DEPARTMENT OF TRANSPORT & REGIONAL DEVELOPMENT

FEDERAL OFFICE OF ROAD SAFETY

DOCUMENT RETRIEVAL INFORMATION

Report No.	Date	Pages	ISBN	ISSN

Title & Subtitle OPTIMISATION OF THE OMNIBUS ROLL CAGE STRUCTURE

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Abstract Improvement of vehicle stability and crashworthiness to reduce rollover and to provide increased occupant protection in the event of rollover requires that the effects of design parameters on vehicle rollover propensity are thoroughly understood. Improvement of rollover characteristics of buses currently requires extensive experimentation and considerable resources associated with rollover destruction of experimental bus structures. This research project presents an alternative approach to enhancing rollover design of buses based on experimental and analytical modal analysis. Inherent structural dynamic characteristics of the bus roll cage structure have been identified and tailored through global and local design sensitivity studies with respect to the overall rollover stability of the bus and its rollover strength.

Keywords bus rollover design modal analysis stability strength

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FINAL REPORT

Optimisation of the Omnibus Roll Cage Structure

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December 1996

ACKNOWLEDGMENTS

The work presented in this report is sponsored by the Australian Federal Office of Road Safety (FORS) through the Road Safety Research Grant 1995/1996. The discussion and concluding remarks represent the opinions of the authors and not necessarily those of the FORS. The authors are also thankful to:

Professor Len Koss from Monash University in Melbourne for kindly lending the large PCB hammer which was used for modal testing,

William Barrett & Sons, Ballarat for providing professional advise and support beyond the expected level during the manufacturing of the full size bus frame,

Mr Shane Preston and Mr David Ip for dedicated research assistance on the project.

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PROJECT TITLE

Optimisation of the Omnibus Roll Cage Structure

SUMMARY

Improvement of vehicle stability and crashworthiness to reduce rollover and to provide increased occupant protection in the event of rollover requires that the effects of design parameters on vehicle rollover propensity are thoroughly understood. Improvement of rollover characteristics of buses currently requires extensive experimentation and considerable resources associated with rollover destruction of experimental bus structures There is an unmet need for a more efficient developmental process which would incorporate computer modelling and simulation. This project presents an alternative research approach based on experimental and analytical modal analysis of the bus roll cage structure. Modal analysis is used to identify the dynamic characteristics of the structure and to tailor those characteristics in order to increase the overall rollover stability of the bus and its rollover strength while minimising the deformation of the internal residual space Full scale tests have been carried out on a standard roll cage structure which has been designed and manufactured to suit typical two axle single deck bus constructions used for route, school or charter bus services.

1. INTRODUCTION

Vehicle rollover accidents represent one of the most dangerous types of crashes with respect to fatalities or incapacitating injuries per occupant involved. Rollovers are second only to frontal crashes in their level of injury severity. In addition, the risk of single vehicle accidents and of passengers being ejected from a vehicle is much higher in case of rollover than in other types of crashes. As a result, regulations regarding the performance of vehicles in rollover accidents are being considered by many countries with realistic prospects for international regulatory harmonisation in the near future

Rollover may occur in multiple or single vehicle accidents. Various accident data studies indicate that the majority of rollovers have occurred in single vehicle accidents. Two basic types of rollover phenomena, tripped and untripped, frequently occur in single vehicle accidents. A tripped vehicle rollover can result if the vehicle strikes a rigid kerb or other obstacle at the vehicle's tires or wheels which induces a rotational motion to the vehicle resulting in rollover. In the case of an untripped rollover, the vehicle is exposed to gradual rollover due to a variety of possible factors such as inappropriate manoeuvring, and vehicle encountering a downslope or embankment [1], [3].

Research has shown that vehicle rollover is due to a complex interaction of a wide range of factors, such as vehicle geometry, inertial and suspension characteristics, position and magnitude of lateral impact forces, resultant lateral acceleration and combined effect of lateral acceleration and braking [1], [2], [3], [4], [8]. Geometric parameters of the vehicle are by far the most influential characteristics in a rollover situation. Parameters associated with the mass properties of the vehicle are relatively important, though not nearly as important as parameters associated with the geometry of the vehicle Although some investigation of the effects of vehicle stiffness and damping parameters in a tripped rollover situation has shown small influence on vehicle rollover propensity, it is of general concern what effect these factors would have in other rollover situations.

Knowledge of how different characteristics describing vehicle's dynamic system and subsystems effect its behaviour during accidents is an essential aspect of understanding the rollover problem. Traditionally vehicle manufacturers and government authorities have been concerned mainly with the vehicle rollover strength assuming that a stronger structure would provide better protection of passengers in the event of rollover. Alternative approaches towards rollover prevention have also been undertaken by researchers where vehicle rollover stability has been expressed in terms of the static rollover threshold. Static rollover characteristics have been described using the following static metrics: Static Stability Factor (SSF), Side Pull Ratio (SPR) and Tilt Table Ratio (TTR) [5], [6]. Although some research shows a strong correlation between these static rollover metrics and vehicle rollover stability, there is a need to investigate in more depth the intrinsic relationships between the vehicle design parameters and its potential dynamic behaviour with respect to rollover prevention.

This report presents results of a research project which aims at identifying the dynamic characteristics of a bus roll cage structure and at relating those characteristics to the vehicle design and rollover propensity. A more efficient alternative approach to rollover design analysis has been proposed based on experimental and analytical modal analysis. Computer model of the bus roll cage structure has been developed through test analysis integration and correlation. This model can be used for computer based simulation of the rollover test and for design optimisation of the roll cage structure with respect to the rollover stability and rollover strength of the entire bus. Some structural modification strategies have been identified in this research through global and local sensitivity studies using the developed computer model

2. VEHICLE ROLLOVER DESIGN

A regulation which addresses bus rollover design has been developed in Australia and a similar regulation is being considered in Europe. The Australian Design Rule (ADR59) defines explicitly the rollover criteria that must be met by all buses in a specific class It requires that manufacturers demonstrate that buses have sufficient strength to withstand a specified sideways rollover, without deforming to the extent that a specified residual space is intruded upon by any part of the bus structure or fittings. The Design Rule offers four possible ways in which compliance may be demonstrated:

- test by rolling a complete bus;
- test by rolling a section or sections;
- test by imposing a pendulum load to a section or sections;
- verification by an approved calculation method.

This is currently used by manufacturers as a benchmark when modifying and improving existing designs, and when developing completely new designs of buses The fact that all buses currently in public use in Australia comply with this Design Rule and that the majority of those buses have distinctively different design characteristics indicates that there is a need to establish general design guidelines and indicators with respect to the desired rollover propensity. In addition, there is an even greater need to adopt a rollover prevention approach in design of buses by establishing standard design procedures for improved vehicle stability leading to a reduction of rollover accidents.

The research described here aims at achieving this goal by integrating modal analysis in the design and development stage of the bus. The focus is on the bus frame which incorporates a rollover protection cage (for roll cage components nomenclature refer to **Fig. 1**) [9], [10]. The bus frame used in this research has been manufactured according to the ADR59 to meet the Federal Office of Road Safety guidelines. This is of particular importance in terms of the versatility of the obtained results because the standard roll cage structure has been designed to suit typical two axle single deck bus constructions used for route, school or charter bus services. Typical examples of such constructions include Isuzu LT1-11P, Hino RG 197, Scania 193 and Mercedes 1418.

