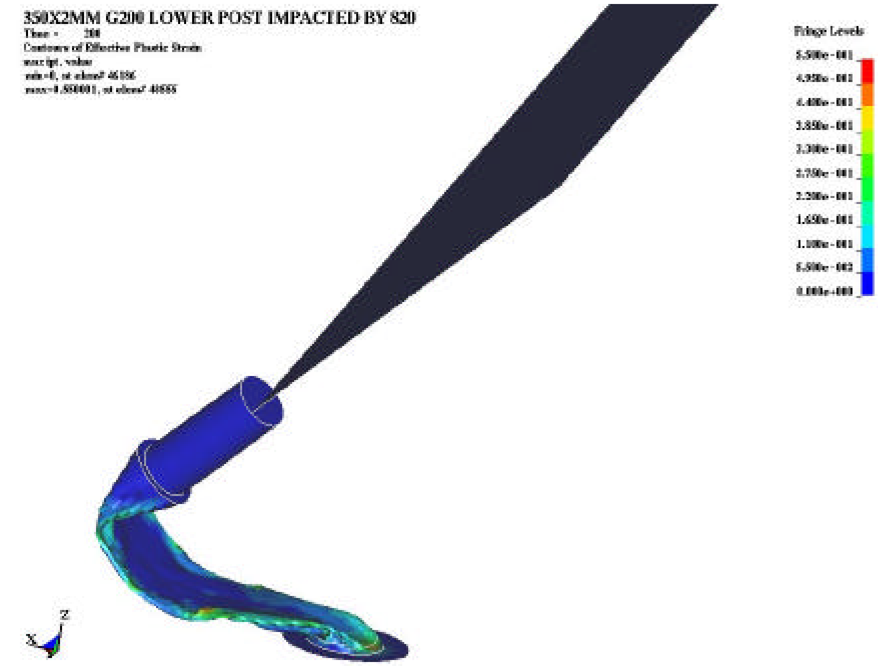

Figure 28 The plastic strain and the deformed shape of the post after impact

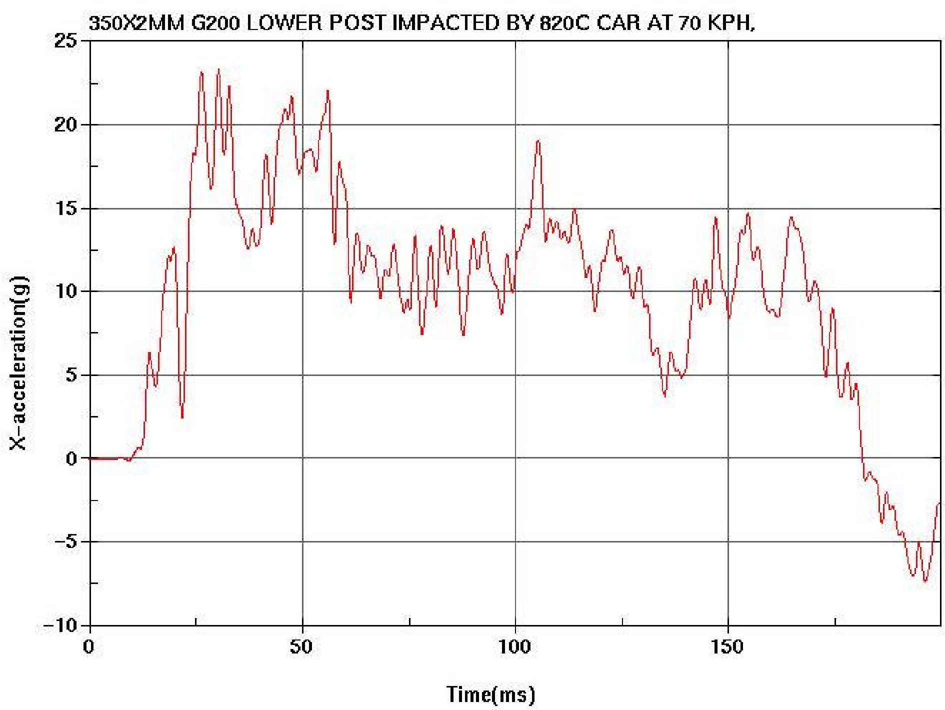

Figure 29 The acceleration history of the car CG

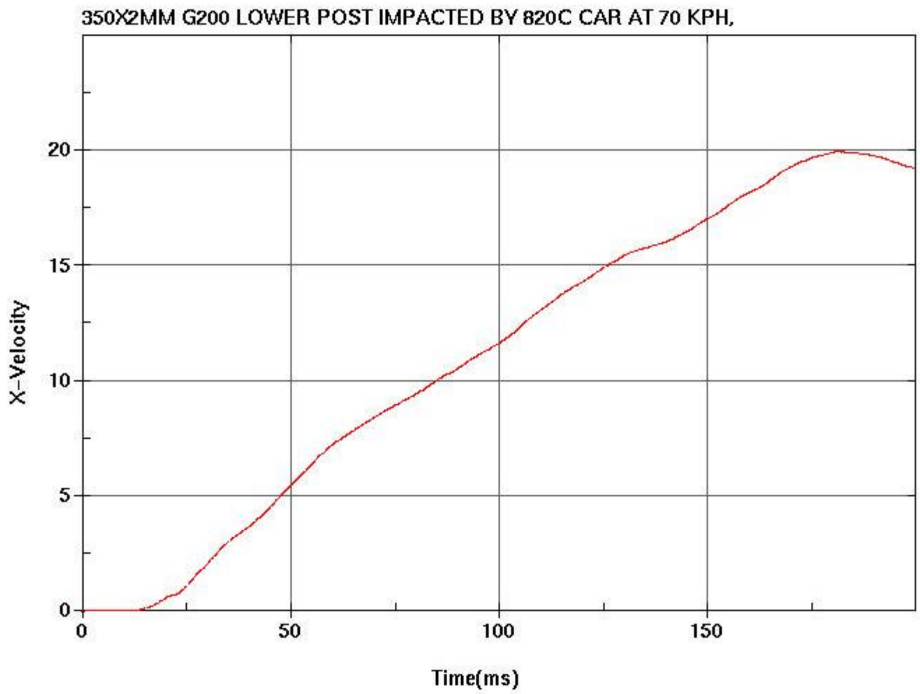

Figure 30 The velocity of the occupant relative to the car

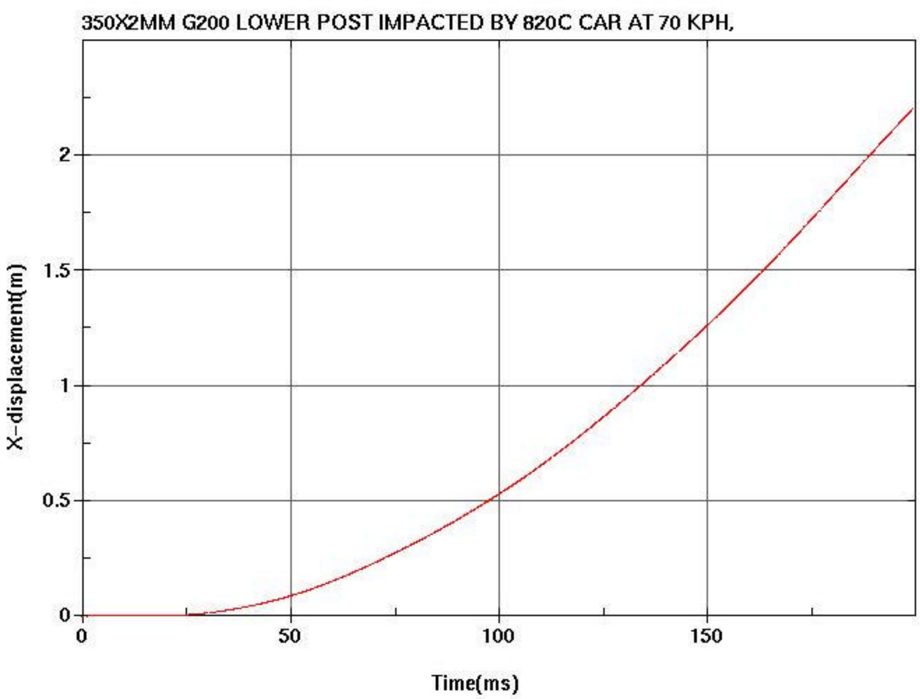

Figure 31 The displacement of the occupant relative to the car

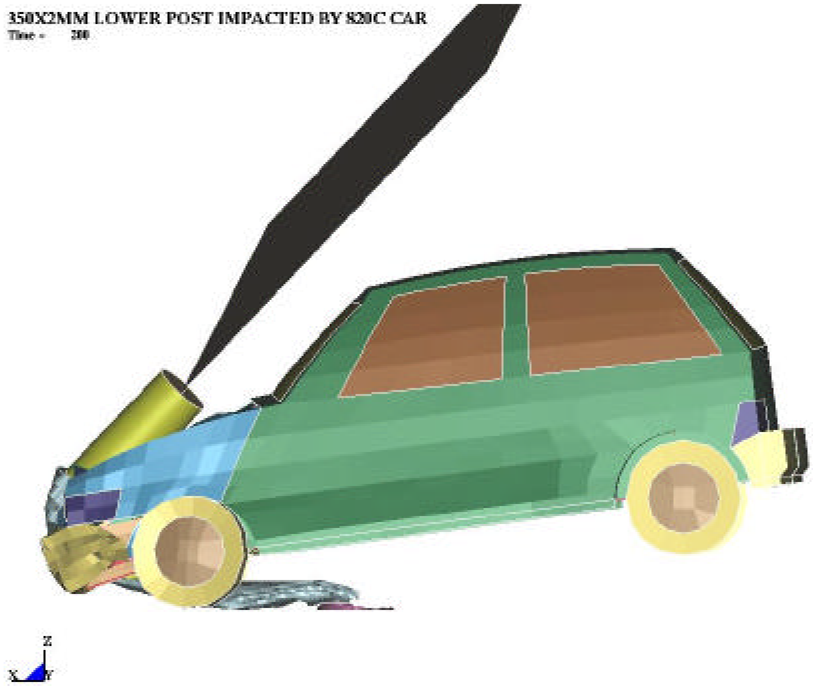

Figure 32 The deformed shape of the post grade 250 and the car

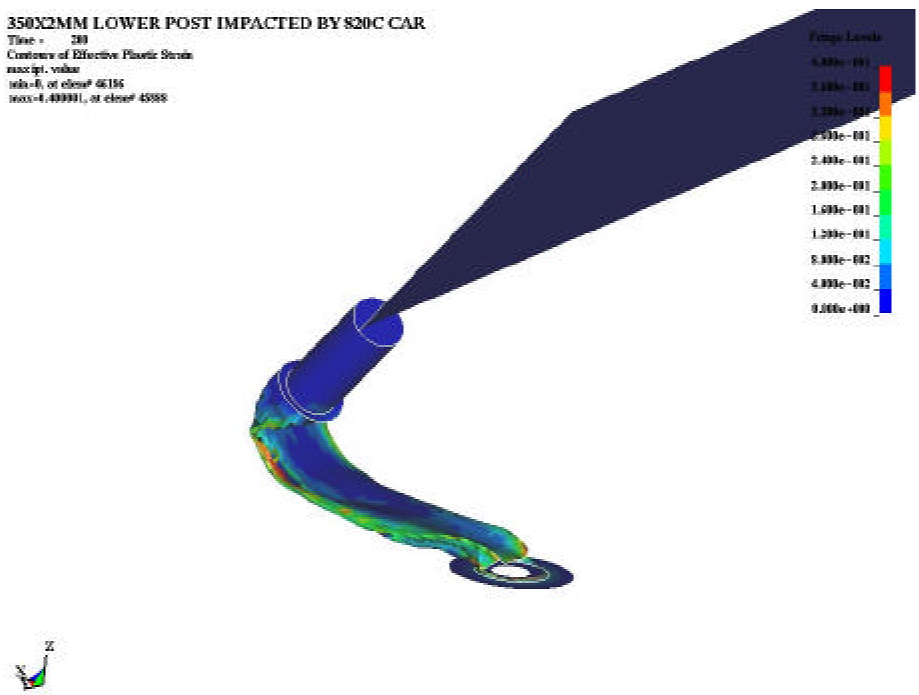

Figure 33 The deformed shape and the plastic strain of the post grade 250

5.2 Static Analysis and Buckling Analysis

The specified static load is 8500N due to wind load and self weight of the post (post extension 60kg and sign board 150kg). The post is the same design as that in section 4 and the static and the buckling analysis has been done in section 4. The following table is a summary of the analysis results for the two post configurations(d=360 mm and d=400 with post thickness t=2 mm):

