

TECHNICAL BULLETIN



Static and Dynamic Analysis of Metal Roof Systems

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Executive Summary

This report attempts to summarize the major achievements in the Finite Element Analysis project conducted at National Steel Corporation and Generalety, LLC, during the last three years.

Static and dynamic analyses of metal roof systems using Finite Element Method indicate that Finite Element Analysis is an appropriate tool for the product development of metal roof structures. The following conclusions are obtained from the study:

- An average of about 10% discrepancy was obtained between the test and the FEA data under the static loading conditions. In addition to the dimensional accuracy of the seams, the adhesive strength between the seams is another major factor that affects the computational accuracy.
- Similar trends between the electromagnetic uplift test and the FEA results were observed in the bracket reaction forces for a roof structure under temporally and spatially non-uniform dynamic loads.
- The ratio of static/dynamic panel deflections is calculated at 1.6 for a panel examined under the same maximum load.
- A standard procedure was established to model the metal roof structures under the static and the dynamic loads.

The following recommendations may be considered for future development and improvement:

- Further verifications of the FEA models using different panel designs against the electromagnetic uplift tests.
- Various roof panel designs assisted by Finite Element Analysis.
- Establishment and adoption of an industrial design standard of roof structures based on FEM study.
- Training classes to the MCA members on the outcome of the project.

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1. Introduction

1.1 ASTM E1592 Test

ASTM E1592 Test (Standard Test Method for Structural Performance of Sheet Metal Roof and Siding Systems by Uniform Static Air Pressure Difference), as shown in Figs. 1 and 2, has been used to determine the structural capacity of the metal roof systems under uplift loading. Due to its static nature, ASTM E1592 Test has been viewed more conservative than the reality. It presents a challenging task to determine the ratio between the static and dynamic tests.

1.2 Magnetic Uplift Load Test

Magnetic Uplift Load Test [1], as shown in Figs. 3 and 4, was developed by Mississippi State University to simulate the dynamic nature of wind load. It is one step closer to the reality. It is expected to generate a reasonable evaluation on roof structures and to determine the difference between the static and the dynamic tests.



Fig. 1 ASTM E1592 Static Load Roof Test Setup



Fig. 2 Deformed Roof Panels during ASTM E1592 Test



Fig. 3 Magnetic Uplift Load Test

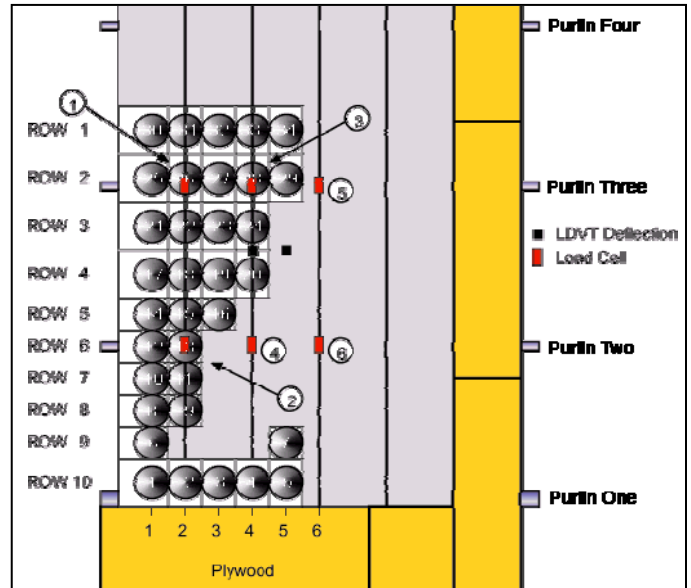


Fig. 4 Distribution of Magnets

1.3 Finite Element Method vs. Conventional Test Method

Finite Element Analysis (FEA) based Computer Aided Engineering (CAE) has been widely used in the product design and development of structural components, such as vehicle bodies, airplanes, etc. As shown in Fig. 5, CAE approach can help shorten new product development time and reduce the development cost, since everything is performed on the computer without physical test. It has been desired since a decade ago to introduce FEA into metal roof industry.

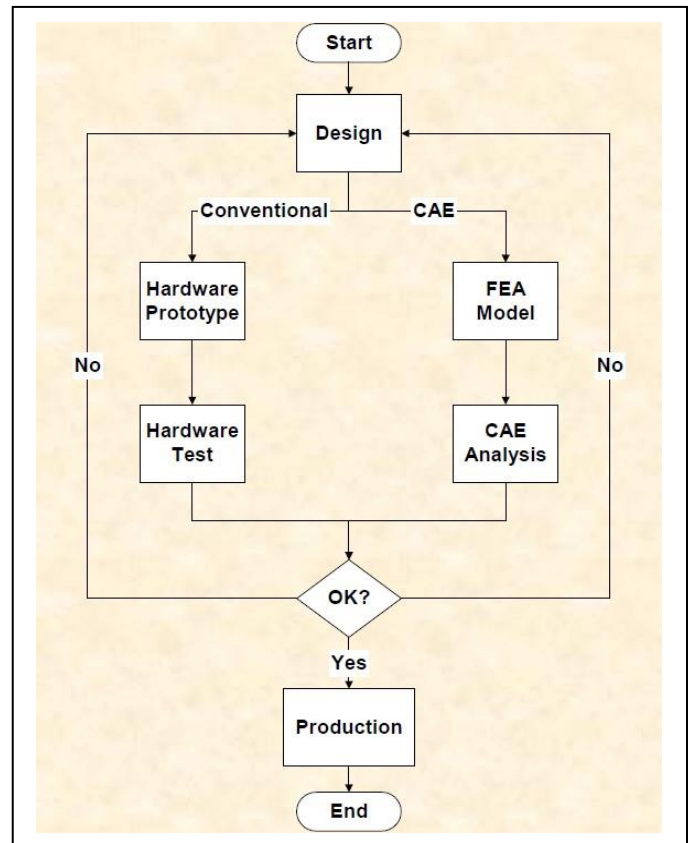


Fig. 5 Comparison of Conventional Test and Computer Aided Engineering Approaches

2. Phase I Project: Static Analysis

In the Phase I Project [2], Finite Element Modeling of ASTM E1592 Tests with four standing seam roof systems, shown in Table 1, were conducted under uniform static pressure. The material yield strength of the roof panels is 56KSI. A commercial software package, LS-Dyna, was used in the analysis to determine deflections and stresses of roof system components at various uniform wind pressures.

Table 1 – Standing Seam Roof Systems Analyzed in Phase I

	Panel	Width	Gauge	Clip
I	Vertical Rib Flat Pan	16"	0.023"	1-piece fixed
II	Vertical Rib Flat Pan	16"	0.030"	1-piece fixed
III	Vertical Rib Flat Pan	16"	0.030"	2-piece floating
IV	Trapezoidal Rib	24"	0.023"	2-piece floating

To reduce the computation time, a simplification of the roof model, shown in Fig. 6, was established, in which one half of a panel width by one half of a panel span with one half of a clip is used in the FEA model. As an example, Fig. 7 shows a simplified FEA model of the roof Panel I. Fig. 8 illustrates the deformed geometry of the roof panels at pressure 60psf (pounds per square foot). Fig. 9 depicts the stress distribution on the clip when a pressure of 60psf is applied to the roof panel. The maximum stress on the clip is about 68KSI (470MPa). Permanent plastic deformation occurred in this case.