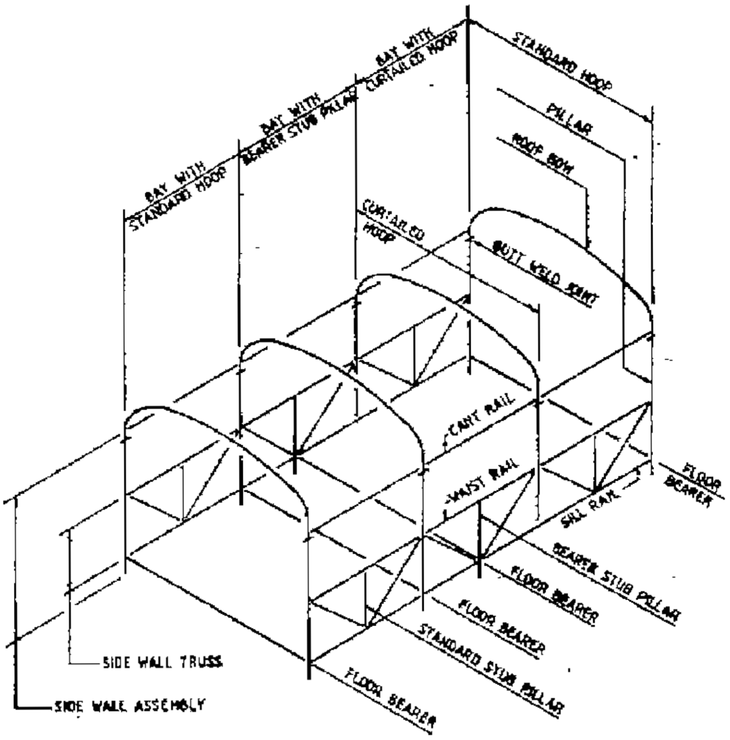


Figure 1. Roll cage components nomenclature (ADR59)

The roll cage impact absorption capacity is directly related to the geometric configuration of the roll cage. The standard design method involves the determination of the code rollover design energy (Ec), and the selection of the required number of hoops and their disposition in the roll cage structure to meet this energy requirement. The total energy absorption capacity of the number and type of hoops selected must be greater than the calculated code rollover design energy. The number of hoops required for any specific vehicle depends upon the vehicle tare mass, location of centre of mass, floor hight, overall length of passenger compartment and overall vehicle length, inclusion and location of air conditioning unit. The individual hoop energy absorption capacity depends upon the hoop profile, hoop construction and overall cage design. Hoop energy is influenced by the collapse mechanism of the total roll cage structure as well as the local collapse mechanism of its individual components. Typical vehicle rollover and corresponding parameters are shown in **Fig. 2**.

Bus frames incorporating the standard rollover protection cage have been found satisfactory in Australia and the United Kingdom with respect to rollover strength. But, this approach to rollover design has not reduced the number of rollover accidents which are directly related to the rollover stability of the bus. In order to improve vehicle stability in case of both tripped and untripped rollover while retaining a satisfactory level of rollover strength a concurrent approach to rollover design based on modal analysis and rollover simulation has been proposed in this research. The main role of modal analysis is to determine the structural dynamic characteristics of the standard bus frame with its rollover protection cage and to identify appropriate structural modification strategies by relating those dynamic characteristics to the design parameters with respect to the desired vehicle stability. The bus frame with the rollover protection cage can be tailored in such a way to produce inherent mode shapes which resist rollover and to absorb lateral impact forces in case of collision thus reducing the amount of energy and the resultant angular momentum which can lead to bus rollover.

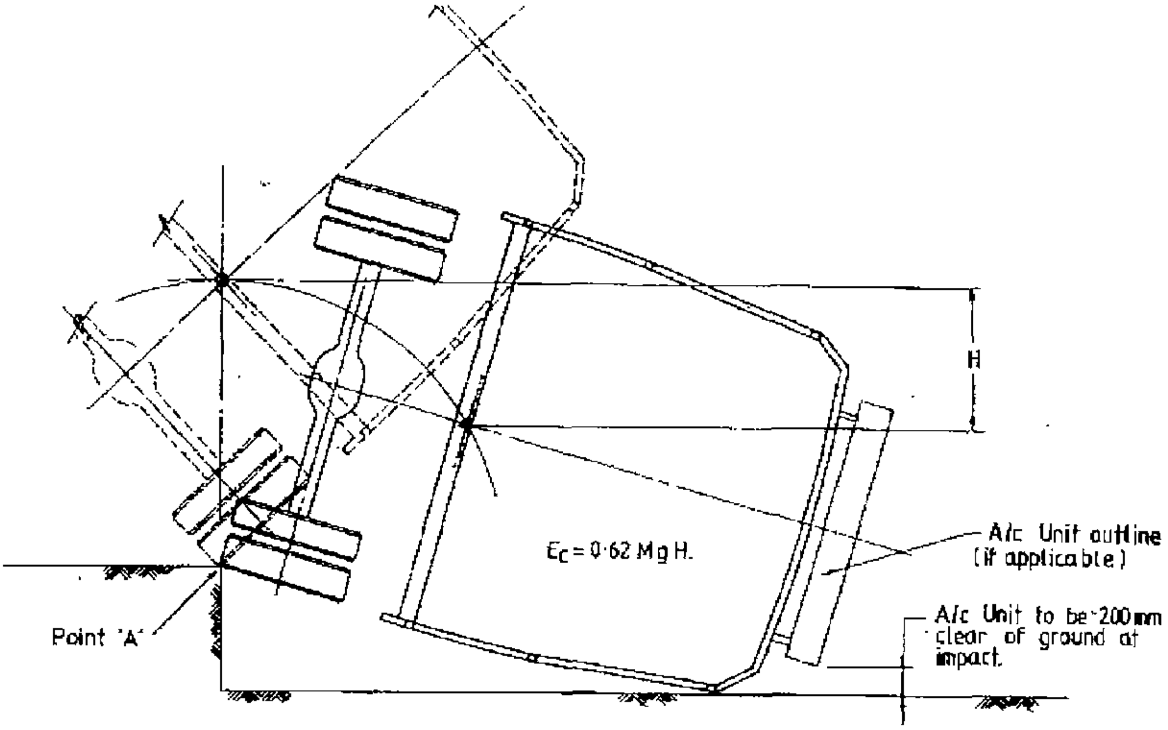


Figure 2. Bus rollover (ADR59)

3. MODAL ANALYSIS OF BUS FRAME

Computer modelling of the bus frame was carried out using the FEM and computer program Pro/MECHANICA. The FE model shown in **Fig. 3** consists of 260 elements (3D beams) A grounded condition of support has been simulated by constraining the model at each floor stool in 3 rotational and 3 translational directions as shown in the diagram. These constraints describe well the welded connections between the frame and the chassis in the actual bus with respect to the relative motion of the consisting parts and the structural dynamic behaviour of the frame. Material properties have been assigned to all elements according to ADR59. **Fig. 4** shows some characteristic mode shapes of the bus frame obtained through computer analysis.