	Static load		Eigen Buckling
3.5 metre single cylinder post	post Von-Mises stress(MPa)	Yield stress required for safety factor of 1/0.6	load factor
360	165.0	275.	3.69
400	135.5	225.	4.14

5.3 Discussion

The analysis results indicated that the best car acceleration achieved is 21 g for diameter ϕ360 and 2 mm wall thickness Grade 200 steel post. This is still higher than the target of 20 g. The static stress on the post is also a little high. The safety factor for static wind load and gravity load is 245/165=1.48 which is less than the required safety factor of 1.67=1/0.6. Therefore the stage 4 analysis (see section 6 below) is required.

The following are suggestions for further design consideration:

1. It is recommended to reduce the sign face area to reduce the wind load.
2. The post diameter may need to be reduced to further reduce the acceleration.
3. Consider more ductile steel material. For example, AISI 1015 normalised steel. The typical property of this type of steel is:

   Yield Strength = 324 MPa
   Tensile Strength = 424 MPa
   Elongation = 37%
   Reduction in Area 69.6%
   Izod Impact strength = 115.5 J

This material appears to be more ductile than the material that we have tried.

6. STAGE 4 : ANALYSIS OF THE REDUCED SIGN SINGLE CYLINDER SHORTER POST IMPACTED BY A SMALL CAR

After the review of the stage 3 analysis results, a number of design changes were made by RTA based on the recommendations from LEAP:

1. Reduce the sign face to 3x2 m, the wind load reduces to 7200N.
2. Change from cantilever to centrally mounted sign face.
3. Reduce the weight of the components above the collapsible post cylinder to 120kg.
4. Choose a more ductile BHP steel material grade HU250.
5. Add cables in the collapsible post to prevent post from being completely sheared off in an impact involving a larger car.

The new design of the post (Drawing SK 500) was supplied by RTA Road Technology Branch. The lower part of the post consists of a single steel cylinder. The diameter of the cylinder is in the range of 250-300 mm. The thickness of the post wall shell was specified between 2 to 3 mm. The FE models of signpost were created using ANSYS FEA software. Models with various post dimensions were created and analysed for parametrical study.

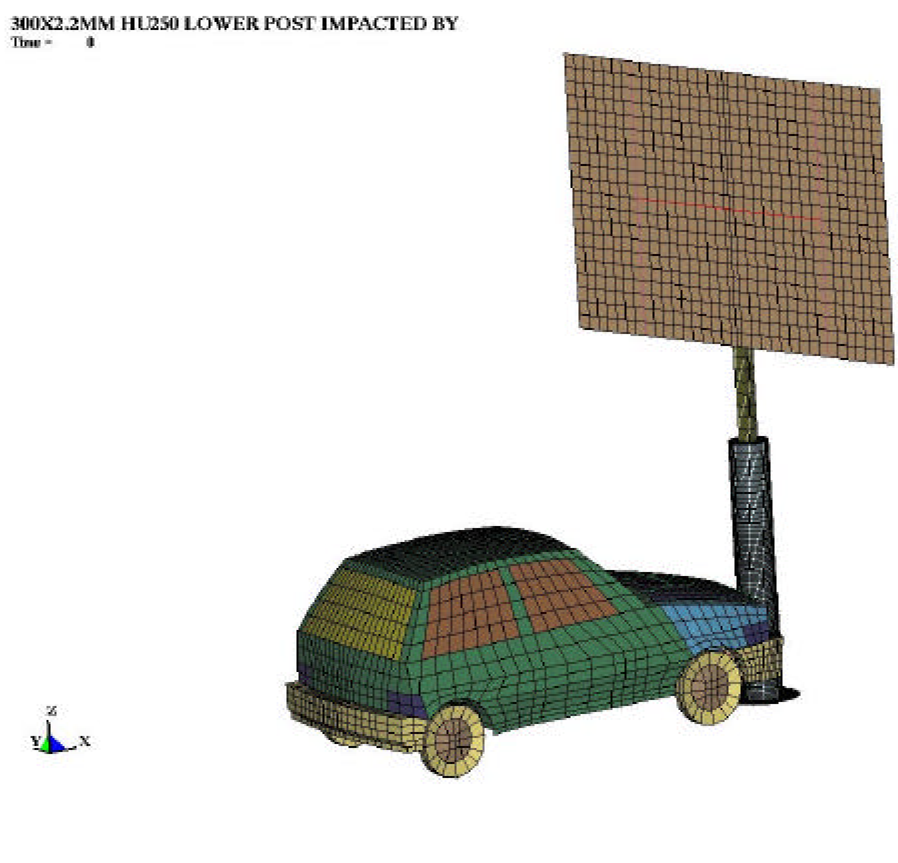

Figure 34 The finite element model of signpost (stage 4) and the colliding car

Steel HU250 was chosen because its reasonable yield strength (guaranteed above 250 MPa) with good ductility. There is no stress-strain test data available from BHP for HU250. The BHP material spec sheet indicated that the typical yield stress is 270-320 MPa. The middle value of 295MPa was taken as the yield point for analysis. The stress-strain curve is assumed to be in the same shape as that of HA200 but scaled up by 40 MPa throughout the curve. The material properties of HU250 steel used in the analysis are listed below:

Grade 250 HU steel

Young modulus: E= 2.0 E5 MPa
Poisson Ratio : γ = 0.29
Yield Stress : σ_y=295 MPa
Failure strain ε_f =50%.

The non-linear stress-strain curve:

True plastic strain	True stress(MPa)
0.0000	295.0
0.0488	334.0
0.0953	397.0
0.140	436.7
0.1823	470.0
0.2623	521.0
0.3364	558.0
0.500	580.0

6.1 Frontal Impact Simulation Using a Small Car at 70kph

A number of crash impact simulations were carried out for several design configurations. The design configurations include:

1) Oval shape post 350x250 (length of major and minor axes) with the major axes parallel with the sign face.
2) Oval shape post 350x250 (length of major and minor axes) with the major axes perpendicular to the sign face.
3) Cylinder diameter d=400-250mm, wall thickness =2 –2.5 mm.
4) Cylinder diameter d=400-250mm, wall thickness =2 –2.5 mm, with a steel cable inside the post.

The best result came from the following configuration of the post: Cylinder diameter d=300 mm, wall thickness =2.2mm, Steel HU250 material. The following are the simulation results for two configurations:

1) The signpost without steel cable inside the collapsible cylinder.
2) The signpost with a steel cable of ϕ20mm in the middle of the collapsible cylinder. The cable was connected to the centre of the bottom plate and top plate with an eyelet. The strength of the eyelet was not included in the analysis. It is recommended not to pretension the cable in the installation.

Figures 35 and 36 show the acceleration v. time graph for the CG of the car for the post without the cable and with the cable respectively. Figures 37 and 38 are the velocity relative to the car (integrated from the acceleration data) for the post with no cable and with cable. Figures 39 and 40 are displacement graphs of the passenger relative to the car for the post without cable and with cable. The occupant impact velocities (the occupant velocity relative to the car at the time the occupant moves 0.6m in the car during the crash impact) were extracted from the graph.

The average acceleration of the car impacting the post without cable is about 19.5g. It can be seen from the acceleration graph (Figure 35) that there were two peaks. The first peak is at about 25 millisecond. The averaged acceleration over 10ms is about 19 g. The second peak is at about 90 ms. At this time, the plate at the top of the collapsible post (the mounting plate for the post extension) started to contact the car. The plate prevented the relative sliding between the post and the car (see Figure 42). The pulling action of the post is greater at this time. Therefore a peak acceleration occurred. The averaged acceleration over 10ms is about 19.5g. The occupant impact velocity is 11.5m/s.

The acceleration of the car impacting the post with a cable is about 19 g. It can be seen from the acceleration graph (Figure 36) that the second peak has been removed due to the addition of the cable. The peak occurred at about 25 ms. The averaged acceleration over 10ms is about 19.0g. After this peak the acceleration did not drop as much as in the previous case for the post without cable. The acceleration remained more or less constant and the second peak did not occur. The occupant impact velocity is 11.5m/s.

Figure 42 shows the car and the post deformed shape after the impact (300 ms) for the post with the cable. The deformed shape for the post without the cable is similar. Therefore only the result for the post with a cable is shown. Figure 43 shows the plastic strain contour of the post. There is no shearing of the cylinder at the base of the post. Figure 44 shows the deformed shape of the cable at time 300ms. The force on the cable is very small (about 30 N) which indicates that the cable has not been fully stretched during this impact simulation. Therefore the effect of the cable is not very significant. Adding the cable inside the collapsible post is mainly for preventing shear off during a crash involving a larger car. The following animation file can be found in the accompanying CD:

post-car-70kph-d300-hu250.avi --- Animation of the post and the car for
configuration: Post d=300, t=2.2, material HU250, with cable,
Car initial speed = 70kph
post-pstrain-70kph-d300-hu250.avi --- Animation of post with plastic strain for
configuration: Post d=300, t=2.2, material HU250, with cable
Car initial speed = 70kph
cable -70kph.avi --- Animation of cable for configuration:
Post d=300, t=2.2, material HU250, with cable
Car initial speed = 70kph