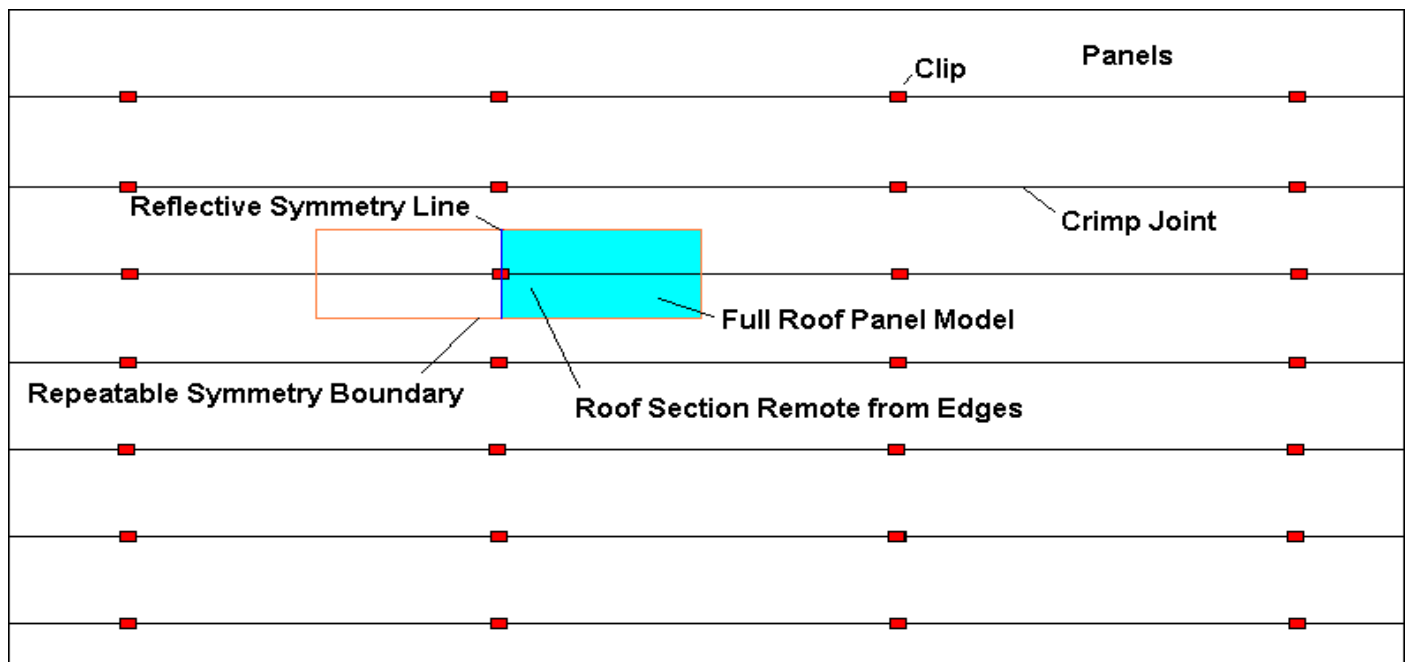


Fig. 6 Phase I FEA Model Simplification

Phase I (Pressure: 0 Psf)
Time = 0.01

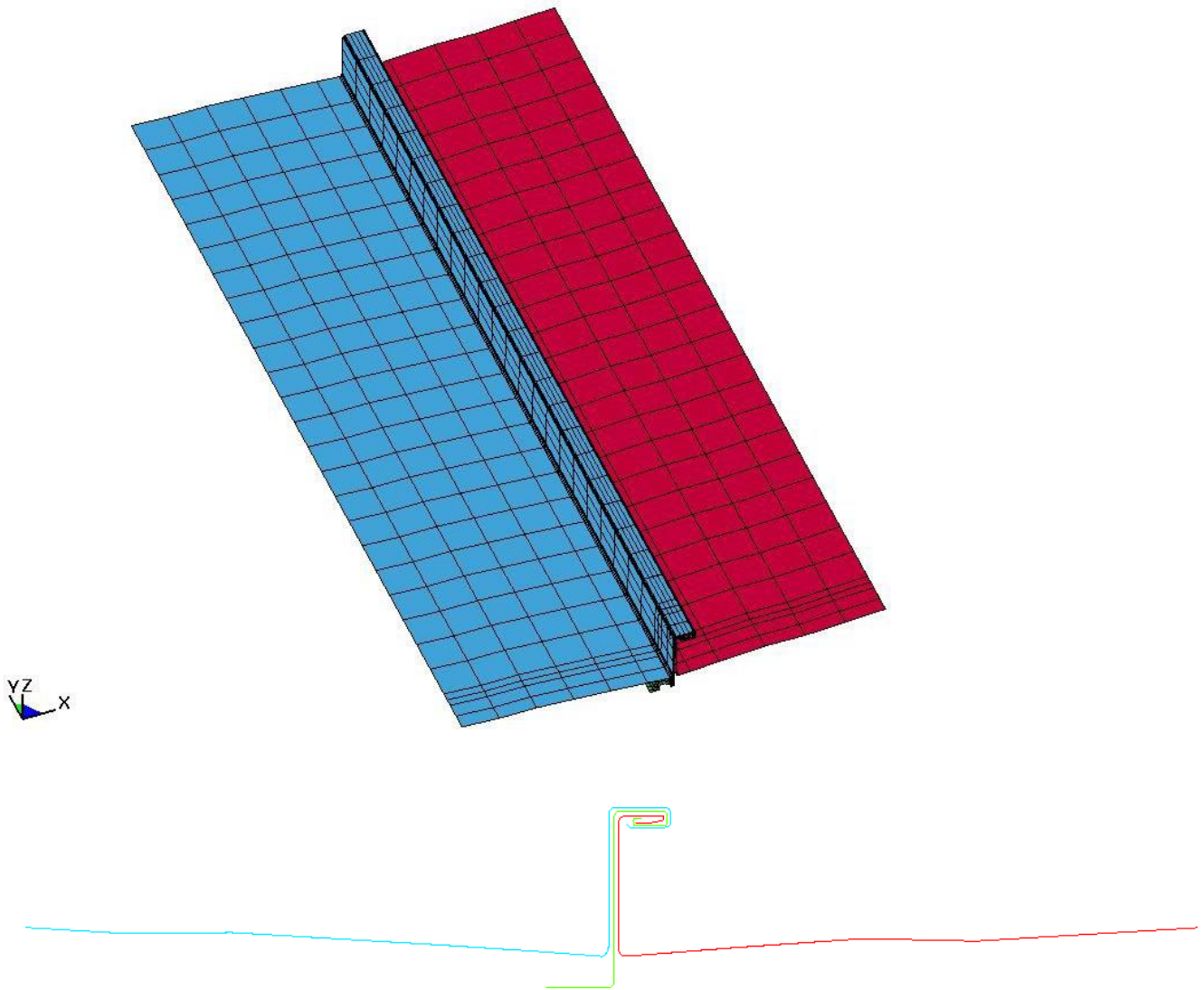
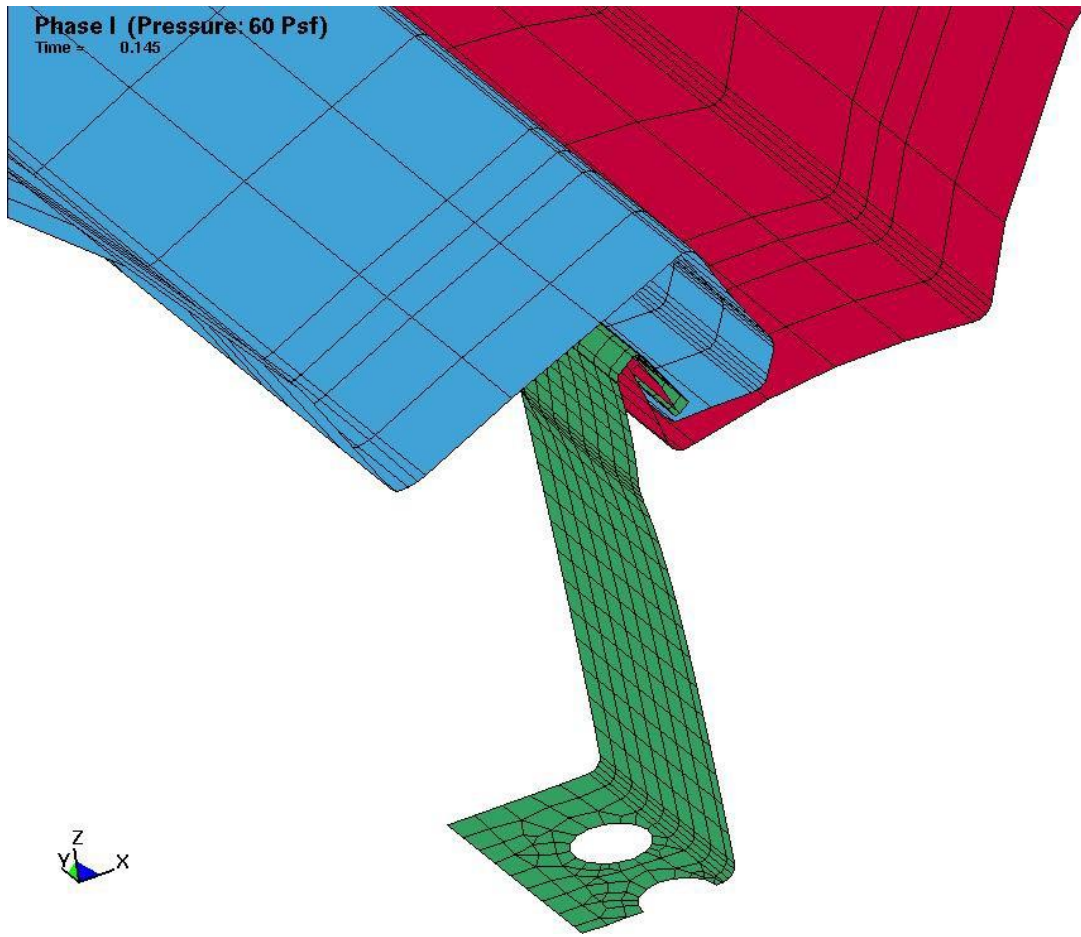


Fig. 7 Panel I at its Initial Position (No Loads)