Additionally to computer modelling of the bus frame, modal testing was carried out on the full scale structure. The main objectives of this experimental investigation are: (1) to derive the dynamic properties of the real structure and to correlate the results with the computer modelling outcome (this will serve for the validation of the computer model); (2) to derive the damping properties of the structure which are not included in the computer model (the information will then be incorporated into the computer model when dynamic response of the structure is simulated); (3) to provide vibration data for preliminary study on optimal structural modification which will lead to better structural stability when experiencing an impact loading in the lateral direction.

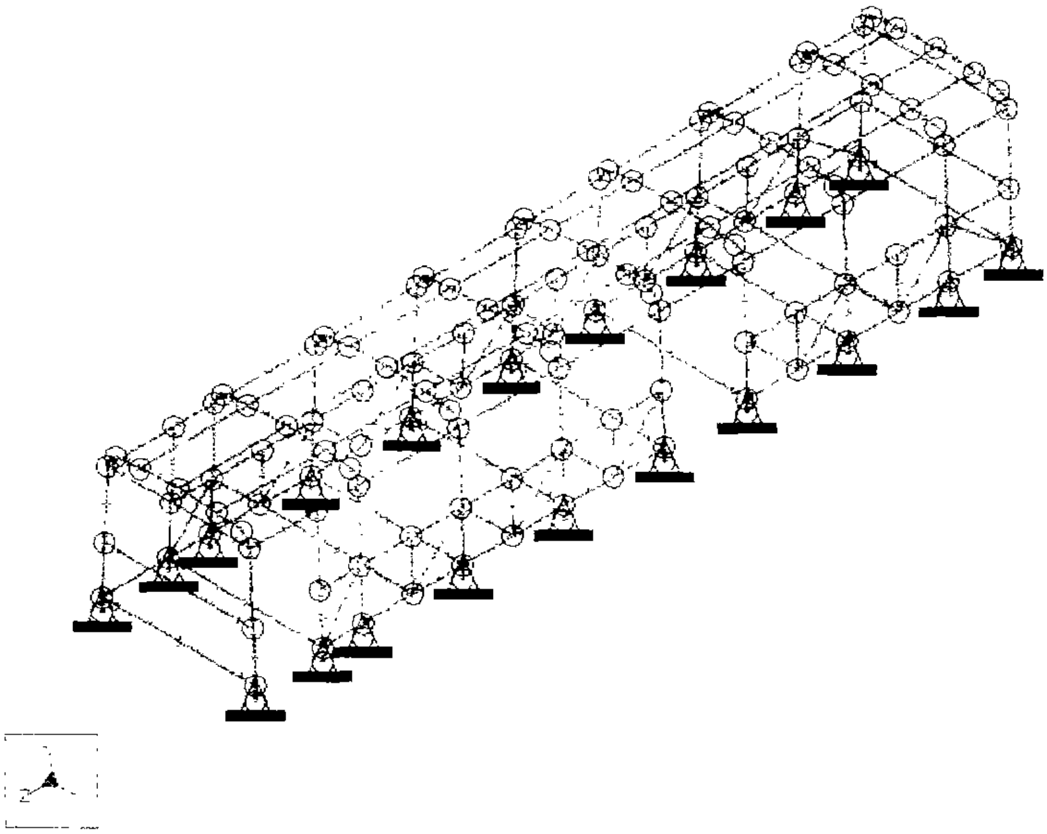


Figure 3. Finite element model of the bus frame

The roll cage structure of the bus is welded to the remaining parts of the bus. Due to the relative rigidity of bus chassis and flexibility of the cage structure, it is believed that the boundary conditions for the cage structure should lie between a free-free and a grounded condition. For the low frequency vibration, this reality should resemble a nearly grounded condition. The structure was therefore cemented on a concrete floor at each floor stool. This resembles the operational condition of the structure and it is consistent with the condition used in computer modelling

A number of coordinates were chosen for vibration measurement. These coordinates represent a discretised system of the cage structure and they should exhibit the characteristics of the structure, especially the vibration mode shapes. The structure weighs 846 kg. It has 8 front-rear beams, 9 left-right inverse U shape frames. There are totally 131 points selected for modal testing purpose. They constitute all the crossing points between the floor line and side bracings, and between hoops and side bracings. For these points, the main interest is the vibration in Y direction. In addition, the crossing points of the roof and the roof beams with hoops and door openings were also selected. For points on the roof, vibration in Z direction were of main concern.