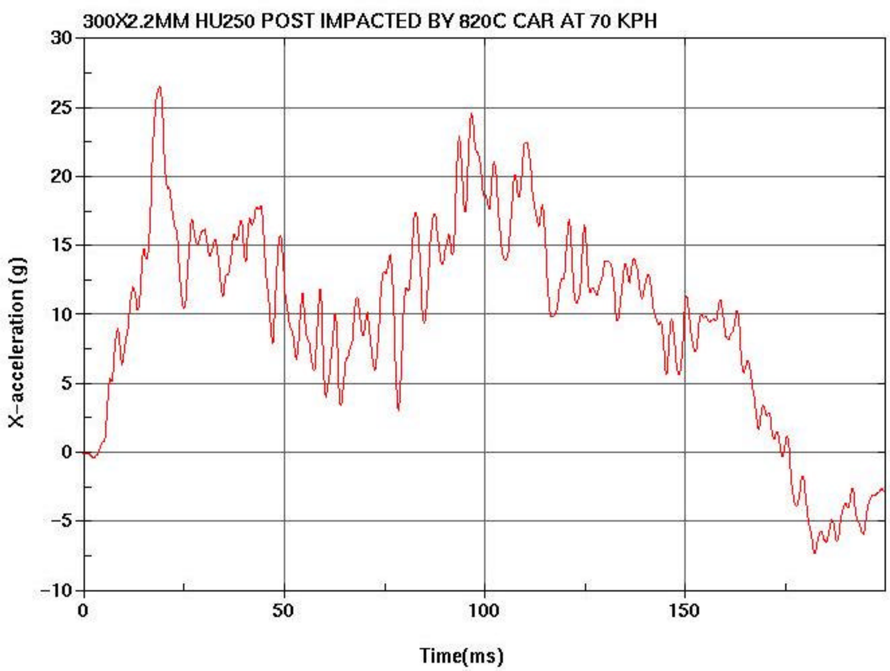

Figure 35 The acceleration history of the car CG for the post without cable

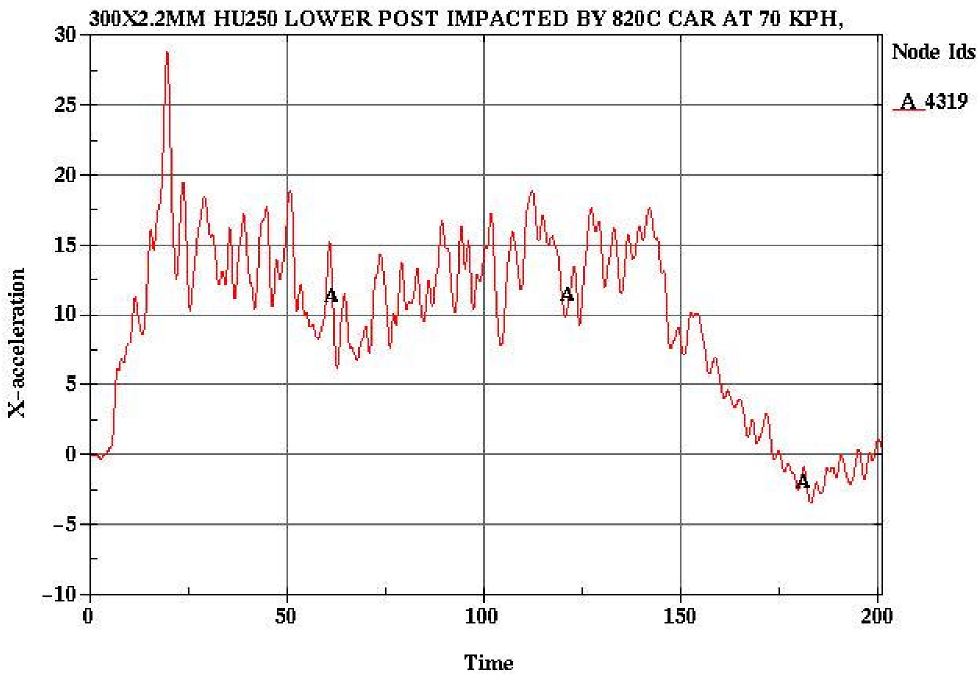

Figure 36 The acceleration history of the car CG for the post with cable

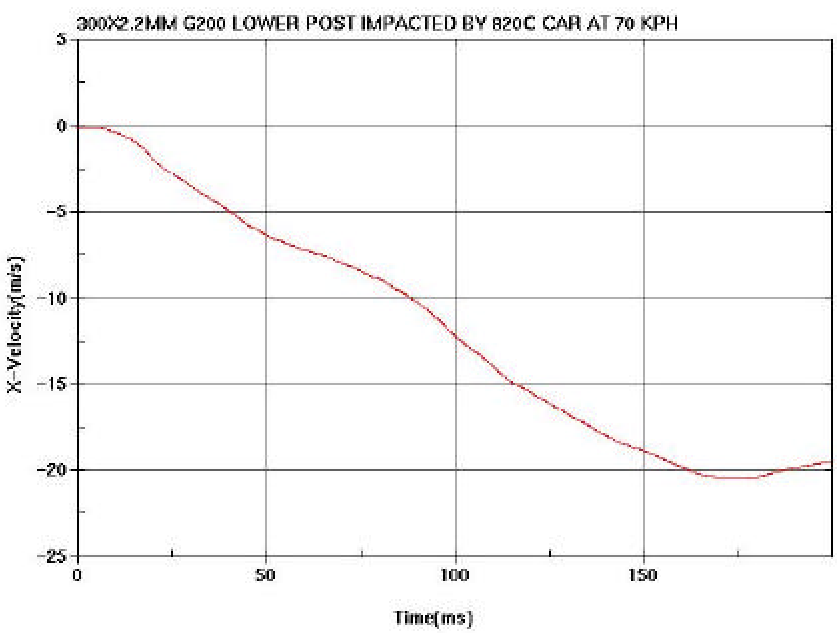

Figure 37 The velocity of occupant relative to the car for the post without cable

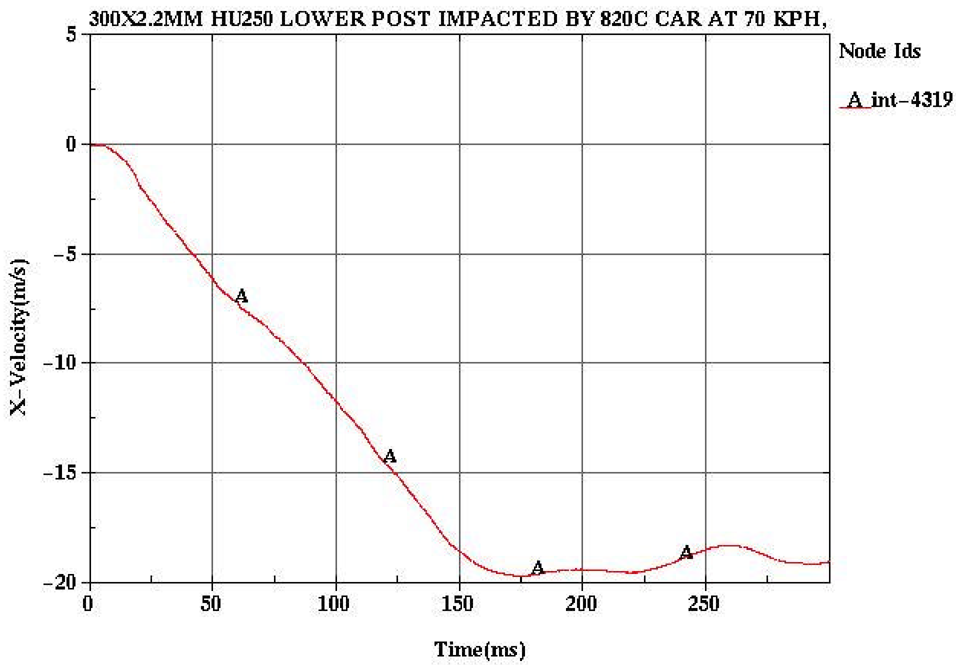

Figure 38 The velocity of the occupant relative to the car for the post with cable

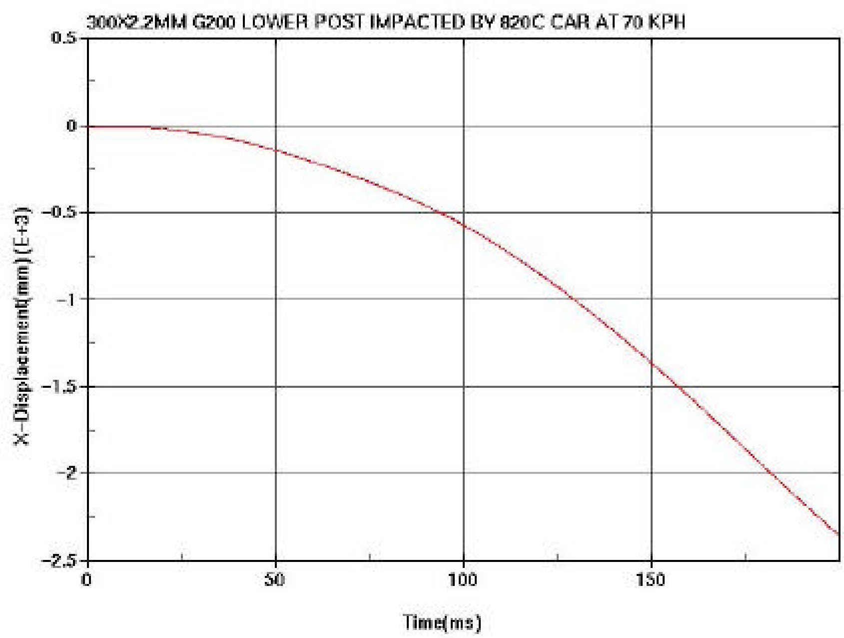

Figure 39 The displacement of occupant relative to the car for the post without cable

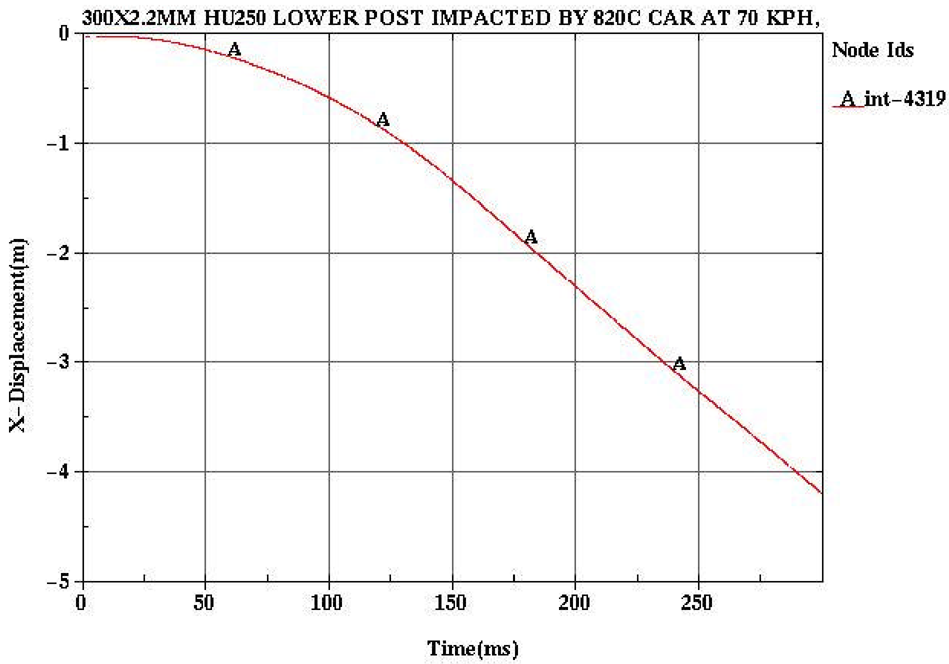

Figure 40 The displacement of the occupant relative to the car for the post with cable