Phase I (Pressure: 60 Psf)
Time = 0.245

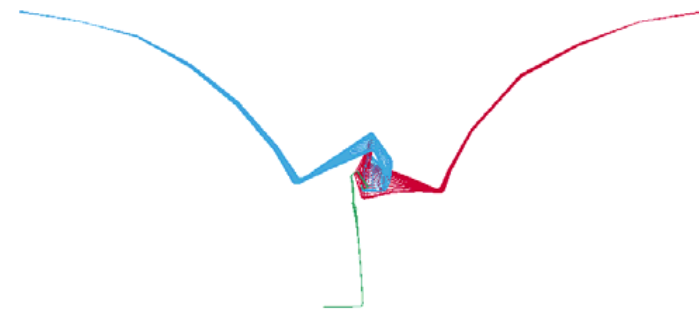


Fig. 8 Deformed Geometry of Roof Panel I at Pressure 60psf

Phase I (Pressure: 60 Psf)
 Time = 0.145
 Contours of Effective Stress (v-m)
 max ipt. value
 min=0, at elem# 1666
 max=476.332, at elem# 1976

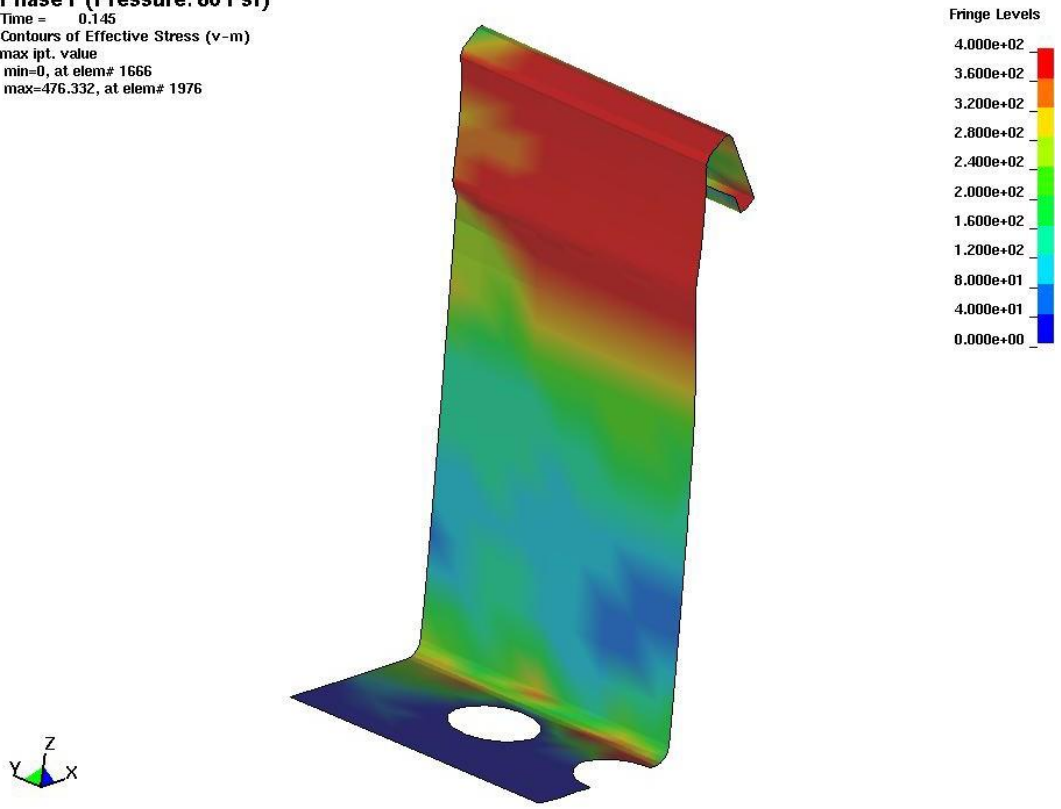


Fig. 9 Clip Stress Distribution at 60psf

Fig. 10 plots the correlation of roof deflections with the physical test data. An average discrepancy between test and analysis is about 10%. By comparing the difference between the test and the analysis results, it was found that the accuracy of the seam dimensions has a large effect on FEA computation accuracy.

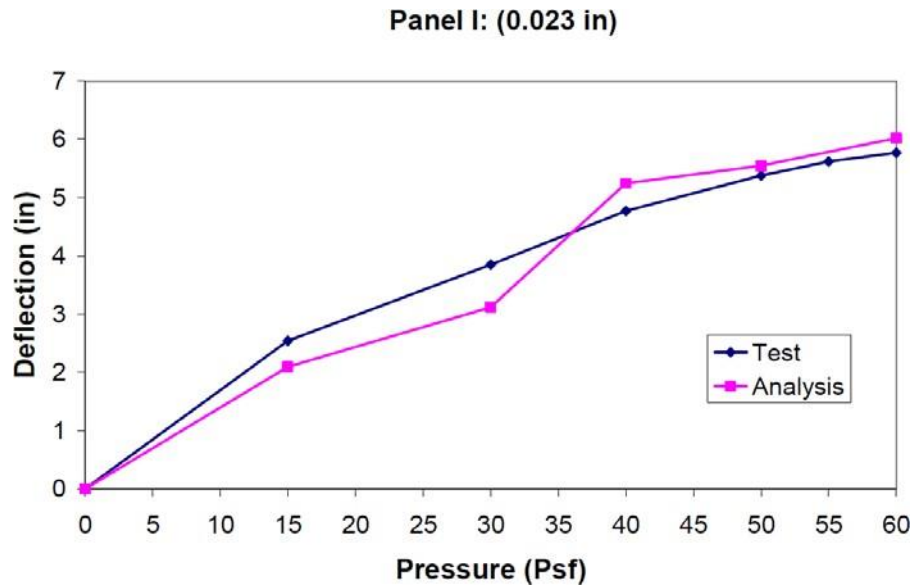


Fig. 10 Correlation with Test Data

To further improve the computation accuracy, analyses were conducted to investigate the effect of adhesive strength at the clips and between the roof panels. Fig. 11 shows the deflection-pressure curves at the adhesive strengths 1.45-11.6KSI (10 – 80MPa), as compared with the Test data of Panel I. The effect of adhesive strength on the computation result can be seen clearly.

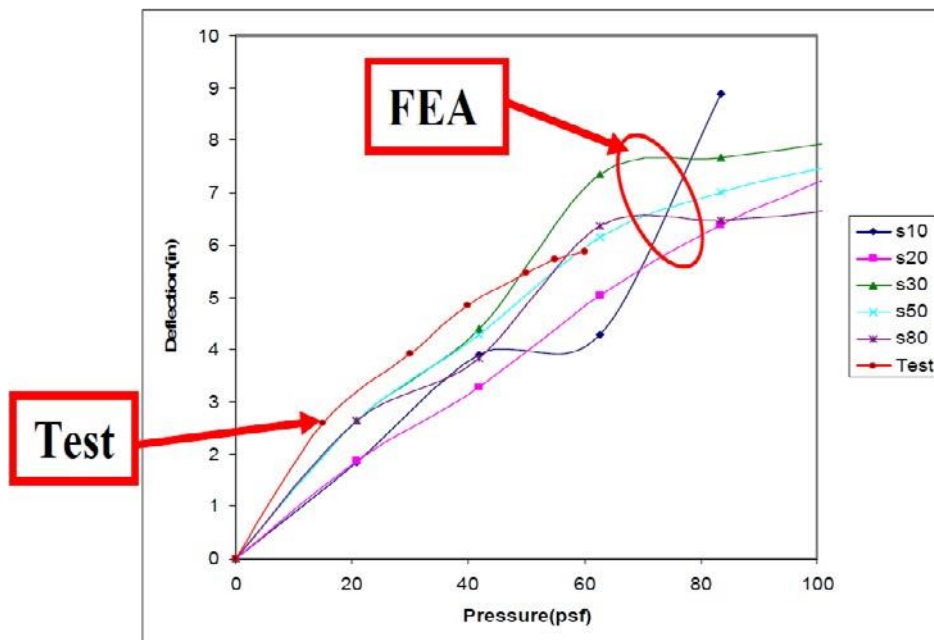


Fig. 11 Effect of Adhesive Strengths on Computation

3. Phase II: Dynamic Analysis

3.1 Project Objective

The objective of the Phase II project is to investigate the feasibility of analyzing the metal roof structures under temporally and spatially non-uniform dynamic wind loads from Hurricane Andrew using Finite Element Method.

3.2 Analysis Conditions

Due to the data availability, data from the dynamic Magnetic Uplift Load Test from MSU, which simulates the Hurricane Andrew wind loads, are used in the analysis. Fig. 12 illustrates the loading conditions. Temporally and spatially varied dynamic wind loads, as shown in Fig. 13, are measured during Magnetic Uplift Test, and applied in the FEA models, at 34 locations (locations noted with numbers 1 - 34 in the figure). In order to compare with the test data, support reaction forces are measured at 6 locations (locations noted with numbers 1 - 6 in the figure). Roof deflections are also measured at 6 locations (locations noted with characters A – F in the figure) for the comparison purpose. Due to the non-uniformity of the load distributions, the full scale model needs to be used in the analysis.