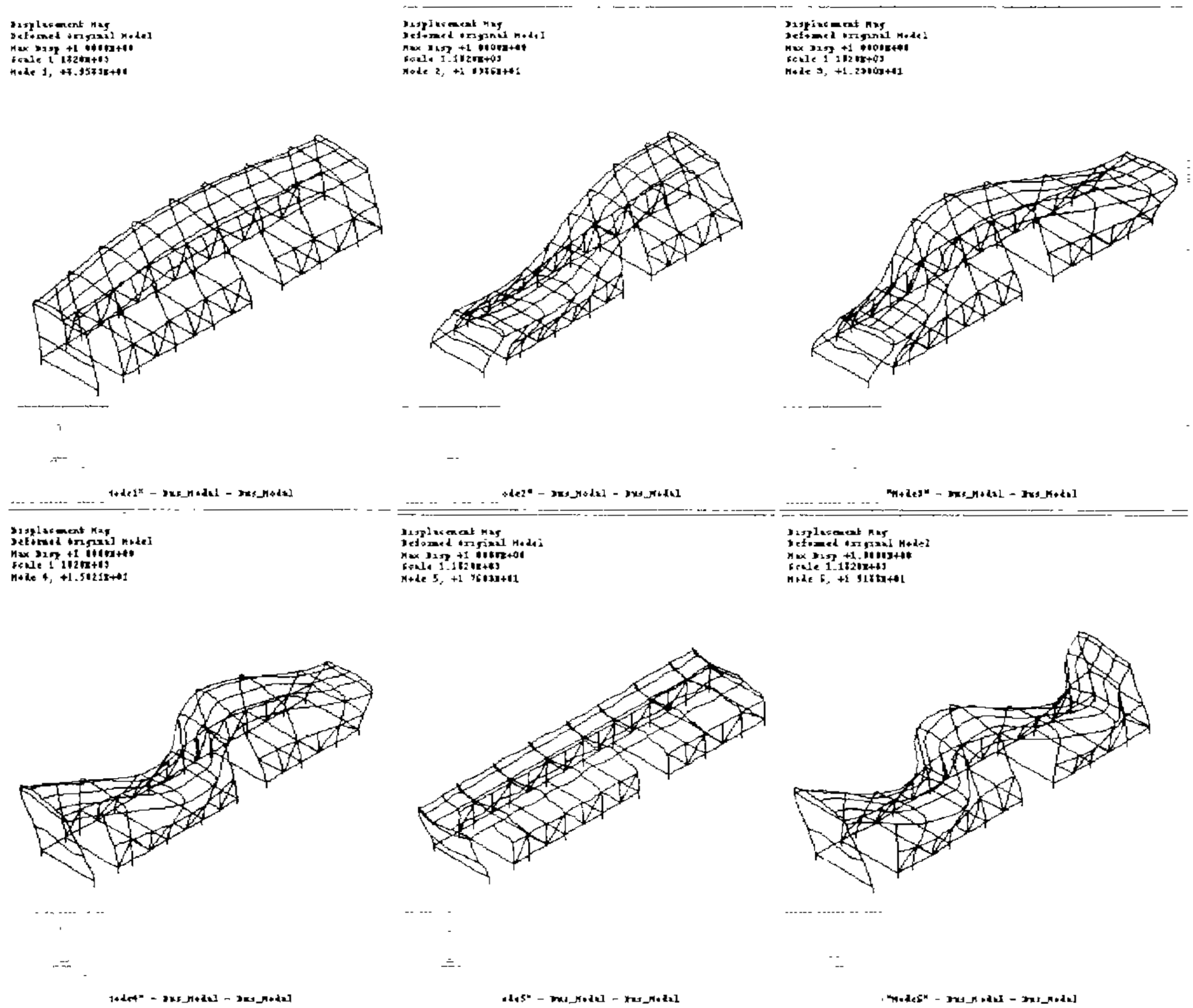


Figure 4. Mode shapes of the bus frame finite element model

The structure was excited by a PCB impact hammer model 086B50 This hammer provides sufficient excitation force for the cage structure. A Bruel and Kjaer 2032 dual channel analyser was used to acquire frequency response function data from the measurement. The response point was selected at 76Y. This was determined after a trial-and-error attempt. Impact force was then applied in Y direction to points on sides and Z direction for points on the roof. **Fig. 5** shows the point FRF of this test. Within 40 Hz, there are well defined modes of the bus frame.

The frequency range of the measurement was baseband 100 Hz. This included main modal activities computer modelling has dealt with. Each record of FRF average took 8 seconds. The exponential window applied to the response was sufficiently long so that little extra damping was added to the signal For each point, three averages were taken before the FRF was recorded. Coherence function was monitored during the test.

The measured FRF data was later processed using ICATS modal analysis software MODENT and MODESH. SDoF analysis was performed first to ascertain the number of modes in the frequency range for analysis. MDoF method was then used to process all 154 FRFs. **Fig. 6** shows a typical regenerated FRF after the analysis has been carried out. **Table 1** shows the natural frequencies and damping loss factors of the first ten modes analysed. **Fig. 7** shows some characteristic mode shapes obtained through experimental modal analysis. All mode shapes have been saved as real modes.

Mode No.	Natural Frequency Hz	Damping Loss Factor	Mode Type
1	7.664	113	first bending
2	9.096	055	second bending
3	10.915	.032	third bending
4	13 338	.028	Roof
5	17.180	.014	Roof & bending
6	21.210	.027	roof mode
7	27.604	.028	roof & bending
8	33.223	.018	roof mode
9	33.812	.012	roof & bending
10	39 554	.014	roof&bend at front

Table 1
Natural frequencies and damping loss factors

The structure exhibits relatively low damping. This needs to be taken into consideration when dealing with the energy absorption estimation of the structure during rollover or in case of side impact. Although the damping loss factor for the first bending mode is considerable, this is partly due to numerical analysis. To ascertain the damping factors, a few FRFs were analysed using SDoF Line-fit method. For the point measurement FRF (76Y76Y), the damping loss factors are shown in **Table 2**.

Mode No.	Natural Frequency Hz	Damping Loss Factor	Method
1	8.14	.043	L-fit
2	9.35	.030	L-fit
3	11.03	017	L-fit
4	13.44	.043	L-fit
5	17.16	.017	L-fit
6	21.18	.014	L-fit
7	26.33	.010	L-fit
8	27.71	.022	L-fit
9	33 13	.026	L-fit
10	33.78	.017	L-fit
11	39.56	011	L-fit

Table 2
Natural frequencies and damping loss factors

The data indicates that damping for bending modes is generally less than 5% while damping for roof modes is less than half of that value. This should have significant effect on the difference in deformation of these components during rollover.