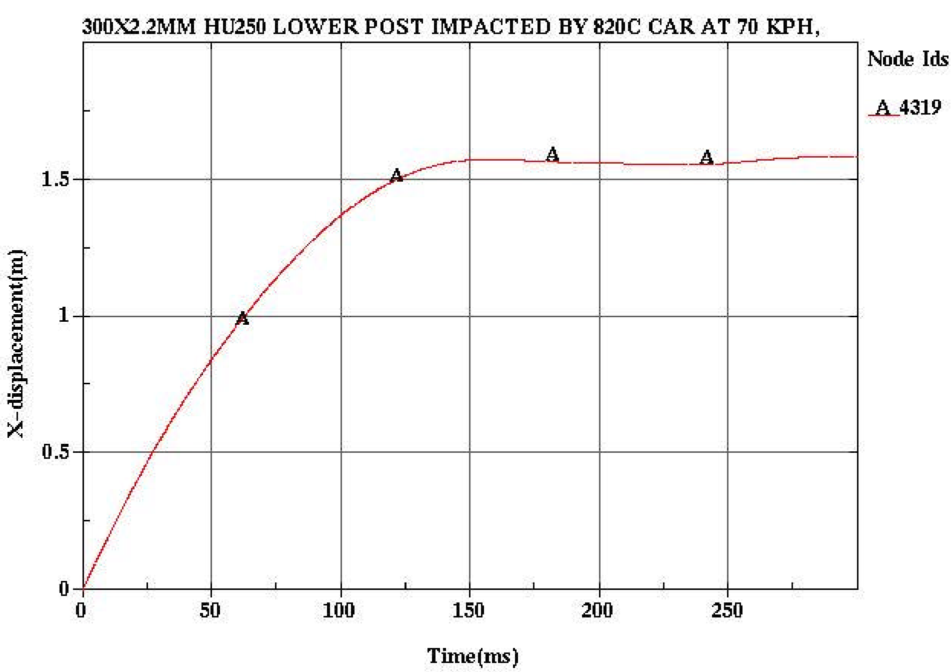

Figure 41 The car movement after the crash for the post with cable

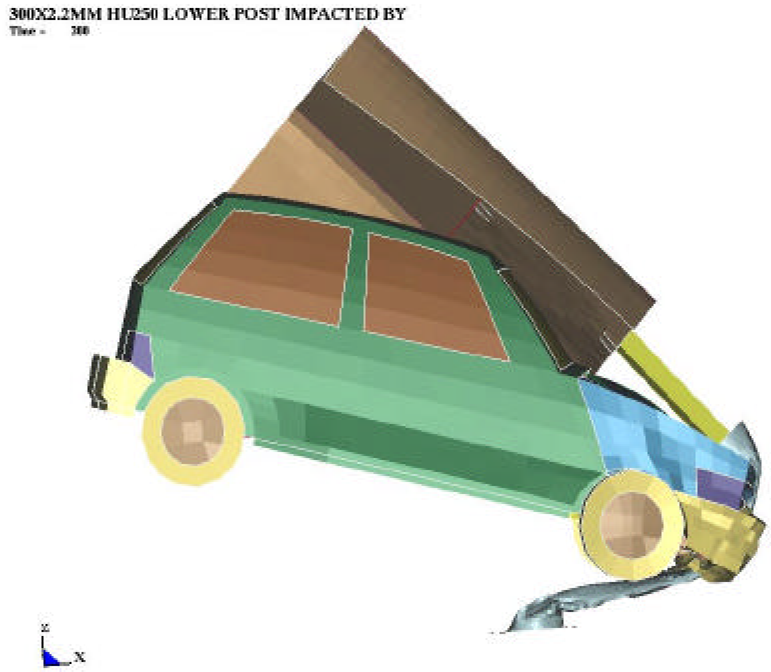

Figure 42 The deformed shape of the post and the car for the post with cable

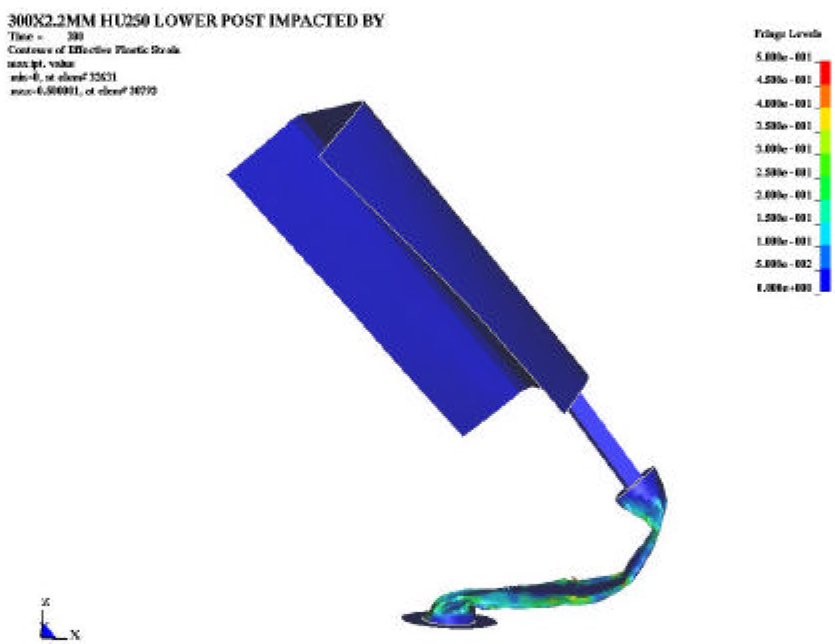

Figure 43 The deformed shape and the plastic strain of the post with cable

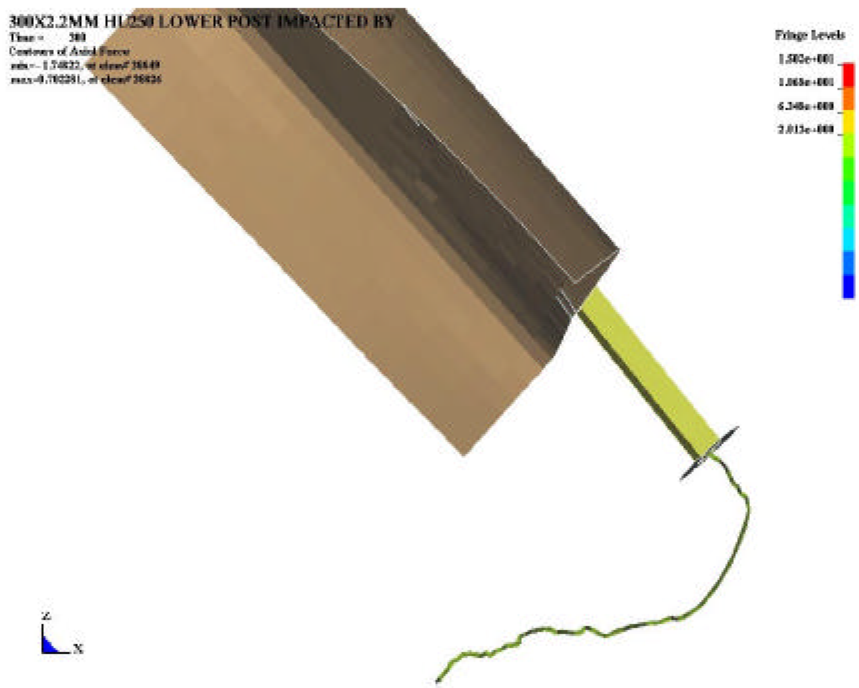

Figure 44 The deformed shape of the cable

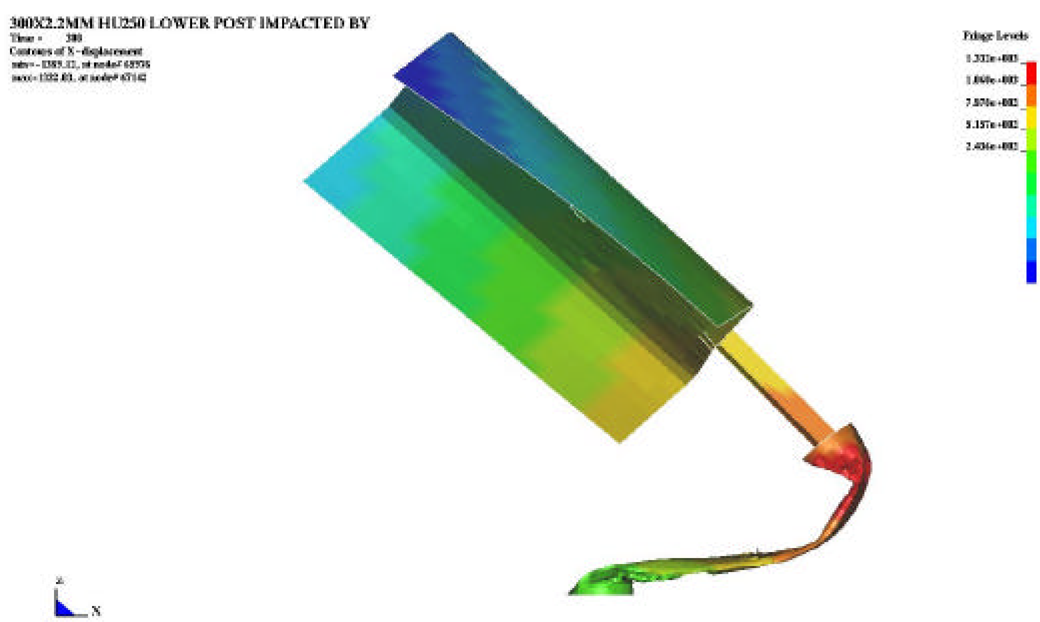

Figure 45 The X-displacement of the post at 300ms

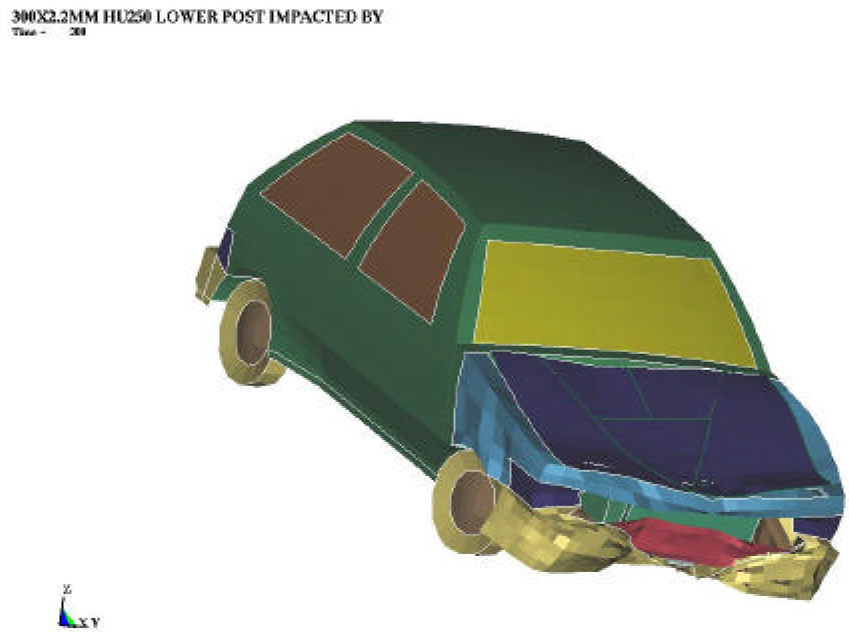

Figure 46 The deformed shape of the car

Two other design configurations were also analysed:

Centrally clamped signboard.

The analysis results (see Figure 47 and attached animation clamp-failure.avi) indicated that the centrally clamped signboard may not be able to take a large bending load. Therefore the sign face did not rotate about the horizontal axis with the post extension and fell down almost straight onto the car (see Figure 47). This behavior of the signpost is not desired for the safety of the occupant. It is recommended to add an extra clamp at the bottom of the sign face which connect the sign face with the post. The analysis results presented above are based on the design that the extra clamp is added.

