Finite Element Analysis (FEA) of the Static and Dynamic Response of the Sheet Mold Compounding (SMC) Structure Using the Enhanced Modeling Technique of the Adhesive Joining Region

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ABSTRACT

An FEA study was conducted to examine the static and dynamic response of an SMC structure fabricated by adhesive joining method using MSC/NASTRAN. The appropriate modeling of the adhesive joining region is essential in precise FEA predictions of static and dynamic response of the SMC structure presented. An enhanced modeling technique for the adhesive joining region is presented in this paper. A composite mechanics approach was used to define the mechanical property of finite elements along adhesive joining region. Static and dynamic predictions of the enhanced modeling technique were compared with predictions of the conventional linkage modeling method in structure analysis.

1.0 INTRODUCTION

Over the past two decades, plastics and composites have come to play a vital role in the automobile industries. At present, one third of all materials used by the automotive industry are made of engineering plastics and composites, and this percentage is rising with each new model introduced. The drive to expand the use of plastics and composites in automotive industries results from the economies of parts consolidation, corrosion resistance, light weight, and flexibility during the forming process. Sheet Mold Compounding (SMC) is the major manufacturing process of plastics and composites in automotive industries. SMC is a composite material consisting of fibers reinforcing a resin matrix. In short-fiber reinforced SMC, the dominant structural feature is the spatial arrangement of the fibers. When the fibers have a random orientation, the properties of the composite can be assumed to be isotropic. However, should the alignment of the fibers be in one direction, the greatest strength and stiffness of the composite is in the fiber direction. A study for predicting the distribution of orientation of the short fibers in the SMC parts was studied by many scientists [1-3].

SMC structures are fabricated by adhesive joining. Therefore, unless proper modeling technique is implemented for the adhesive joining area of a large SMC structure, static and dynamic predictions of the numerical modeling analysis may not be precise. Using the proposed modeling technique can prevent not only the over- and under-stiffening but also the ill-conditioned stiffness matrix of a SMC structure assembled by the adhesive joining [4]. Moreover, this technique allows the prediction of stress distribution along the adhesive joining region as well as the fiber orientation effect on SMC structure analysis. Thus, the stress effect on the adhesive joining region can be investigated with very good accuracy.

2.0 ANALYSIS MODEL OF ADHESIVE JOINING

Figures 1 and 2 show two versions of FE models of a truck hood with different methods to simulate the adhesive bond. Model 1 utilizes rigid linkage, while Model 2 uses equivalent adhesive joining elements. A description of element summaries for the model is contained in Table 1. Quadratic and triangular plate elements were used for finite element modeling of the truck hood surface. The front hinge and rear latch mechanisms were modelled using spring elements and single point constraint conditions in translational directions. Two FEM modeling techniques were compared for the adhesive joining of SMC hood. The first is a rigid linkage modeling technique for the adhesive joint. The other utilizes elements of the adhesive joint which are co-shared by components held by the adhesive. The mechanical property of these elements is determined on the basis of mechanical and volume ratio of adhesive and SMC materials.

2.1 Rigid Linkage Using a Rigid Beam Element

Consider two grid points A and B as shown in Figure 3 connected with a rigid link connection. The rotation of the two points are θ_A and θ_B respectively, and the displacements are $\hat{U}_A$ and $\hat{U}_B$. The displacement and rotation of B can be expressed in terms of the displacement at A by:

$$\hat{U}_B = \hat{U}_A + \theta_A \times \lambda \qquad (1)$$

and

$$\theta_B = \theta_A$$

where λ is the vector from point A to B.

This vector equation can be rewritten in scala form as follows:

$$U_{1B} = U_{1A} - \lambda_y U_{6A} + \lambda_z U_{5A} \qquad (2)$$

$$U_{2B} = U_{2A} - \lambda_z U_{4A} + \lambda_x U_{6A} \quad (3)$$

$$U_{3B} = U_{3A} - \lambda_x U_{5A} + \lambda_y U_{4A} \quad (4)$$

$$U_{4B} = U_{4A} \quad (5)$$

$$U_{5B} = U_{5A} \quad (6)$$

$$U_{6B} = U_{6A} \quad (7)$$

where λ_x, λ_y, and λ_z are the components of λ in the x–, y–, and z–directions.