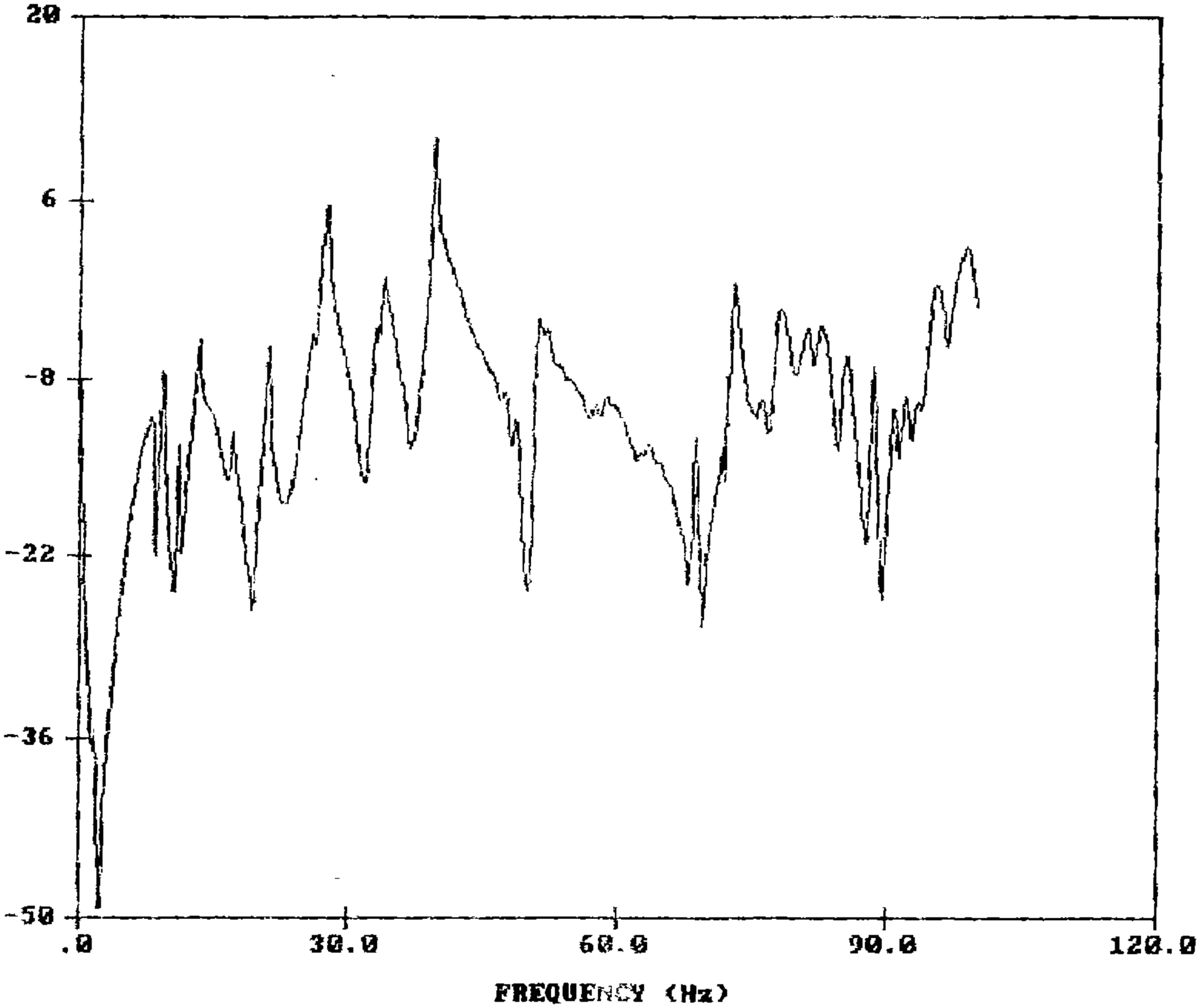


Figure 5. Point FRF

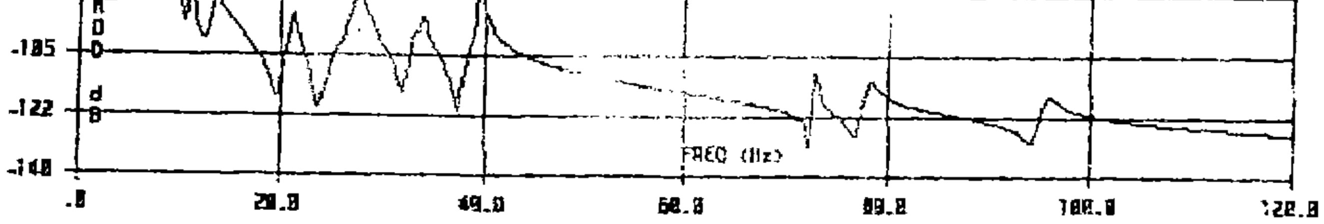
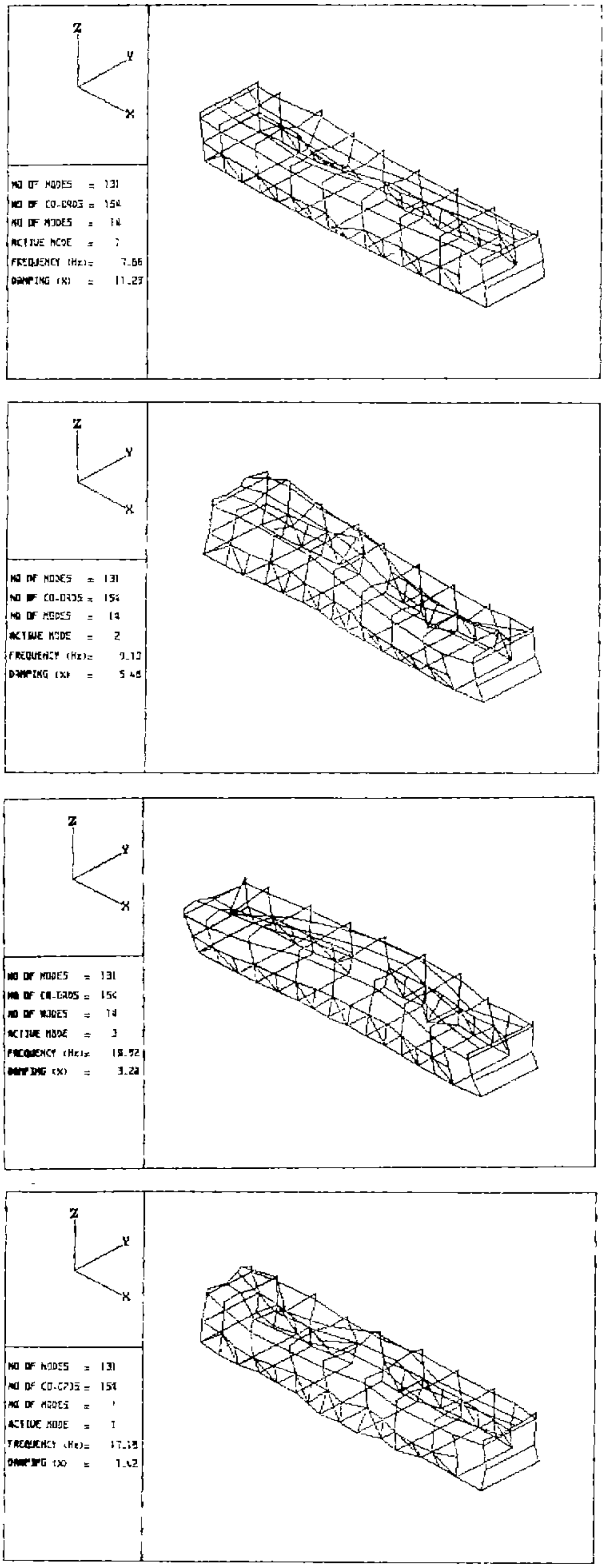


Figure 6. A typical regenerated FRF



```
NO OF NODES    =  131
NO OF CO-ORDS  =  154
NO OF MODES    =   14
ACTIVE MODE    =    1
FREQUENCY (Hz) =     7.66
DAMPING (X)    =    11.23
```

```
NO OF NODES    =  131
NO OF CO-ORDS  =  154
NO OF MODES    =   14
ACTIVE MODE    =    2
FREQUENCY (Hz) =     9.13
DAMPING (X)    =     5.48
```

```
NO OF NODES    =  131
NO OF CO-ORDS  =  154
NO OF MODES    =   14
ACTIVE MODE    =    3
FREQUENCY (Hz) =    15.52
DAMPING (X)    =     3.28
```

```
NO OF NODES    =  131
NO OF CO-ORDS  =  154
NO OF MODES    =  [illegible]
ACTIVE MODE    =    1
FREQUENCY (Hz) =    17.35
DAMPING (X)    =     1.42
```

Figure 7. Characteristic mode shapes obtained through experimental modal analysis

4. SENSITIVITY DESIGN STUDIES

Through analytical and experimental modal analysis a general computer model of the bus frame has been developed. This refined model made possible a series of sensitivity design studies to be carried out in order to identify strategies for viable modification of the frame structure and improvement of the rollover design of the bus. Types of design studies included in software Pro/MECHANICA and their descriptions are given in **Table. 3** below.

Design Study Type	Description	Results
Standard	Calculates results for one or more *analysis* for different parameter settings for each analysis.	1. Quantities valid for each analysis in the study 2. Measure values
Global Sensitivity	Calculates the changes in the model's *measures* for a variable *parameter* over a specified range.	1. Graphs of a measure vs a parameter 2. Shape history animation
Local Sensitivity	Calculates the *sensitivity* of the model's *measures* to slight changes in one or more *parameters.*	1. Graphs of measure vs a parameter 2. Measure sensitivity
Optimisation	Adjusts one or more *parameters* to best achieve a specified *goal* or to test feasibility of a design, while respecting specified *limits*.	1. Graphs of measure vs the study's iterations 2. Shape history animation 3. Optimised model results

Table 3
Overview of Pro/MECHANICA design studies

The focus of sensitivity design studies in this research has been on the identification of the effects:

- the higher values of structural damping would have on impact energy absorption, distribution of load, stress and strain, and general structural dynamic behaviour of the bus frame;
- the structural modification of the bus roof would have on the mode shapes and integrity of the roof design;
- the structural modification of the sides of the bus frame would have on bending modes in the lateral direction and corresponding rollover stability of the bus.