Taller collapsible cylinder post (H=2200mm).

A taller collapsible cylinder post (H=2200 mm) was also analysed which was intended to reduce the second peak which was seen in the previous analysis result for the post without the centre cable. However the result from the taller collapsible cylinder post did not show any improvement (see Figure 48). Therefore it was recommended to keep the collapsible cylinder post at the original design height of H=1800mm.

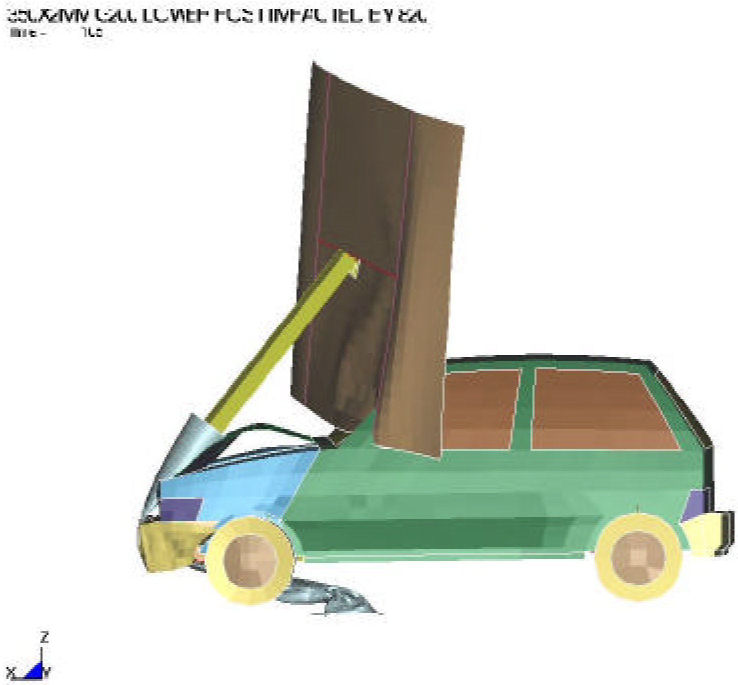

Figure 47 The deformed shape when only sign face centre was clamped.

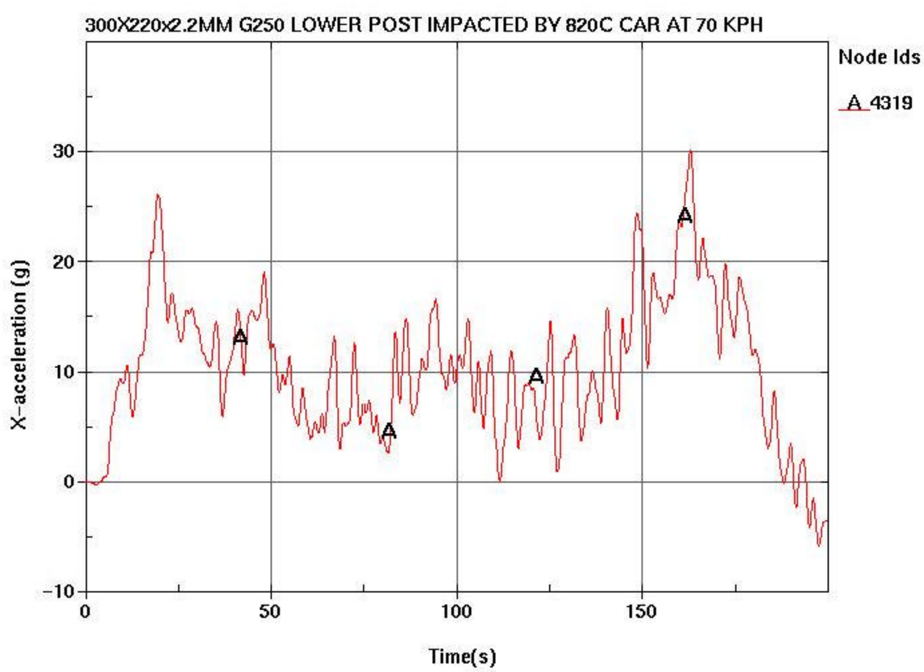

Figure 48 The acceleration history of the car CG for the taller cylinder post

The following are a few observations of the results:

1) Figure 41 shows that the car stopped at about 150 ms and the CG of the car traveled about 1.6 metre after the impact. Figure 45 shows the x-displacement (the displacement in the car's initial travel direction) of the post at time 300ms. The maximum x-displacement of the post is 1.3 m. The car indented about 0.3m (see Figure 46).
2) The post has collapsed without shear failure at the base of the post for the grade HU250 material. The shear failure is very sensitive to the failure strength or the failure strain of the material. An accurate simulation result is very much dependent on the accuracy of material data.
3) The occupant impact velocity is 11.5m/s which is below the allowable level (12 m/s) specified by the Report 350 (Reference 1).
4) Adding a cable in the post has removed the second peak in the acceleration curve. The overall peak acceleration reduced slightly.
5) The sign face stiffness was an approximation, as the horizontal ribs were not modeled. As the main purpose of this analysis is to evaluate performance of the post, this approximation should not affect the accuracy of the result for the post.

6.2 Static Analysis and Buckling Analysis

The specified static load is 7200N wind load and the self weight of 120 kg (including all the parts that are above the collapsible post - mainly post extension and sign board, the post extension is the part of the post above the cylinder collapsible part of the post. For later designs the post extension are made of 100x100x5 SHS, see Figure 47). The following is a summary of the analysis results for this post configuration (d=300 mm with post thickness t=2.2 mm).

Figure 49 shows the stress on the collapsible cylinder is 177 MPa. Assuming the typical yield stress of BHP steel HU250 is 295MPa, the safety factor for the post is 295/177=1.667.

Figure 50 shows the stress on the post extension (100x100x5 SHS) is 269 MPa. The BHP Grade 350 is going to be used. Assuming the typical yield stress of Grade 350 is 350MPa, the safety factor for the post is 350/269=1.3. The high stress is at the interface with the base flange plate. It was assumed that the combined thickness of the flange plates is 20 mm in the FE model. This is a conservative assumption. The two flanges each with a thickness of 20 mm are connected by bolts. If we change the combined flange thickness to 40 mm in the FE model, the stress at the base of the post extension reduces to 220 MPa. Since the high stress is localized, local thickening should be able reduce the stress to an acceptable level.

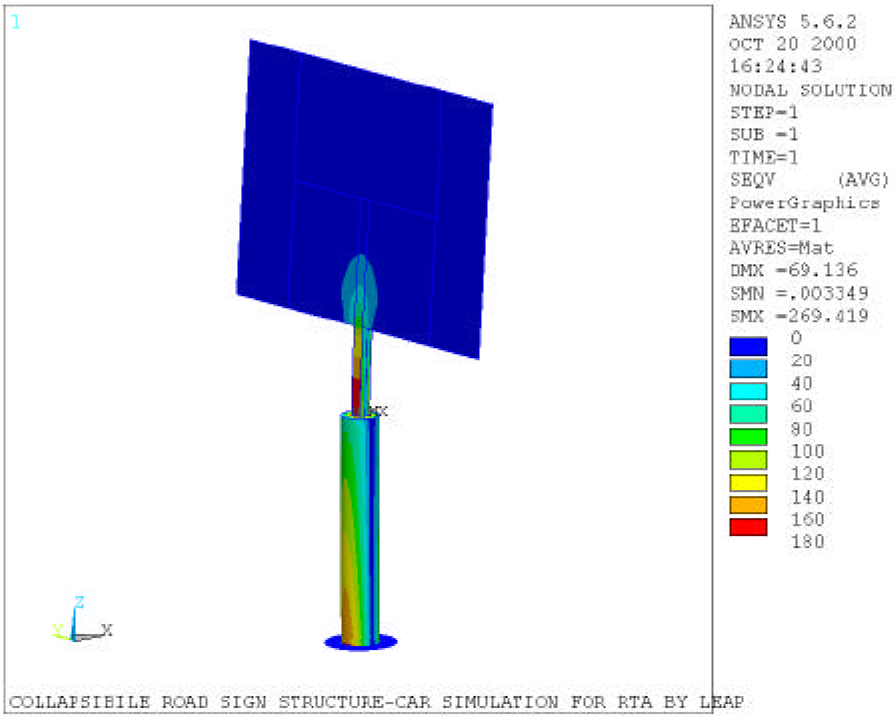

Figure 49 The Von-Mises stress on the single cylinder post300

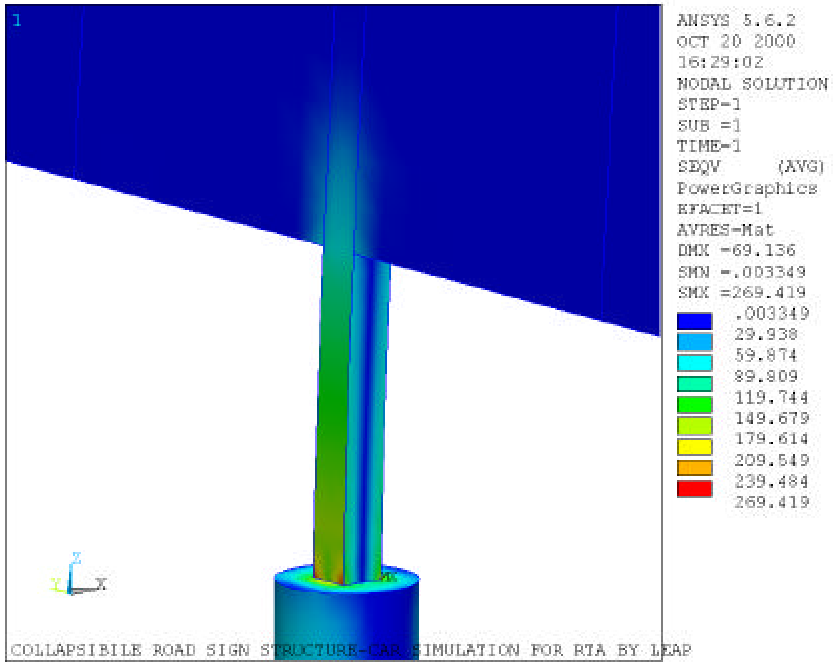

Figure 50 The Von-Mises stress on the extension post 100x100x5

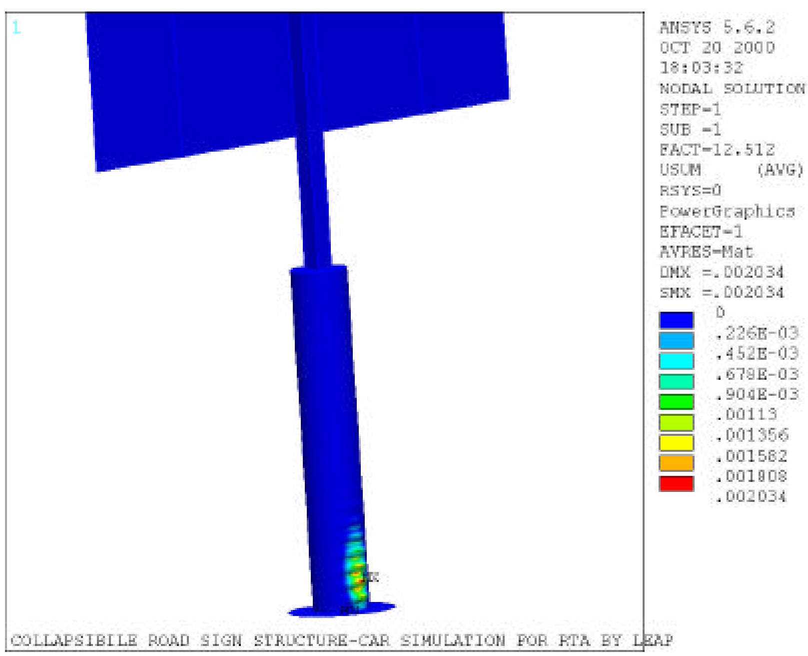

Figure 51 The buckling mode of the single cylinder post 300

The buckling load factor from Eigen buckling analysis for the 300x2.2mm post is 12.5. The first buckling mode is shown in Figure 51. As the buckling load factor is much larger than 1, the buckling is not likely to occur if there is no pre-existing imperfection.