The use of a rigid beam element for the adhesive joining may result in an too much stiffness in the region. This practice will also create stress concentrations at the dependent and independent nodes of the rigid beam elements. Consequently, when the zone of interest is close to the rigid element, the FEA prediction of stress in that area could be erroneous. Since the most critical region subject to failure in SMC structure are the adhesive joining region, the use of the rigid linkage modeling technique along an adhesive joining region may produce unreliable stress estimations.

2.2 Modeling Adhesive Joint Using Equivalent Adhesive Element

This technique enables the layer thickness and material property of adhesive material and SMC parts as well as the fiber orientation in the SMC component to be included in modeling of adhesive joint. As shown in Figure 2, the equivalent adhesive elements are co–shared by components connected by adhesive joining. Figure 4 shows a enlarged side view of adhesive joining region. The adhesive joining region can be considered as a composite structure consist of SMC components 1 and 2 and adhesive material. Using composite mechanics for the material property definition, the material properties of adhesive elements can be determined. Young's modulus in the direction parallel to the fiber orientation of SMC part can be determined as follows:

$$E_{lc} = \upsilon_{s1}\ E_{sL1} + \upsilon_a\ E_a + \upsilon_{s2}\ E_{sL2} \qquad (8)$$

where υ_{s1}, υ_{s2}, and υ_a is volume ratio of SMC components 1 and 2 and adhesive material, respectively,
E_{sL1} and E_{sL2} are Young's modulus of SMC components 1 and 2 in the direction parallel to the fiber orientation,
E_a is Young's modulus of adhesive material.

Young's modulus in the direction perpendicular to the fiber orientation of SMC part can be determined as follows:

$$E_{lc} = \upsilon_{s1}\ E_{sT1} + \upsilon_a\ E_a + \upsilon_{s2}\ E_{sT2} \qquad (9)$$

where υ_{s1}, υ_{s2}, and υ_a is volume ratio of SMC components 1 and 2 and adhesive material, respectively,
E_{sT1} and E_{sT2} are Young's modulus of SMC components 1 and 2 in the direction parallel to the fiber orientation,
E_a is Young's modulus of adhesive material.

By using Equations (8) and (9), the fiber orientation effect of SMC part can also be included in modeling of adhesive joining. Thickness of the equivalent adhesive joining elements is determined by:

$$t_e = t_{s1} + t_a + t_{s2} \qquad (10)$$

where t_{s1} and t_{s2} is thickness of SMC parts 1 and 2,
t_a is thickness of adhesive material and t_{s2} is thickness of SMC part 2 (see Figure 4).

The density of the equivalent adhesive elements can be determined as follows;

$$\rho_c = \upsilon_{s1}\rho_{s1} + \upsilon_a\rho_a + \upsilon_{s2}\rho_{s2} \qquad (11)$$

where υ_{s1}, υ_{s2}, and υ_a are volume ratio, of the SMC (components 1 and 2) and adhesive material, respectively,
ρ_{s1}, ρ_{s2}, and ρ_a are the respective density of SMC components and adhesive material.

By using this technique, the material property definition and thickness of elements along an adhesive joining region can be determined adequately without introducing the risk of an too much stiffness or artificial stress concentrate. Thus, in the SMC structure fabricated by adhesive joining, using this modeling technique will provide more accurate predictions in both static and dynamic FEA.

3.0 RESULTS AND DISCUSSIONS

Model 1 using rigid beam element for the modeling of adhesive joining is shown in Figure 1. Model 2 using equivalent adhesive elements is shown in Figure 2. Static and dynamic analyses of the SMC truck hood were performed for the two models. Comparisons between these two models for static and dynamic FEA are described in following sections.