This investigation has also established the intrinsic relationships between the effects highlighted above, and the important design parameters of the bus such as the overall mass of the bus frame and the corresponding position of the center of gravity. Two characteristic design modifications of the bus frame and the results of modal analysis for each case are given in **Appendices A** and **B** at the end of this report.

These studies show that the structural dynamic characteristics of the bus frame, and modes of oscillation of the frame in particular, can be effectively modified by introducing some strategic design changes that can also lead to lowering the position of the center of gravity of the bus and to reducing the overall mass of the bus. The reduction of mass has been achieved by substituting the two longitudinal bars with diagonal bars on the roof, and by changing the cross section of the diagonal bars on the sides of the bus from 50x25x2 RHS to 20x20x1.6 SHS. These modifications would definitely lead to higher rollover stability of the bus. Also, in case of rollover the effects of rollover impact would be reduced through the reduction of inertia and angular momentum during rollover. Modified design of the bus roof displays higher structural integrity providing a more significant contribution to the overall strength and stability of the bus.

5. CONCLUDING REMARKS

The report has presented final results of a research project which aimed at determining the structural dynamic characteristics of a standard bus frame and relating those characteristics to the intrinsic design parameters influencing rollover stability and strength of the entire bus. The ultimate outcome of this research is rollover prevention through better design.

Experimental and analytical (FEA) modal analysis has been carried on the bus frame incorporating the protective roll cage structure. Obtained results show excellent correlation (apart from mode 5 of the finite element model which has displayed elements of rigid body motion) As expected, well defined modes of oscillation of the bus frame with corresponding natural frequencies have been determined in the low frequency range of up to 40 Hz. The difference between the experimentally and analytically determined natural frequencies is lower than 10% for the first 10 modes. The obtained mode shapes also display similar forms of oscillation. Torsional modes have not occurred at lower frequencies and have been combined with bending at higher modes of oscillation This may relate to the way the response measurements have been carried out (only in the lateral direction).

The results reveal an inherent vulnerability of the standard bus roof design with respect to structural integrity. The structure overall exhibits relatively low damping which needs to be taken into consideration when dealing with the energy absorption estimation of the bus frame during rollover. Also, the determined bending modes in the lateral direction of the bus frame indicate an inherent sensitivity of the design to excitation in the lateral direction which has a negative effect on vehicle stability and rollover propensity in general (even more so in case of side impact).

These findings should be addressed by manufacturers through structural modification of the bus frame. Some strategies have been identified through initial sensitivity design studies. For example, the bus frame can be modified to enable the spreading of the impact deformation over a large distance thus increasing the amount of plastic deformation of the vehicle. The amount of unrecoverable work used to crush the vehicle will be increased, reducing the amount of energy which can contribute to the rolling motion of the vehicle

Also, the structure of the bus can be modified to reduce its vulnerability in the lateral direction and increase the level of damping. The roof configuration can be modified by substituting the longitudinal bars with diagonal bars across the entire length of the structure. The new bars should have a different cross section which can be optimised to satisfy a number of different requirements, such as the reduction of the mass of the frame while maintaining satisfactory strength of the structure.

The sensitivity design studies have identified these strategies as viable design approaches (see **Appendices A** and **B**) resulting in a lower mass of the bus frame and in reducing the height of the centre of gravity of the bus, thus producing a better rollover design. These aspects of design are essential in developing a preventive rollover design approach in industry

6. RECOMMENDATIONS

On the basis of the obtained results and the discussions presented in this report, a number of specific recommendations can be made. It is strongly advised that these recommendations be considered by bus manufacturers

TITLE	**RECOMMENDATION NUMBER**	**RECOMMENDATION**
Modal Analysis	1	Analytical and experimental modal analysis should be incorporated in the bus design
Rollover Design	2	Bus frames should be optimised with respect to rollover stability and strength using sensitivity design studies
Damping	3	Bus frame design should be modified to produce higher structural damping
Roof Design	4	Longitudinal bars across the roof structure should be substituted with diagonal bars giving higher structural integrity and improved modes
Frame Design	5	Additional diagonal bars should be introduced at the sides of the bus in the opposite direction of the existing in order to improve lateral stability and strenght
Bar Profiles	6	Profiles of diagonal bars should be optimised, initial changes are suggested in the Appendices
Frame Mass	7	Bus frame design should be optimised to reduce the overall mass of the bus
Centre of Gravity	8	Bus frame design should be optimised to reduce the hight of the centre of gravity
Materials	9	Deatiled investigation of alternative materials for structural elements and for the purpose of increasing damping and for distribution of plastic deformation more uniformlly across the structure

7. REFERENCES

[1] Nalecz, A. G.
Influence of Vehicle and Roadway Factors on the Dynamics of Tripped Rollover
Int. J. of Vehicle Design, Vol.10, No.3, pp 321-346, 1989.

[2] Wood, D. P.
A Model of Vehicle Rollover Due to Side Impact Collision
Proc. Instn. Mech. Engrs., Vol.204, pp 83-92, 1990.

[3] Nalecz, A. G., Bindemann, A. C. and **Brewer, H. K.**
Dynamic Analysis of Vehicle Rollover
Proc. 12th ESV Conference, Gothenburg, 1989.

[4] Jones, I. S.
*Vehicle Stability Related to Frequency of Overturning for Different Models of Cars*Proc. Austral. Road Res. Board, Vol.7, No.5, pp 159-172, 1974

[5] Chrstos, J. P. and **Guenther, D. A.**
The Measurement of Static Rollover Metrics
SAE Technical Paper Series, No. 920582, pp 691-702, 1992.

[6] Chrstos, J. P.
An Evaluation of Static Rollover Propensity Measures
Transport Institute of Ohio, DOT HS 807 747, 1991.

[7] Kumagai, K. et al
An Analysis Method for Rollover Strength of Bus Structures
Proc. 14th ESV Conference, Munich, 1994.

[8] National Highway Traffic Safety Administration
Technical Assessment Paper: Relationship Between Rollover and Vehicle Factors
NHTSA Report, Docket 91-68-NO1, 1991.

[9] Federal Office of Road Safety
Design Parameters Necessary for Compliance with ADR59/00 Omnibus Rollover Strength - Part A
National Code of Practice, Bulletin No.7, May 1992.

[10] Federal Office of Road Safety
Design Parameters Necessary for Compliance with ADR59/00 Omnibus Rollover Strength - Part B
National Code of Practice, Bulletin No.7, June 1992

[11] Zaveri, K.
Modal Analysis of Large Structures
Bruel&Kjaer, 1985.

[12] **Subic, A.** et al
Modal Analysis of Bus Roll Cage Structure for Optimum Rollover Design
Proc. of the International Modal Analysis Conference IMAC-XV, Orlando, 1997.

[13] **Parametric Technology Corporation**
Pro/MECHANICA Design Study Reference - Release 17.0
Parametric Technology Corporation, Waltham, MA, 1996.

[14] **Parametric Technology Corporation**
Pro/MECHANICA Strategies Guide - Release 17.0
Parametric Technology Corporation, Waltham, MA, 1996.

[15] **Jones, N.** and **Wierzbicki, T.**
Structural Crashworthiness
Butterworths, London, 1983.