6.3 Discussion

The analysis results indicated that the best car acceleration achieved was 19.0 g for ϕ300 collapsible post with wall thickness of 2.2 mm using HU250 steel and with a steel cable ϕ19.5 inside. The static stress on the post was 177MPa. If the middle value of the typical yield stress is used as the typical yield stress (295Mpa), the safety factor for static wind load and gravity load is 295/177=1.67 which satisfies the safety factor requirement 1.67=1/0.6. The buckling load factor from Eigen buckling analysis for the 300x2.2mm post is 12.5. The buckling is not likely to occur if there is no pre-existing imperfection.

7. Stage 5: Impact Simulation Using a Pick-up Truck

It was desired that the posts perform well for a wide range of vehicles. Apart from the vehicles used in the previous analyses (medium car Ford Taurus and small car Ford Festiva) the two-tonne pickup truck is another popular vehicle that was used in the Safety Performance Evaluation test [Reference 1]. Impact simulation using the two-tonne truck was conducted.

The two tonne pick-up truck model was a public domain finite element model generated by The FHWA/NHTSA National Crash Analysis Center at The George Washington University. The major dimensions of this truck are:

Length of car = 5.422 m
Width of car = 1.96m
Height of the car = 1.84 m
Total mass = 2000 Kg

Figure 52 shows a Finite Element (FE) model of the pick-up truck and the signpost used for the simulation.

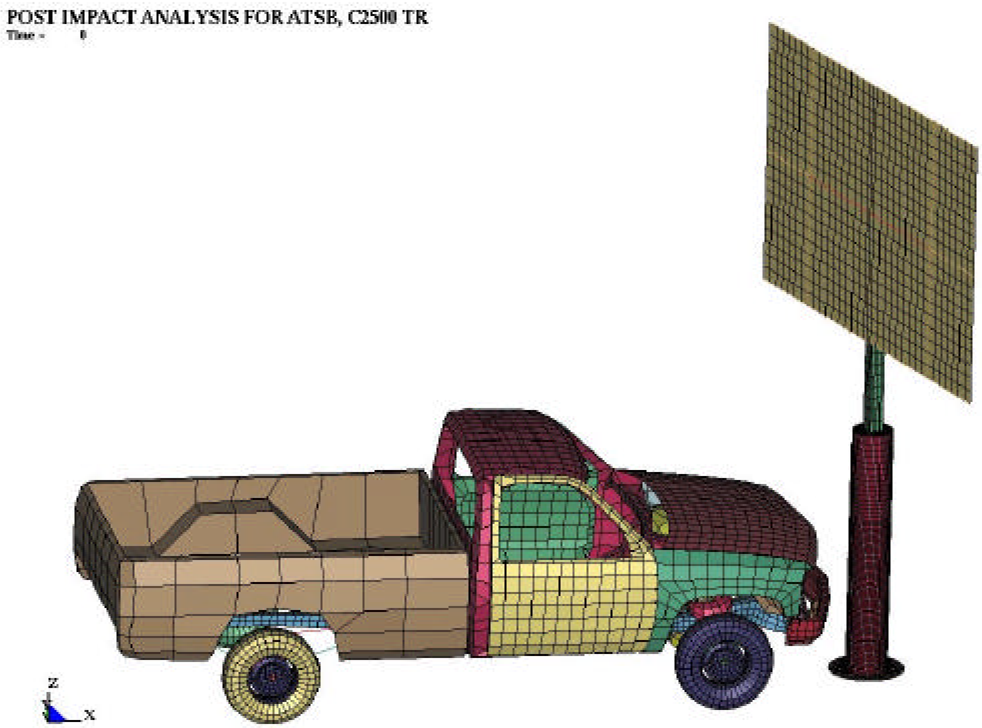

Figure 52 The finite element model of the signpost and the colliding car

The units used in the FE model are:

Quantity	Units
Length (L)	mm
Force (F)	N
Modulus of elasticity (E)	N/mm^2 (Mpa)
Mass (m)	tonne
Density (ρ)	$tonne/mm^3$
Time (t)	s
Acceleration (a)	mm/s^2

7.1 Frontal Impact Simulation Using a pickup truck of 70kph

Crash simulations were carried out using the two-tonne pick-up truck to impact on the post at 70 km/hour (kph). The best performing post design from the previous analysis and design work was used for these simulations. The post design parameters are: Collapsible Cylinder diameter d=300 mm height H=1800mm, Wall thickness =2.2mm, Steel HU250 material.

The following two simulations were conducted:

1) The signpost without steel cable inside the collapsible cylinder. The post was expected to be sheared off at the lower section.
2) The signpost with a steel cable of diameter of ϕ20 mm (breaking load of 27.3 tonnes) inside the collapsible cylinder to prevent the upper part of the signpost from being completely sheared off and separated from the base. The cable was assumed to be connected to the centre of the bottom plate and top plate with an eyelet. The eyelet, which anchors the cable, was assumed to have adequate strength that will not break during the impact. The eyelet was not included in the analysis. It was assumed no pretension of the cable during installation. In fact, a slightly slack cable would be better for the performance.

Figures 53 and 54 show the acceleration v. time graph for the CG of the truck for the post without the cable and with the cable respectively. Figures 55 and 56 show the velocities relative to the truck (integrated from the acceleration data) for the post with and without cable. Figures 57 and 58 are displacement graphs of the passenger relative to the car for the post without cable and with cable. The occupant impact velocities (the occupant velocity relative to the car at the time the occupant moves 0.6 metre in the car during the crash impact) were extracted from the graph.

The acceleration (averaged over 10ms) of the truck for the post without cable is about 14.5g (see Figure 52). The peak is at about 105 ms. The post is then sheared off. The occupant impact velocity is 8 m/s.

The acceleration of the truck for the post with a cable is about 20 g. It can be seen from the acceleration graph (Figure 54) that the peak occurred at about 180 ms. This peak is caused by the cable which is fully stretched by now and applying the stopping force onto the vehicle. The occupant impact velocity is 10.m/s.

Figure 59 shows the car and the post deformed shape after the impact (300 ms) for the post without the cable. The post has been sheared off completely. Figure 60 shows the truck and the post deformed shape after the impact (300 ms) for the post with a cable. Figure 61 shows the post deformed shape after the impact (300 ms) for the post with a cable. It can be seen that cable has prevented the post from being completely sheared off. Figure 64 shows force on the cable. The peak force on the cable is about 200 kN (or 20 tonnes). The following animation file can be found in the accompanying CD:

post-truck-nocable-70kph.avi - Animation of the post for configuration:
Post d=300, t=2.2, material HU250, without cable,
truck initial speed = 70kph
post-truck-cable-70kph.avi -- Animation of the post for configuration:
Post d=300, t=2.2, material HU250, without cable,