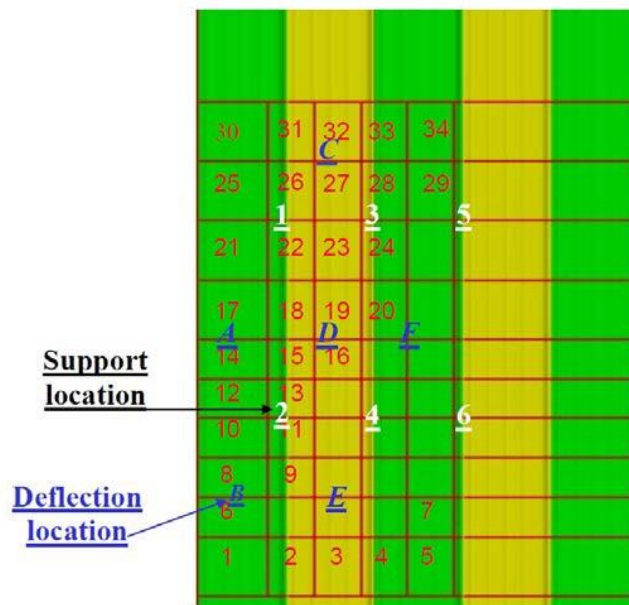


Fig. 12 Magnetic Uplift Test Setup

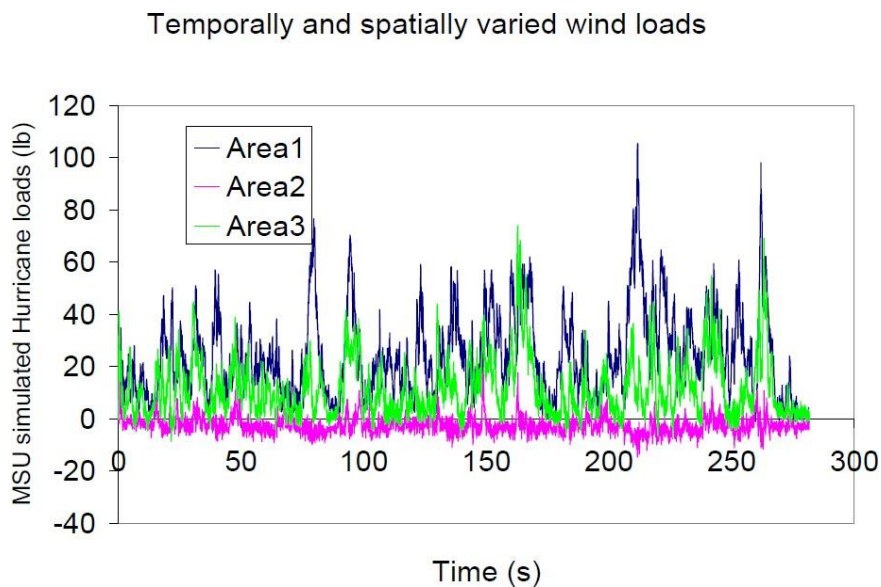


Fig. 13 Wind Load at Selected Areas

3.3 Roof Panels and Load Cases Used in the Simulation

Two roof panels, Panel I and IV, were selected for the analysis. Two types of load cases are employed in the project:

- Static Load - uniform static load of 22.9 psf, which supports the gravity of the panels.
- Superimposed Dynamic Load - Superimposed Dynamic Magnetic Uplift loads at 34 distributive areas on the 22.9Psf uniform static loads, as applied in the Magnetic Uplift Load Test. Load curves from the same time duration of 5 seconds are picked as the input.

Fig. 14 illustrates the deformed roof Panel I at the end of loading time. Figs. 15 and 16 plot the panel deflections with the time at 6 selected locations under the static and the dynamic loads, respectively. The deflections tend to approach a constant value for the static load. The deflections under the dynamic loads show variations with the time. Fig. 17 and 18 plot the Support Reaction Forces at 6 selected locations under static loads and superimposed dynamic loads, respectively.

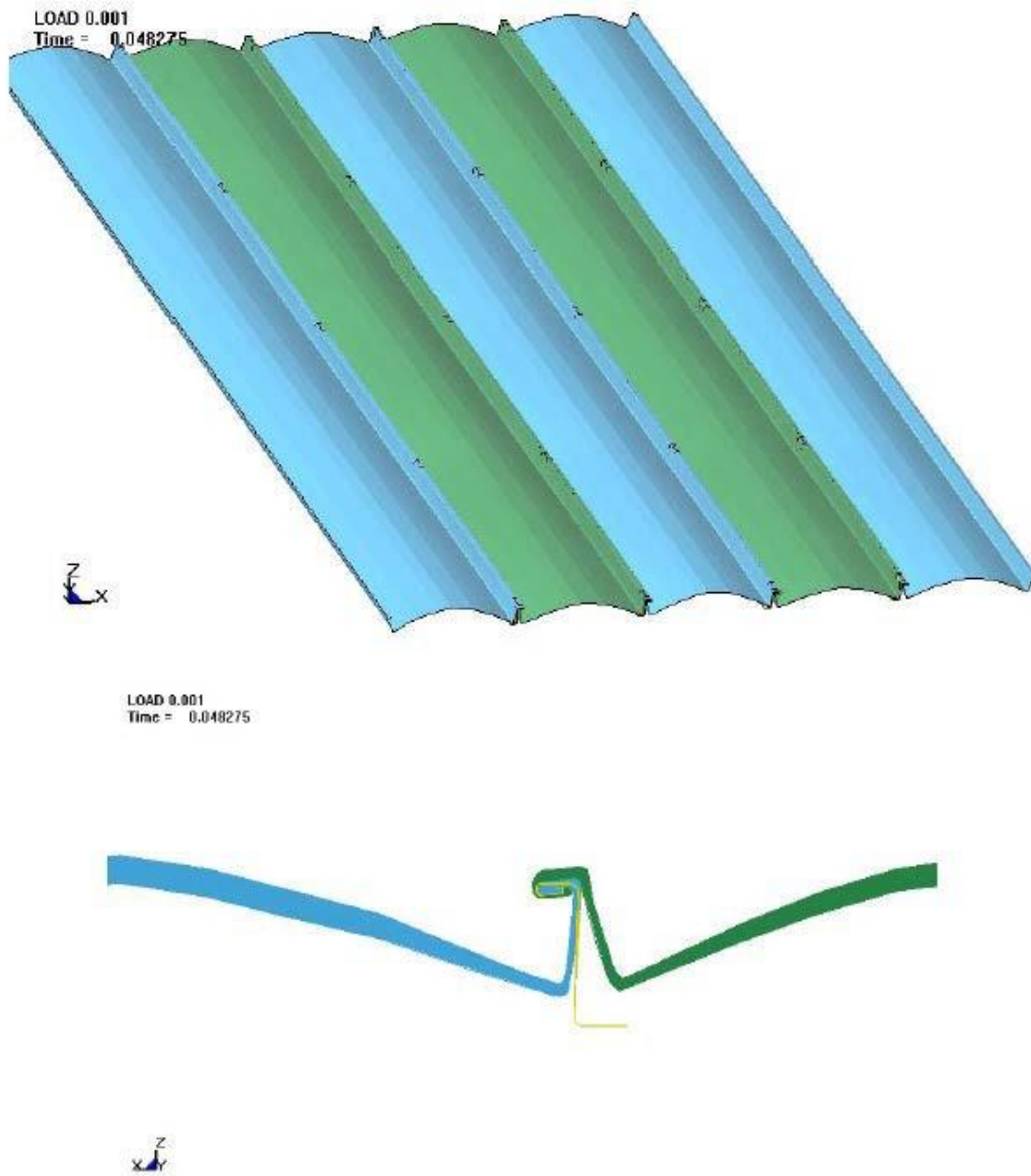


Fig. 14 Deformed Roof Panel

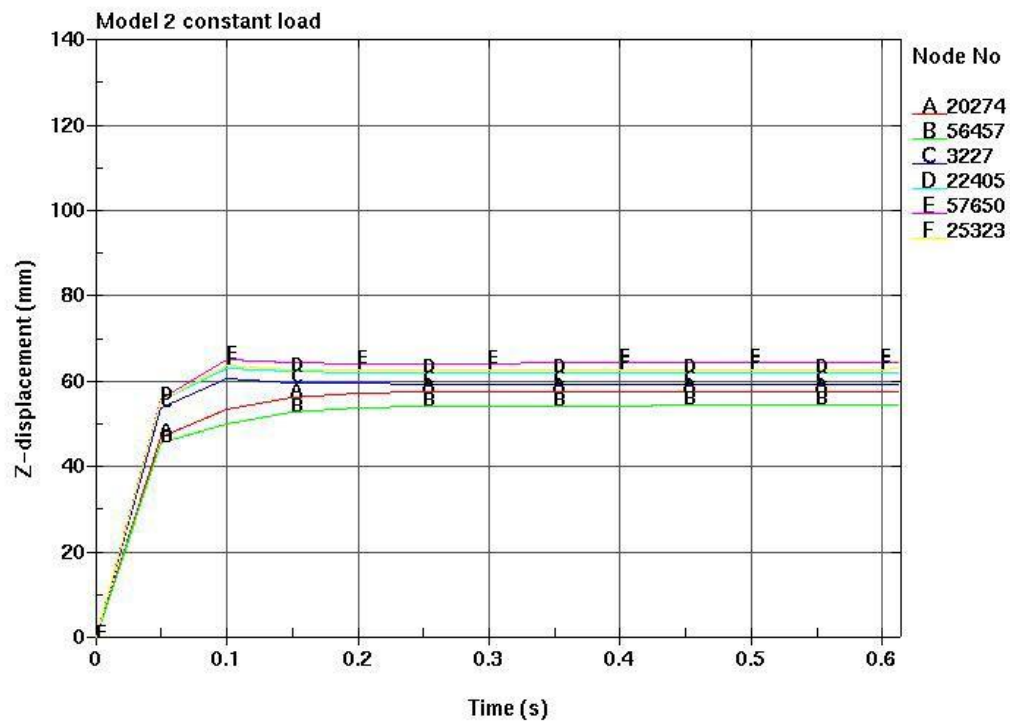


Fig. 15 Deflections under Static Loads (60mm=2.36inch)