APPENDICES

APPENDIX A :

Modal analysis of bus frame with modified roof design

Two longitudinal bars across the bus roof substituted with diagonal bars.

1. Center of gravity brought down by 2%;
2. Mass of the bus frame reduced by 1% .

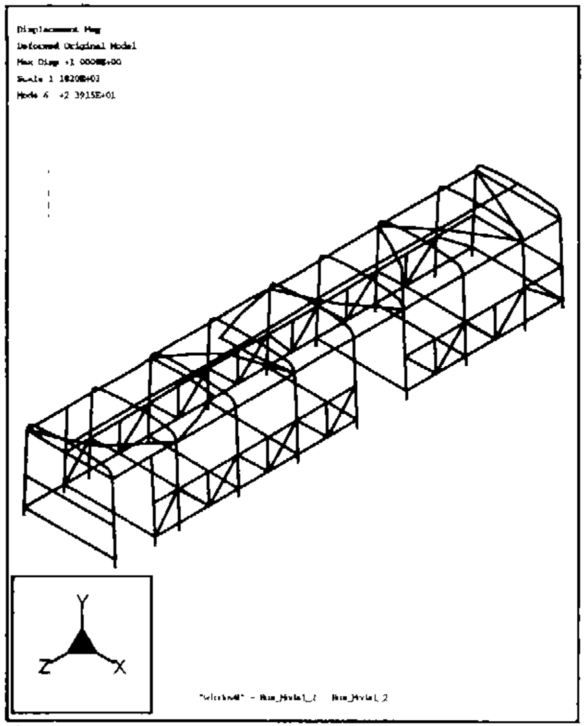
APPENDIX B :

Modal analysis of bus frame with modified roof and sides

Two longitudinal bars across the bus roof substituted with diagonal bars.
Diagonal bars added to the sides of the bus frame - cross sections of all diagonal bars changed from 50x25x2 RHS to 20x20x1.6 SHS.