truck initial speed = 70kph
cable-truck-70kph.avi --- Animation of cable

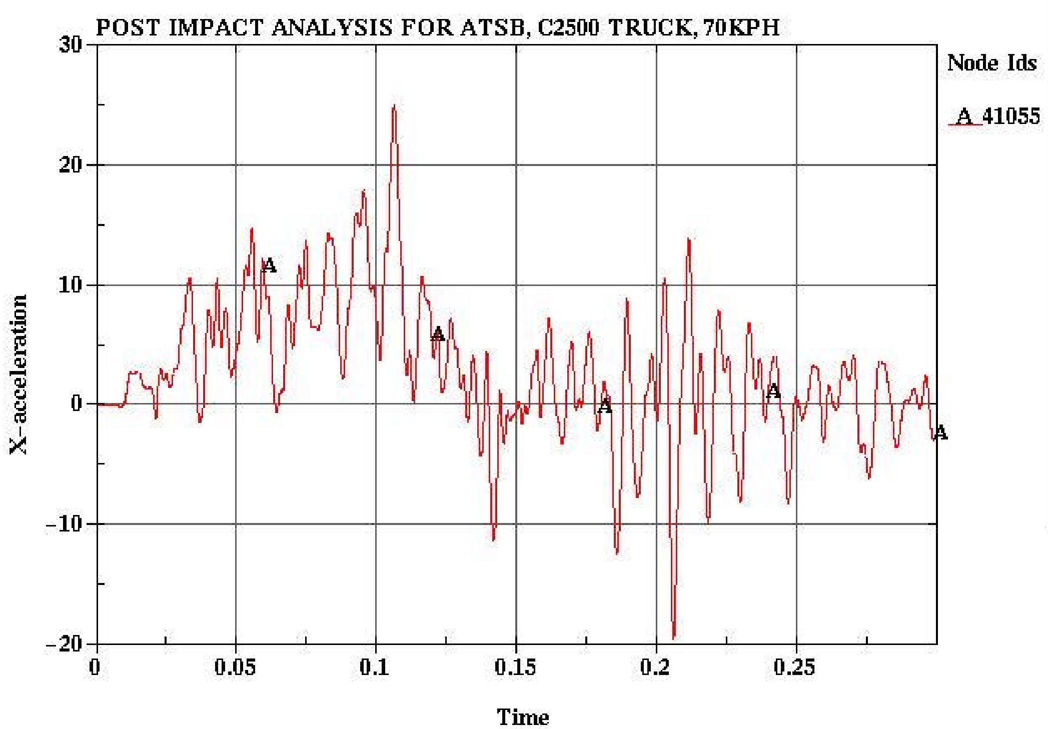

Figure 53 The acceleration history of the truck CG for the post without cable

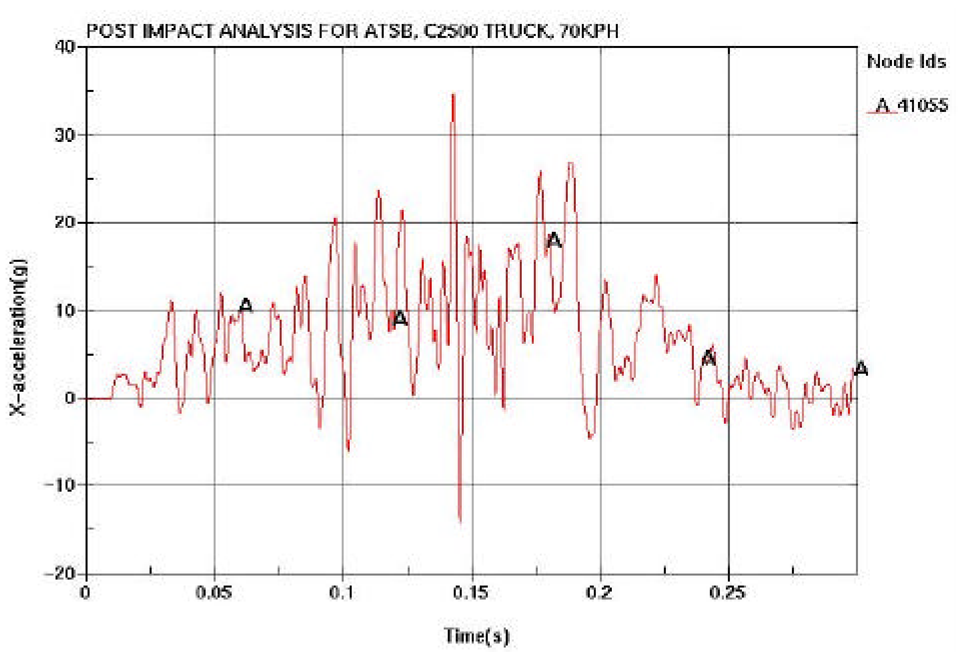

Figure 54 The acceleration history of the truck CG for the post with cable

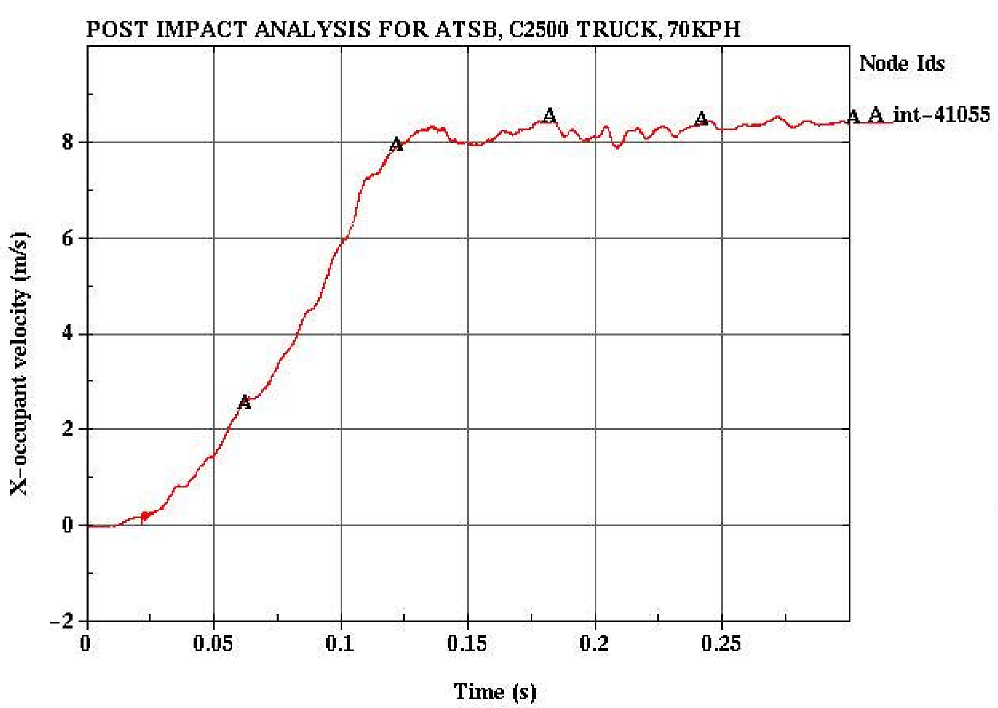

Figure 55 The velocity of the occupant relative to the truck for the post without cable

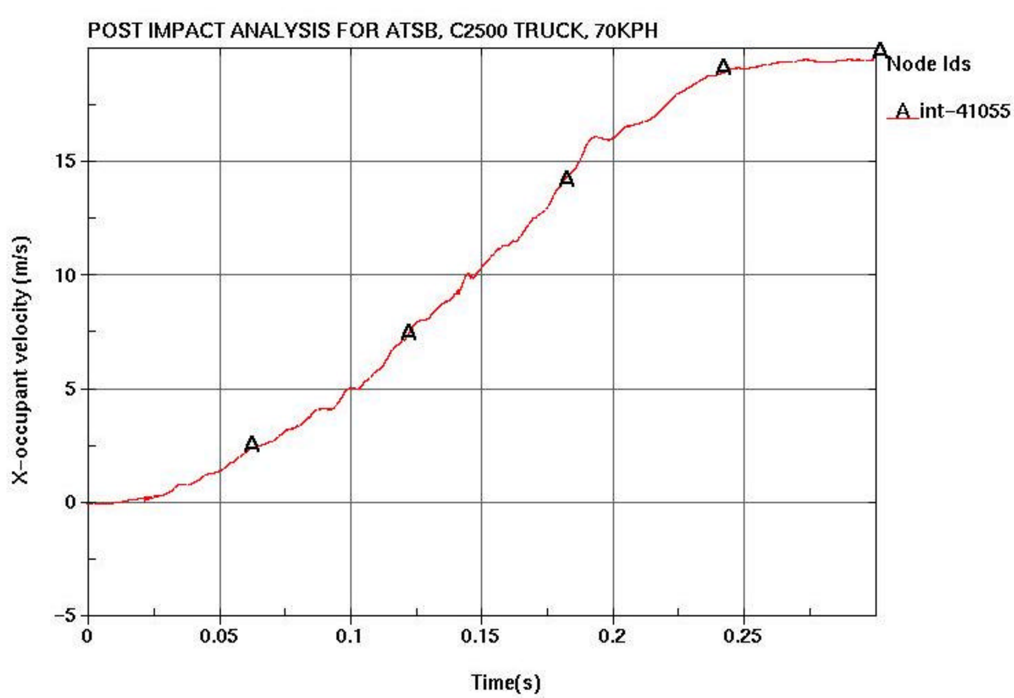

Figure 56 The velocity of the occupant relative to the car for the post with cable

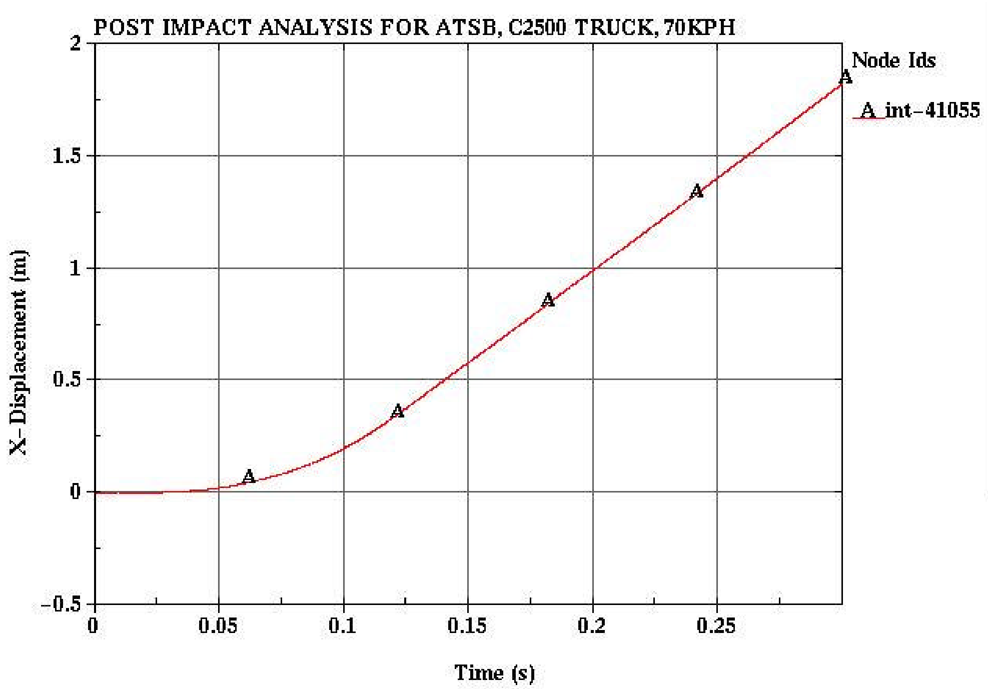

Figure 57 The displacement of the occupant relative to the car for the post without cable

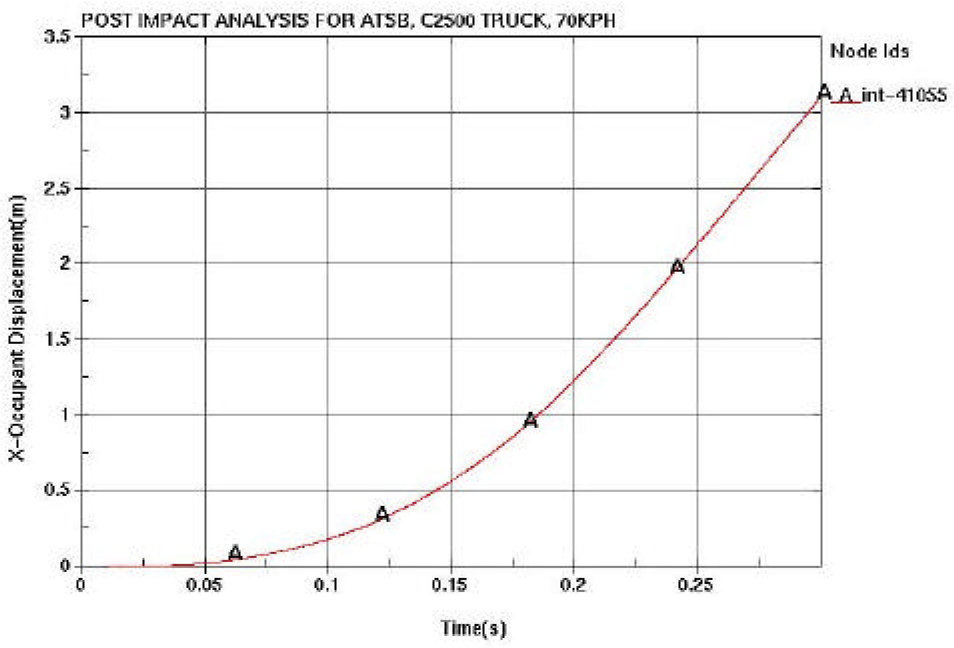

Figure 58 The displacement of the occupant relative to the car for the post with cable