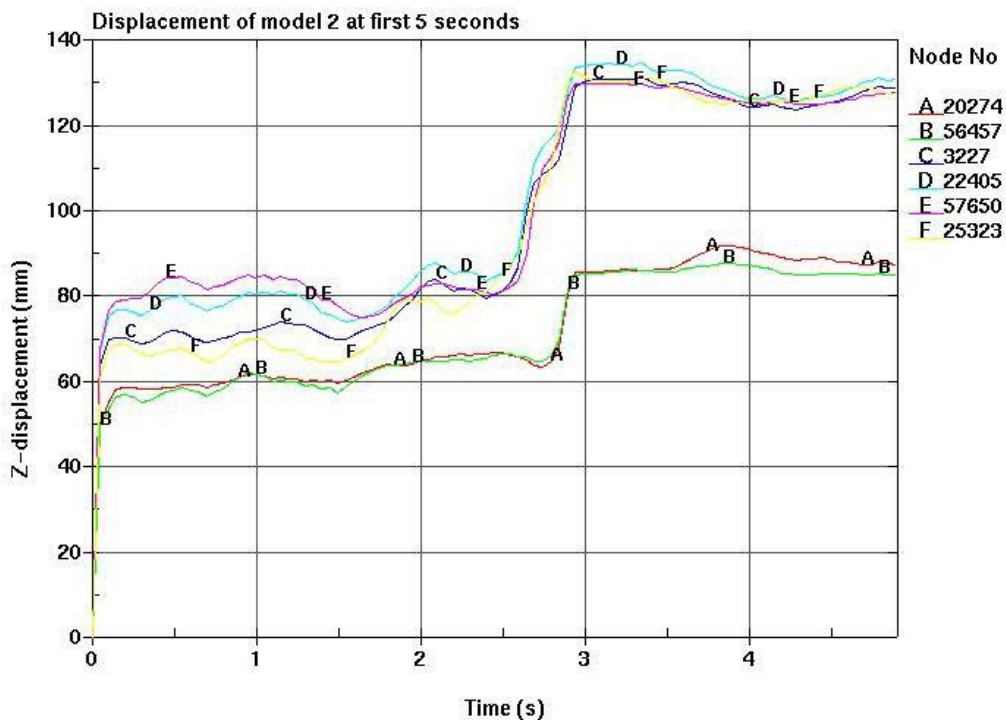


Fig. 16 Deflections under Superimposed Dynamic Loads

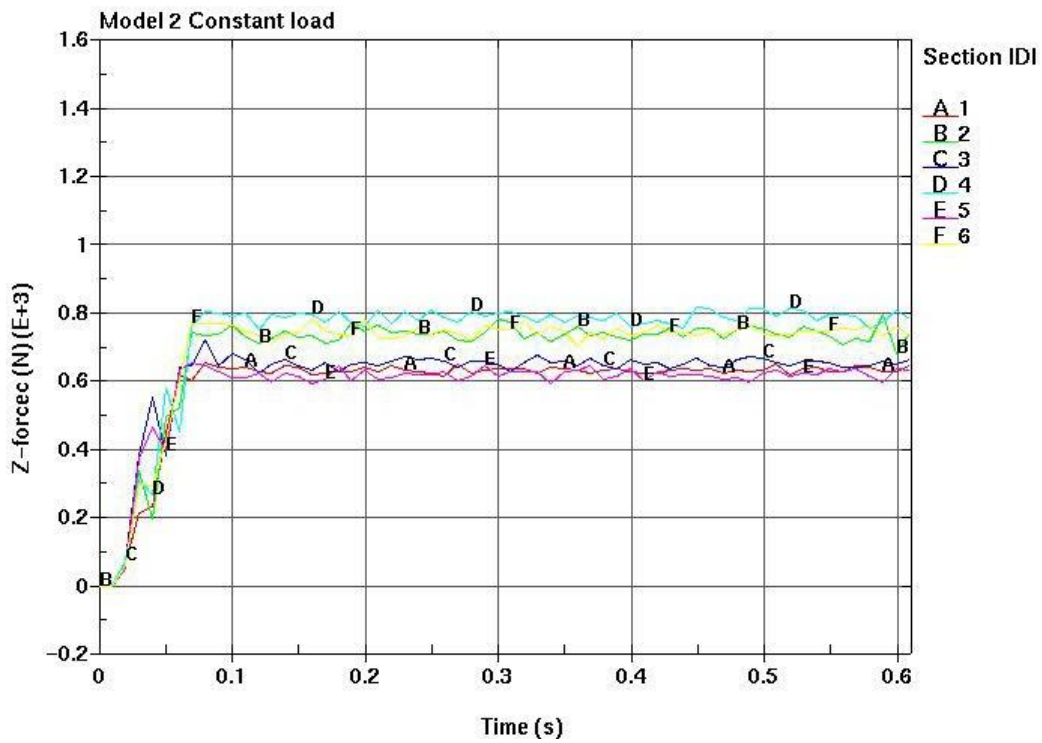


Fig. 17 Support Reaction Forces under Static Loads

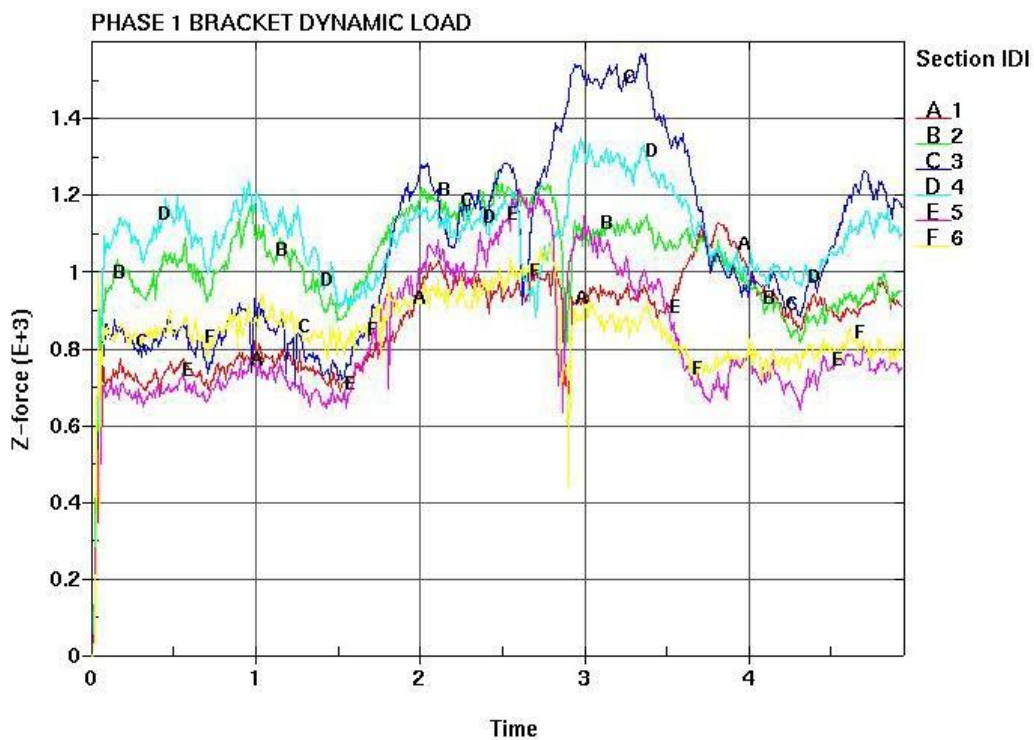


Fig. 18 Support Reaction Forces under Superimposed Dynamic Loads(1500N=337 lbs)

Similarly, Fig. 19 illustrates the deformed roof Panel IV at the end of the loading time. Figs. 20 and 21 plot the panel deflections with the time at 6 selected locations under the static and the dynamic loads, respectively. The deflection tends to approach a constant value for the static load. The deflections under the superimposed dynamic loads show variations with the time. Figs. 22 and 23 plot the Support Reaction Forces at 6 selected locations under the static loads and the superimposed dynamic loads, respectively.