1. Center of gravity brought down by 1 3%;
2. Mass of the bus frame reduced by 2% .

APPENDIX A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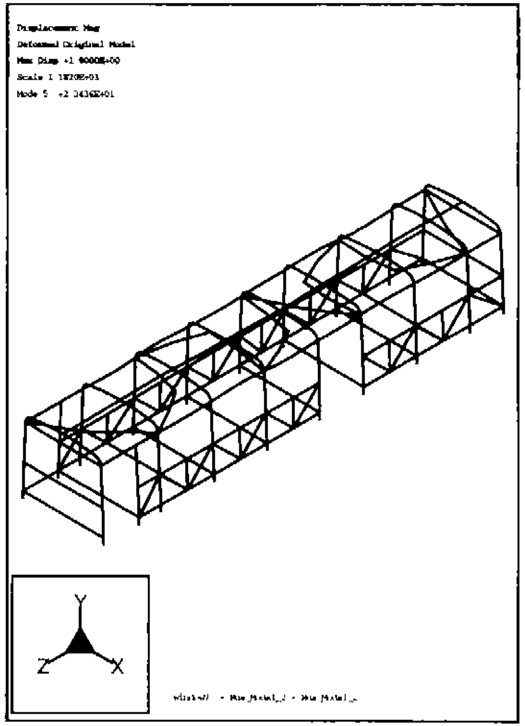
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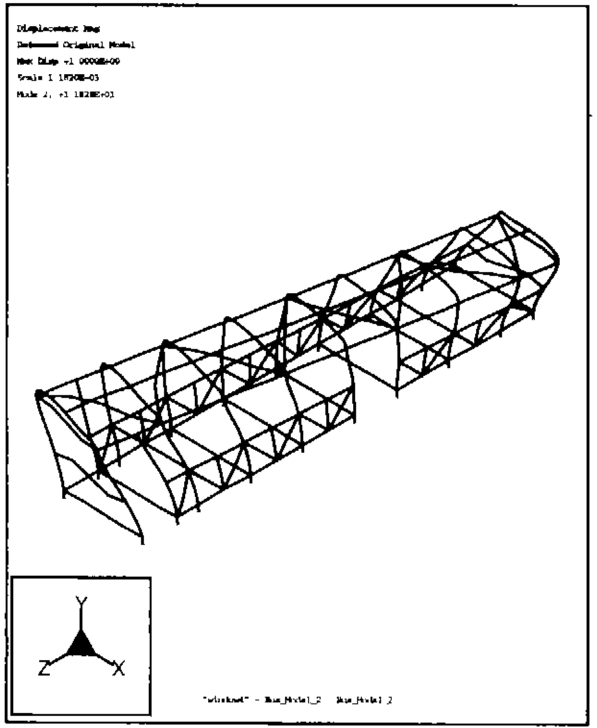
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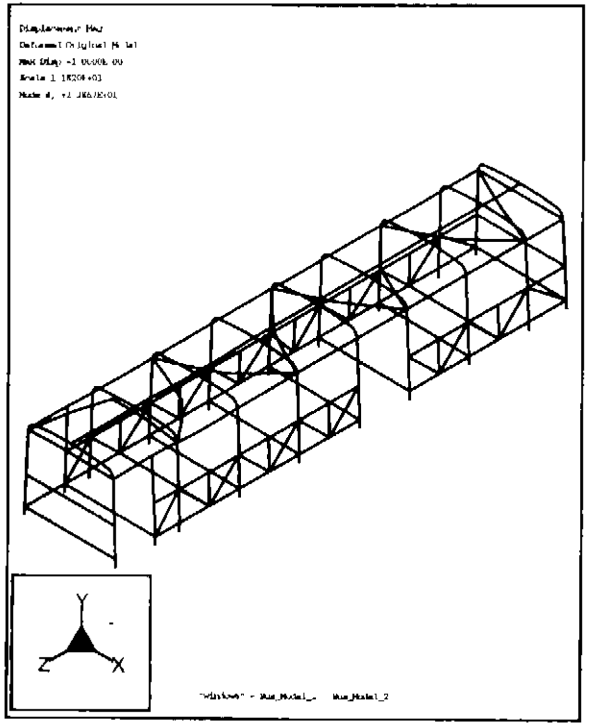
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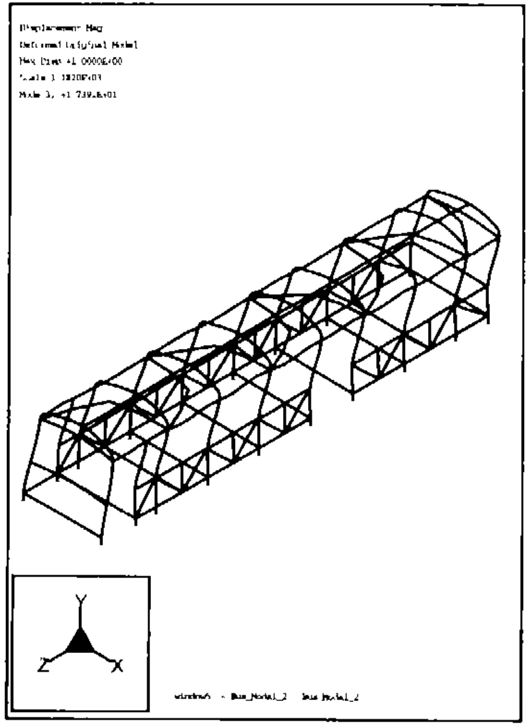
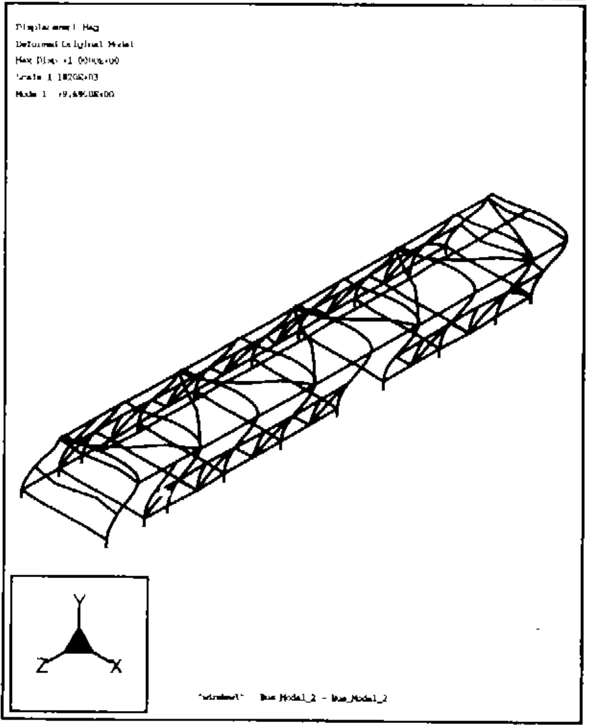
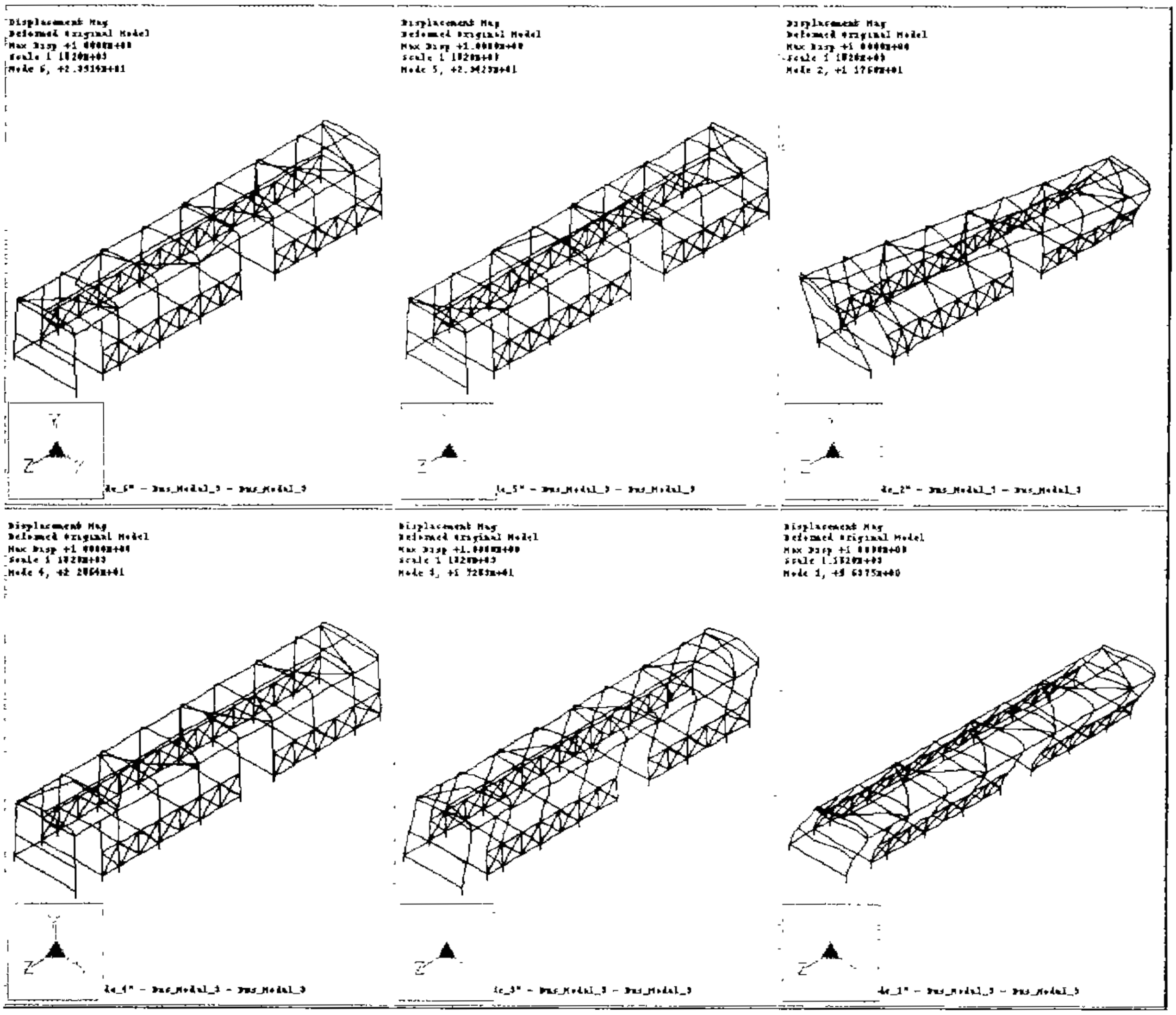
X
- Bus_Model_2 Bus_Model_2


Displacement Mag
Deformed Original Model
Max Disp +1 0000E+00
Scale 1 1820E+03
Mode 3, +1 7391E+01
Y
Z
X
window6 - Bus_Model_2 Bus_Model_2


Displacement Mag
Deformed Original Model
Max Disp +1 0000E+00
Scale 1 1820E+03
Mode 1 +9 6960E+00
Y
Z
X
"window1" Bus_Model_2 - Bus_Model_2

APPENDIX B


Displacement Mag
Deformed Original Model
Max Disp +1.0000E+00
Scale 1.1820E+03
Mode 6, +2.3519E+01
de_6" - Bus_Modal_3 - Bus_Modal_3
Displacement Mag
Deformed Original Model
Max Disp +1.0000E+00
Scale 1.1820E+03
Mode 5, +2.3423E+01
de_5" - Bus_Modal_3 - Bus_Modal_3
Displacement Mag
Deformed Original Model
Max Disp +1.0000E+00
Scale 1.1820E+03
Mode 2, +1.1760E+01
de_2" - Bus_Modal_3 - Bus_Modal_3
Displacement Mag
Deformed Original Model
Max Disp +1.0000E+00
Scale 1.1820E+03
Mode 4, +2.2064E+01
de_4" - Bus_Modal_3 - Bus_Modal_3
Displacement Mag
Deformed Original Model
Max Disp +1.0000E+00
Scale 1.1820E+03
Mode 3, +1.7283E+01
de_3" - Bus_Modal_3 - Bus_Modal_3
Displacement Mag
Deformed Original Model
Max Disp +1.0000E+00
Scale 1.1820E+03
Mode 1, +9.6375E+00
de_1" - Bus_Modal_3 - Bus_Modal_3
Y
Z
X