Figure 59 The truck movement after the crash for the post without cable

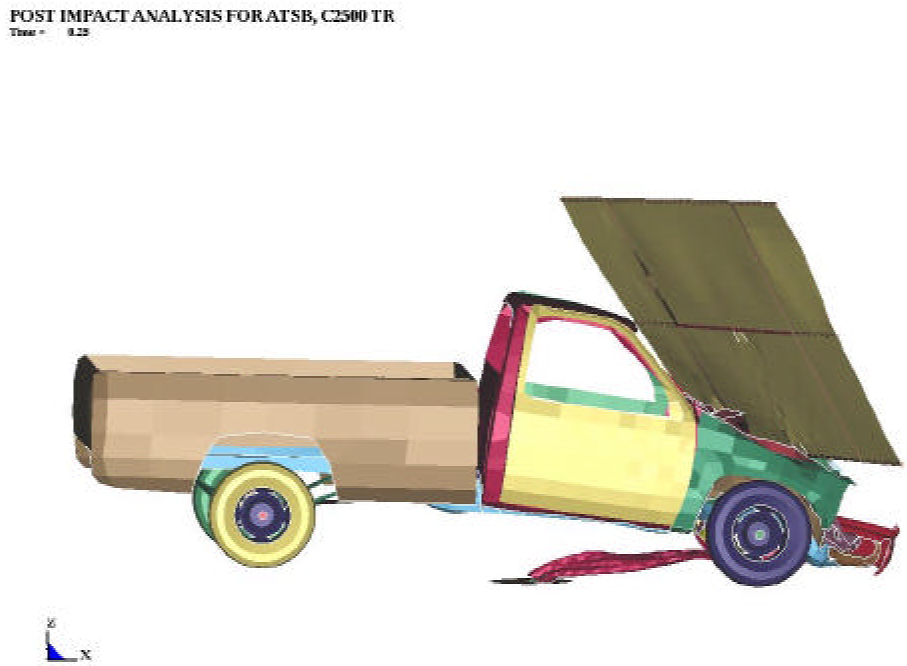

Figure 60 The deformed shape of the post and the truck for the post with cable

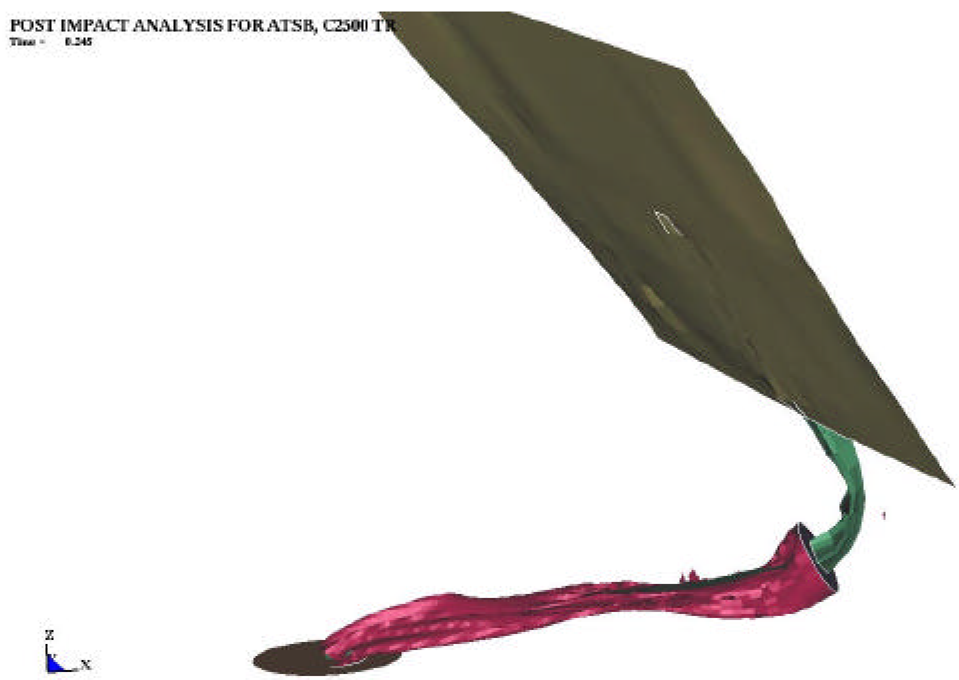

Figure 61 The deformed shape of the post with cable

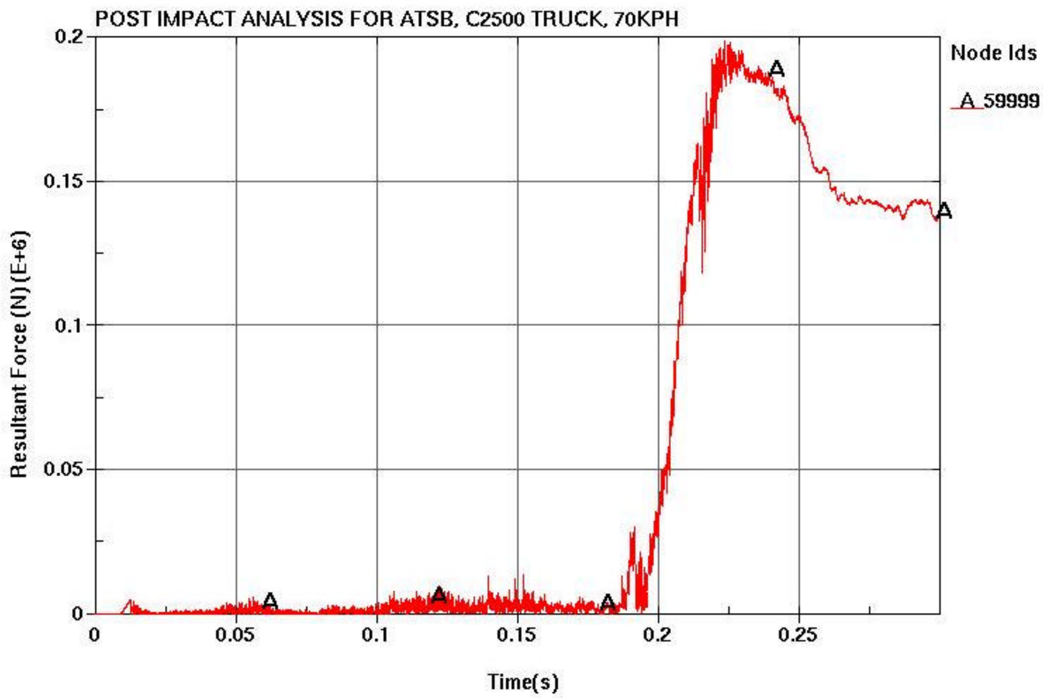

Figure 62 The force on the cable.

8. CONCLUSIONS

The objectives of the project have been achieved by the work of this report, which is to investigate the viability (strength, ability to support the signs, performance in the event of crash) of the thin walled collapsible sign post as a replacement to the existing rigid structure. A range of collapsible post designs has been analysed and evaluated to investigate the viability (strength, ability to support the signs, performance in the event of crash) of the thin walled collapsible sign post as a replacement to the existing rigid structure. The finite element analysis software was used to predict the behaviour of the alternative sign posts. Design optimization has been carried out to achieve better performance under both wind load and crash impact. The work done in this project also demonstrated that computer simulation could be a very useful tool for design and optimizing the roadside furniture such as signpost. It could save many expansive physical crash tests and speed up the product development process.

The computer simulation and analysis results indicated that the collapsible post could reduce the acceleration of an impacting car or vehicle significantly when the design parameters are optimized. The below is a summary of the findings:

1) There are two main design requirements for the collapsible post. One is withstanding the wind load and the self-weight. The other is to collapse easily during a crash impact so it is safer for the car occupants. These two requirements are contradictory to each other. A compromise has to be made to satisfy both requirements.

2) In the first stage of the analysis double cylinder post was investigated. The minimum thickness and the strength of the lower part of the post has be the sufficient to withstand the wind load. In the double cylinder post design, the high stress occurs on the outer cylinder shell, the inner cylinder does relieve much of the bending load from the outer cylinder. While in the crash impact, the inner post adds significant stiffness and mass to the post. The acceleration of the car is relatively higher. The double cylinder post configuration is not the most efficient use of material, The manufacturing cost is also relatively higher. It does not offer any advantage over a single cylinder design. The single cylinder post design was adopted in the second stage of the project.

3) For tall signpost (7.5 m to the centre of the sign face), the bending moment on the post due to the wind load is high, and a larger diameter post and (or) a thicker wall shell is required. The simulation result indicated that it is very difficult to achieve the impact acceleration below 20g with a small car impact on the post at 70KPH under the current design constraints (no base shear off, the wind load rating and steel material and cost considerations). However with a small car 19.0g acceleration was achieved for a shorter post (3.5 m to the centre of the sign board) with optimized design parameters.

4) It is possible that the collapsible post will be sheared off when a larger car or truck crashes into the post at 70 kph or higher. A steel cable can be placed inside the post to prevent the post being completely sheared off. The cable should not be pretensioned. A slack cable would have no effect when a small car impacts into the post, but would help to restrain the post when impacted by a larger vehicle.

5) Many post designs (tall, short, different diameters and wall thickness, cantilever mounted sign (see Figure 1), centrally mounted sign (see Figure 52), different steel materials) were analysed and a number of impacting vehicles were used in the impact simulations. The following are the general observations from the analysis:
    - Tall posts have to have thicker wall thickness and/or larger diameter cylinder for the collapsible post to withstanding the wind load and self-weight load. Such posts are stiffer and harder to deform in the event of the crash impact. Therefore the acceleration is higher.
    - Larger diameter of the post and thicker cylinder wall make the post stronger against the wind load but is more stiff and harder to deform in the event of a crash impact. Therefore the acceleration is higher.

- The wind load creates a twist moment on the post from the cantilever mounted sign face. The self-weight of the sign board also creates an bending moment on the post because its centre of gravity is off the centre of the post. Therefore a greater wall thickness and or larger diameter cylinder is required to withstand the wind load and self-weight load. It is stiffer and harder to deform in the event of a crash impact. Therefore the acceleration is higher.
- More ductile material can deform more without breaking and can absorb more energy during a crash impact and therefore is desired.
- The smaller the car, the smaller the mass is, the less kinetic energy it has at a certain travel velocity. The post deforms less in the event of crash. The car travels less distance to fully stop. The acceleration is higher.

6) A couple of oval shape posts were analyzed. One with long axis perpendicular to the road or car traveling direction. The other with the long axis parallel to the road or car traveling direction. The diameter dimensions of the post were the same for the two posts: Da=350 (long axis), Db=250 (short axis). The analysis results indicated that the oval posts do not have significant advantages over the simple circle cylinder post. The manufacturing cost was relative higher for the oval post, therefore it is not recommended.

7) For taller signposts, split base design and other innovative post designs may be more appropriate. The split base post allows the post base to break off in the event of crash impact. The car or vehicle can still travel forward after the impact. The impact acceleration of the car can be relatively smaller and the passenger's risk is reduced. Material other than steel (e.g. AL, plastics, and foams) is also worth considering. These materials can be more ductile, the post can deform more during the crash impact. More energy can be absorbed. Further investigation is recommended.

9. REFERENCES

1. National Cooperative Highway Research Program Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features. National Academy Press, Washington DC 1993.

10. Appendix

10.1 Appendix A, File Backup Details

Database File Name	Description	Date of Backup	Revision Details
P400-200low-static.db	ANSYS db for stage 1 static analysis	25/11/00	20/11/00
P400-200low-dyna.db	ANSYS db for stage 1 crash analysis	25/11/00	20/11/00
Folder\lowpost	Stage1 crash result without cable	25/11/00	20/11/00
P300-static.db	ANSYS db for stage 2 static analysis	25/11/00	20/11/00
P300-dyna5.db	ANSYS db for stage 2 crash analysis	25/11/00	20/11/00
P300-stat-linear.rst P300-hu250-t22	Stage 2 static result Stage2 crash result without cable	25/11/00 25/11/00	20/11/00 20/11/00
P300-hu250-t22-cable1	Stage2 crash result with cable	25/11/00	20/11/00
		25/11/00	20/11/00

10.2 Appendix B, Material Property Specifications

The following steel specifications were obtained from BHP CPD Port Kembla Technical Services:

1) Hot-Rolled Carbon H1010.
2) Hot-Rolled Carbon HU250
3) Hot-Rolled Carbon HU300
4) Hot-Rolled Carbon HA350

10.3 Appendix C, Material Property Test

The following test data was provided by BHP CPD Port Kembla Technical Services.

1) Test data for Grade HA200
2) Test data for Grade 250
3) Test data for Grade HA350

10.4 Appendix D, Design Drawings

1) Drawing SK 491
2) Drawing SK 494
3) Drawing SK 495
4) Drawing SK 500