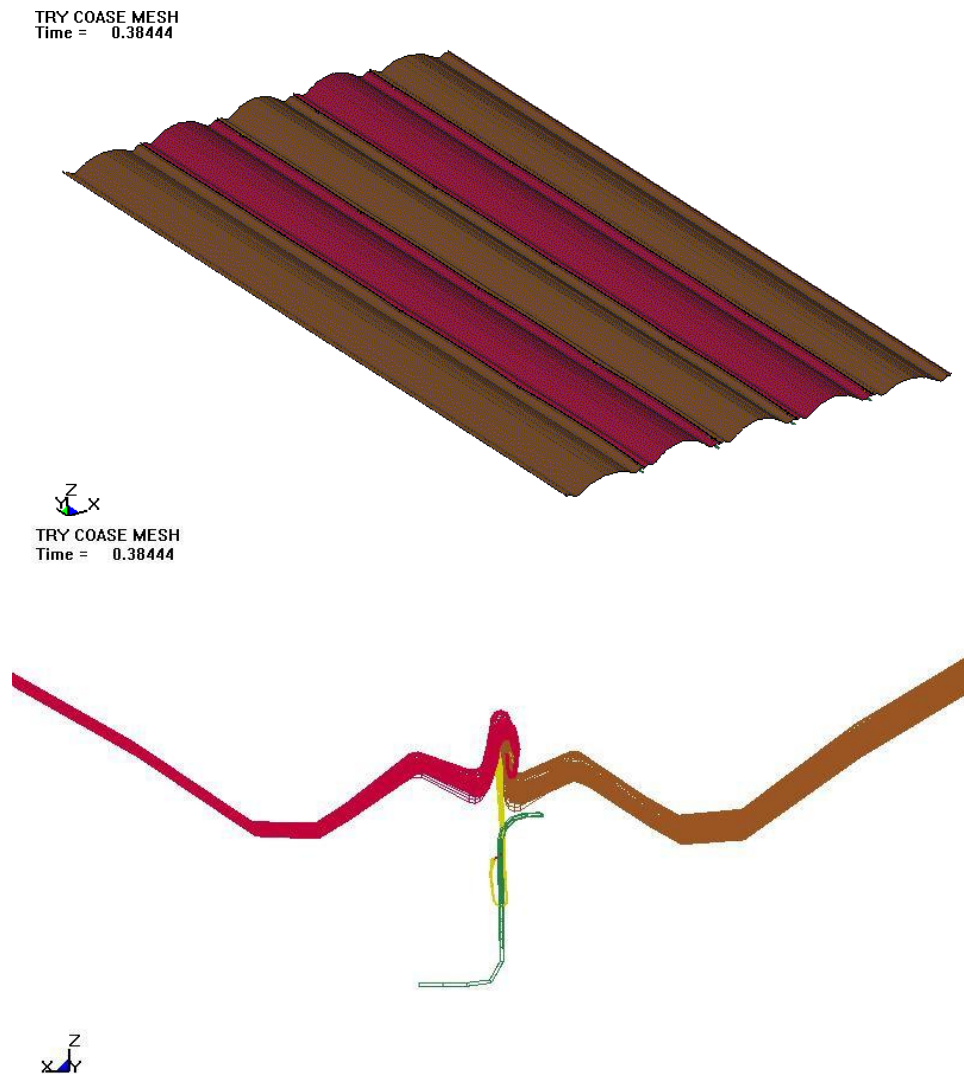


Fig. 19 Deformed Roof Panel IV

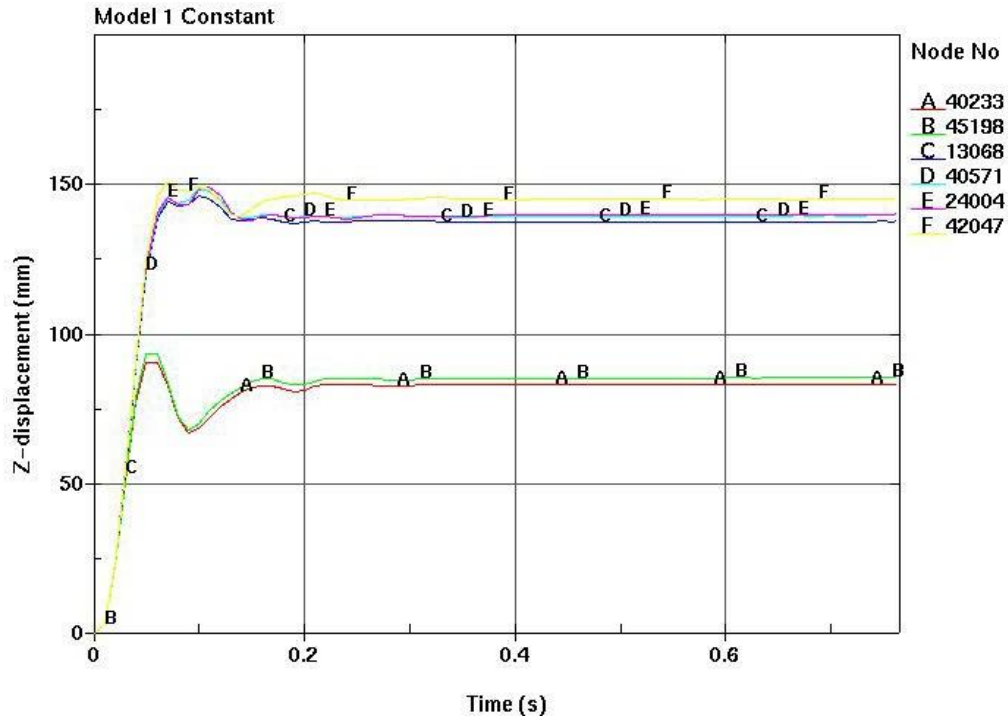


Fig. 20 Roof Panel Deflection under Static Loads

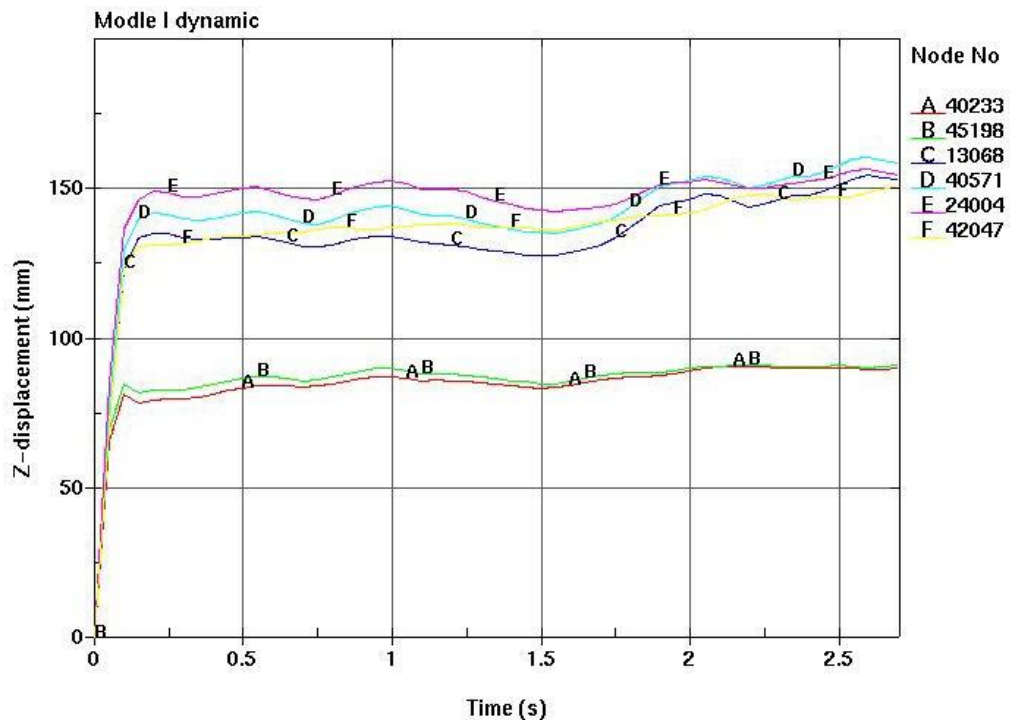


Fig. 21 Panel Deflection under Superimposed Dynamic Loads (150mm=5.9 inch)

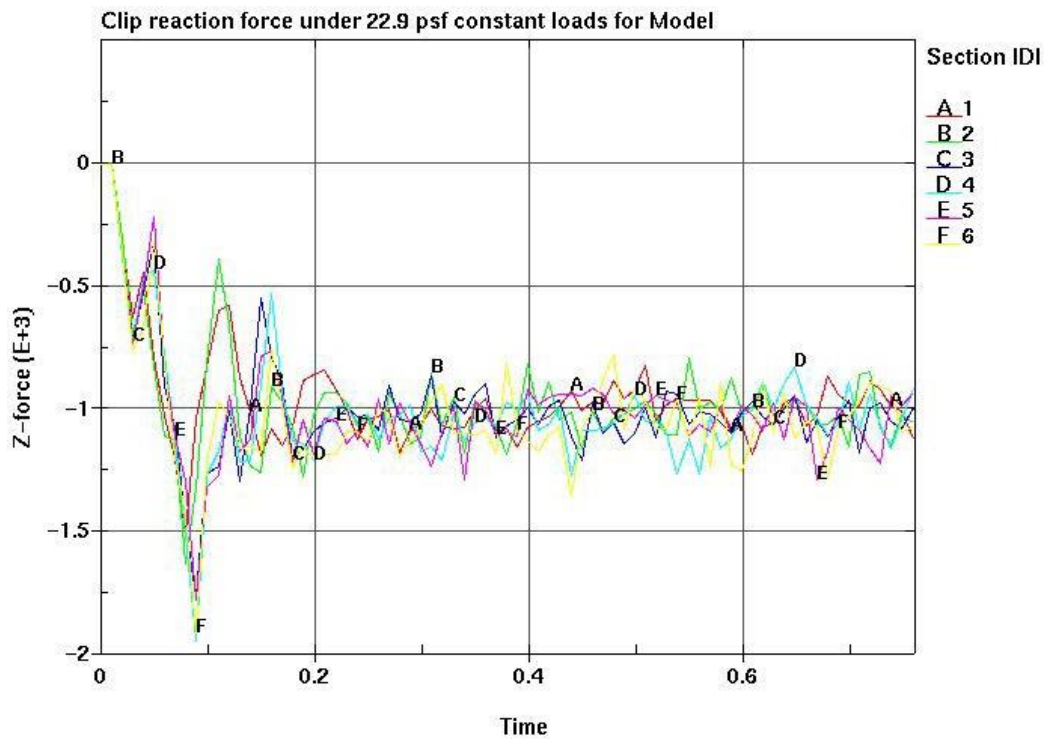


Fig. 22 Support Reaction Forces under Static Loads (2000N=449.5 lbs)

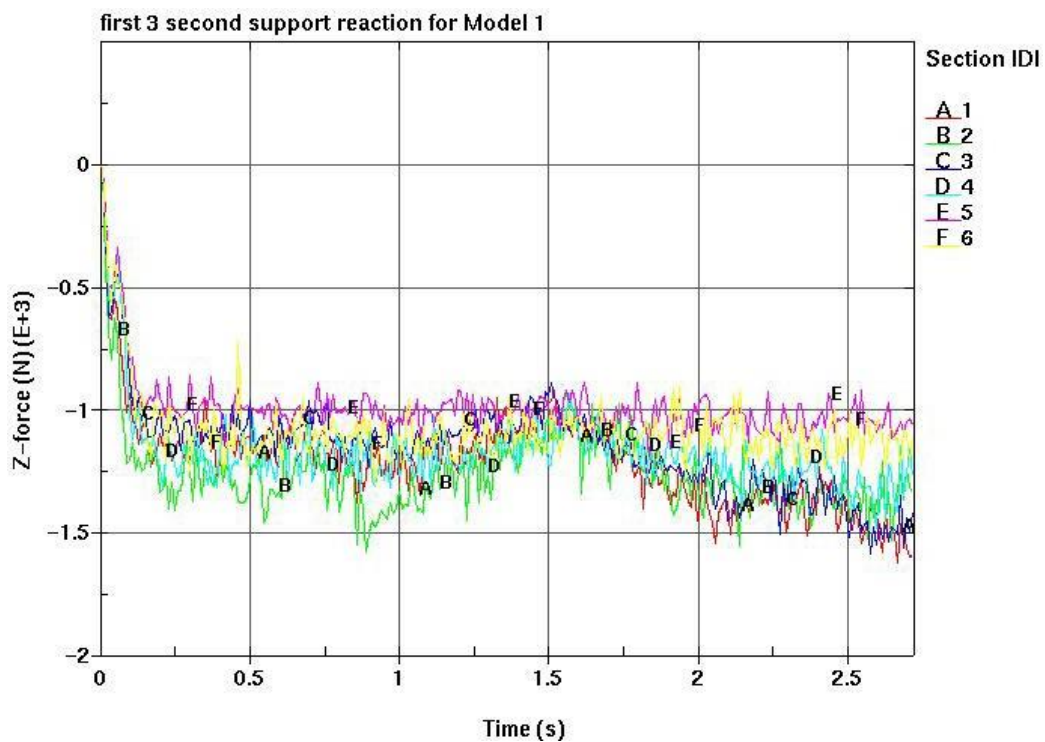


Fig. 23 Support Reaction Forces under Superimposed Dynamic Loads (1500N=337 lbs)

3.4 Comparison of Clip Reaction Forces Between FEA and Test

Fig. 24 plots the clip reaction forces of roof Panel I due to the dynamic loads. Similar trends are seen between the FEA and the Test data.

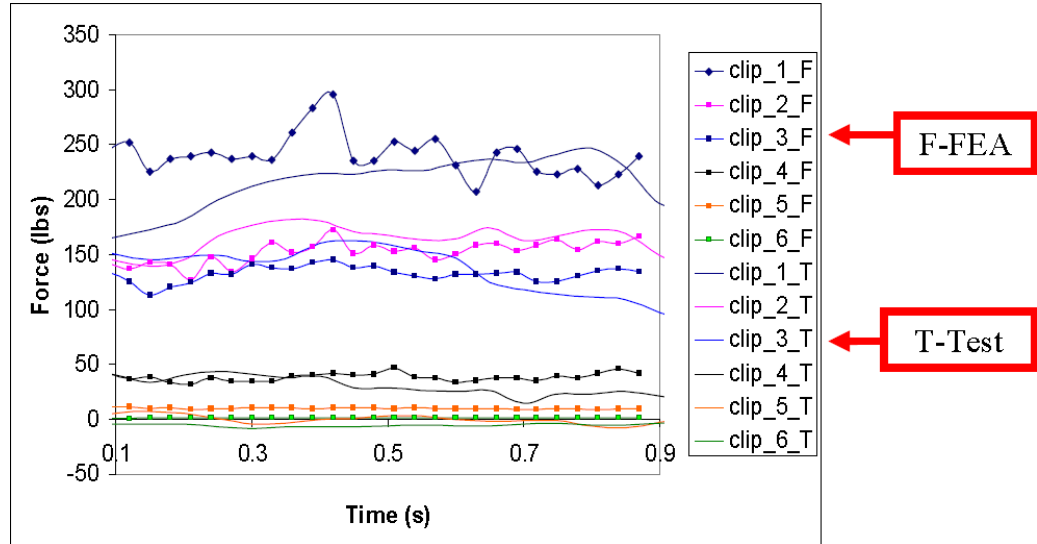
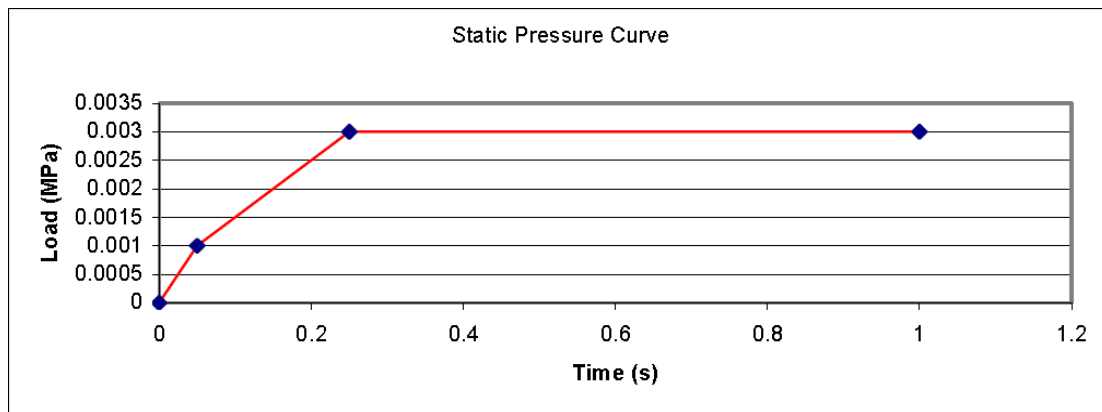


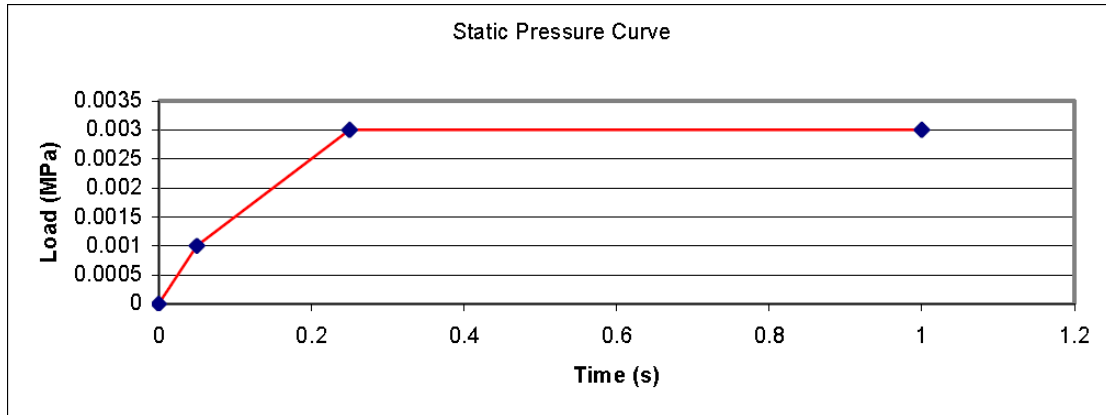
Fig. 24 Comparison of Support Reaction Forces by FEA and Test

3.5 Frequency Effect on Panel Deflections

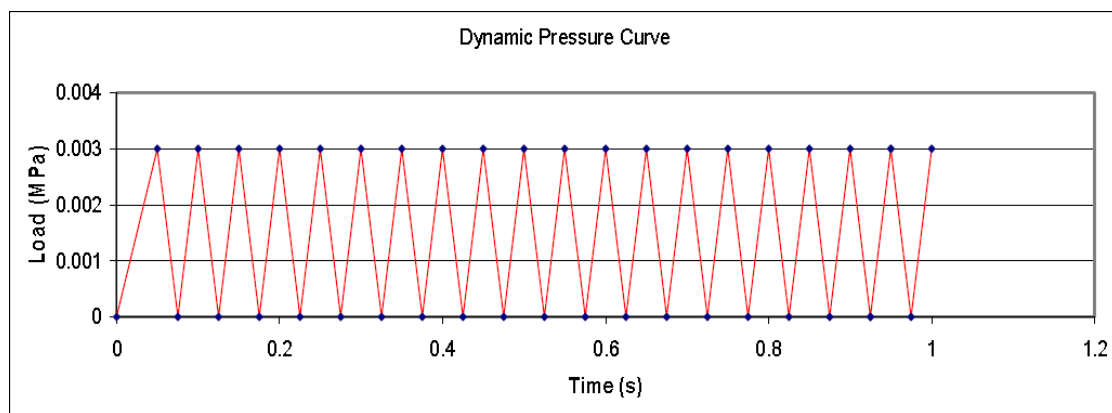
In order to investigate the deflection ratio between static and dynamic loads, a load with a maximum of 62.7psf (0.003MPa) is applied to the roof structure with various frequencies. This simulates the static loading conditions when the frequency is 0Hz, while a dynamic loading condition can be simulated with a high frequency. In this case, 10Hz, 20Hz and 100Hz, as shown in Fig. 25, were used in the analyses.



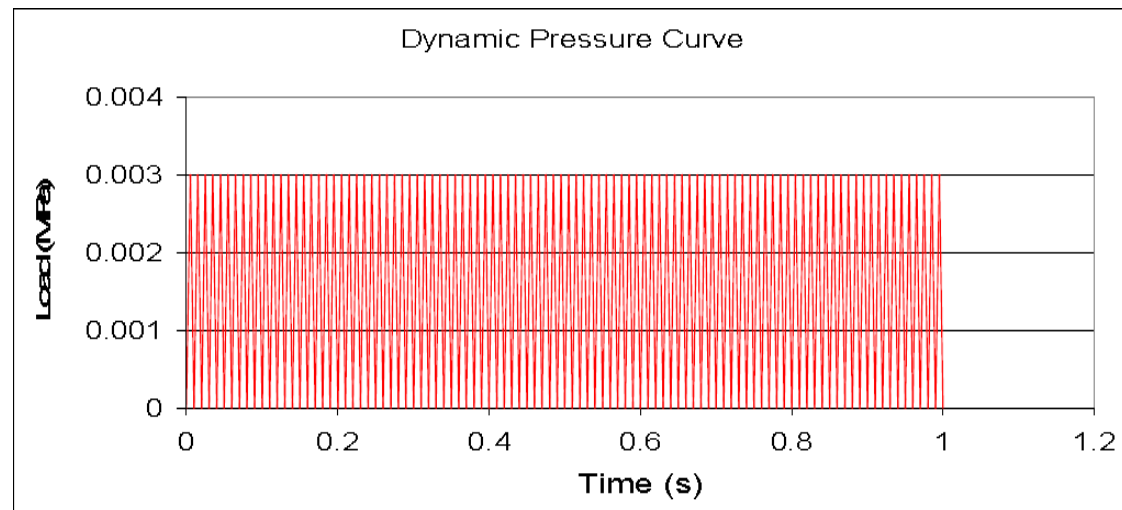
a) Static Load (0Hz)



b) Dynamic Load (10Hz)



c) Dynamic Load (20Hz)



d) Dynamic Load (100Hz)

Fig. 26a–d Static and Dynamic Loads at Various Frequencies Applied to the Roof Structure (0.003MPa=62.7psf)

Fig. 26 shows the calculated roof deflections at various load frequencies. One can see that the maximum deflection decreases when the frequency increases. One can also see that the variations in the deflection are almost ignorable at 100Hz. It indicates that the dynamic effect has reached to a limit. The ratio of static to dynamic deflections can be obtained by comparing the maximum deflections at static load and at 100Hz load, that is, approximately 1.6. This result was later confirmed by Dr. Sinno from Mississippi State University at 2nd Annual MCA Technical Forum in August, 2004.

A theoretical calculation indicates that the ratio between the static and the dynamic deflections is 1.4142 under a sinusoidal load when the frequency approaches infinite. The ratio may be increased with the increased motion resistance. This may be a good reference to the number obtained above.

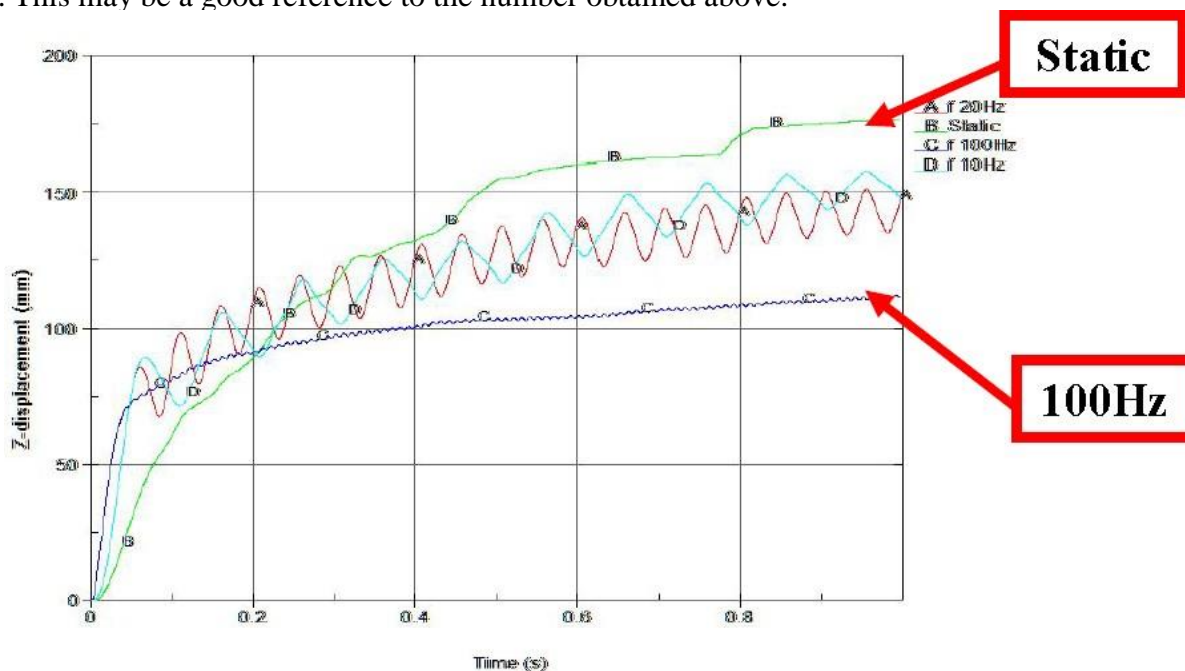


Fig. 26 Effect of Load Frequency on Panel Deflections

4. Concluding Remarks

Static and dynamic analyses of metal roof systems using Finite Element Method indicate that Finite Element Analysis is an appropriate tool for the product development of metal roof structures. The following conclusions are obtained from the study:

- An average of about 10% discrepancy was obtained between the test and the FEA data under the static loading conditions. In addition to the dimensional accuracy of the seams, the adhesive strength between the seams is another major factor that affects the computational accuracy.
- Similar trends between the electromagnetic uplift test and the FEA results were observed in the bracket reaction forces for a roof structure under temporally and spatially non-uniform dynamic loads.
- The ratio of static/dynamic panel deflections is calculated at 1.6 for a panel examined under the same maximum load.
- A standard procedure was established to model the metal roof structures under the static and the

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- Establishment and adoption of an industrial design standard of roof structures based on FEM study.
- Training classes to the MCA members on the outcome of the project.

5. Acknowledgments

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6. References

1. R. Sinno, J. Nail, S. Fowler: *Simulation of Nonuniform Unsteady Wind Pressures (Roof Uplift Test)*, MBMA 98-01 Report, July 2001.
2. National Steel Corporation: *Metal Roof Finite Element Analysis – Metal Construction Association Report*, February 7, 2002.

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