3.1 Normal Mode Analysis

Model 1 predicted 8 normal modes below 20. Model 2 predicted 9 normal modes below 20 Hz. Figure 5 shows a comparison of normal mode frequency difference between the two models. Figure 6 shows the difference of normal mode frequencies in the prediction of two models. Equation 12 relates the structural stiffness to the normal mode frequency.

$$K \propto f^2 \qquad (12)$$

where K is a structural stiffness,
f is the normal mode frequency.

The normal modes predicted with rigid links are always about 10 % higher than those predicted by an equivalent adhesive joining elements. Applying Equation 12 to this case, the stiffness of Model 1 is found to be 21 % higher than Model 2. As expected, the structural stiffness of SMC hood fabricated by adhesive joining is highly dependent on the modeling technique of adhesive joining region. Thus, using rigid beam elements (RBE2) for modeling of the adhesive joining results in errors due to over–stiffening and potential ill–conditioning of the stiffness matrix around RBE2 in the structure.

3.2 Static Analysis

For the static loading condition, a 200 lb. pre–load force was applied to the hood to simulate the latch mechanism. Figures 7 through 10 show the maximum Von Mises and shear stress distribution in Models 1 and 2. The maximum Von Mises stress is 162 MPa for Model 1 and 228 MPa for Model 2. Model 2 prediction of Von Mises stress is higher by 28.9 %. This is because the equivalent adhesive joining approach probably changed the load path such that the adhesive joining regions will carry more deformation. Table 2 contains a summary of stress results for the comparative analysis.

Through this FEA, it was found that a conceivable difference in static and dynamic prediction exits in the two approaches. As the adhesive joining region becomes larger, the difference between two modeling techniques will become greater. Since using equivalent adhesive joining elements is a more realistic approach for modeling adhesive joining, this modeling technique will provide FEM models with more realistic stiffness and more precise predictions of static and dynamic response of the system.

4.0 CONCLUSION

Use of a rigid linkage to model an adhesive joining region in SMC components produces an overly stiff connection that affects both static and dynamic analysis. The rigid beam approach also has the potential of producing an ill–conditioned stiffness matrix and localized stress concentrations at the rigid beam ends. The difference between the two modeling techniques become more pronounced as the adhesive joining region in SMC structure gets larger. The predictions of equivalent adhesive joining element approach are more conservative than that of the rigid linkage approach. Therefore, for SMC structures fabricated with adhesive joining, the modeling technique suggested in this paper will provide better accuracy in both static and dynamic element analysis.

5.0 REFERENCES

1. W. C. Jackson, S.G. Advani, C.L. Tucker, "Predicting the Orientation of Short Fibers in Thin Compression Molding", J. Comp. Materials, Vol. 20, Nov. 1986
2. J. P. Bell, "Flow Orientation of Short Fiber Composites", J. Compos. Mat., Vol. 3, 1969
3. P. F. Bright, R. J. Crowson, M. J. Folkes, "A Study of the Effect of Injection Speed of Fiber Orientation in Simple Moldings of Short Glass Fiber–Filled Polypropylene", J. Mat. Sci., Vol. 13, 1978
4. H. G. Schaeffer, MSC/NASTRAN Primer, Static and Normal Mode Analysis, pp 142 – 154, Wallace Press, Inc., Milford, New Hampshire, 1988

Element Entities	Model 1 (Rigid Linkage)	Model 2 (Equiv. Adh. Element)
Grid	597	496
Quad. Plate	487	409
Triangular Plate	100	97
Spring (CELAS1)	23	23
Rigid Bar (RBE2)	97	**

Table 1. Element Entities of Model 1 (Rigid Linkage) and Model 2 (Equivalent Adhesive Element).

	Max. Von Mises Stress (MPa)		Difference (%)
	Model 1	Model 2	
SMC	162	228	29
Adh. Join. Region	162	171	6
	Max. Shear Stress (MPa)		Difference (%)
Adh. Join. Region	19.2	26.3	38

$$\text{Difference (\%)} = \frac{\text{Model 2 - Model 1}}{\text{Model 1}} \times 100$$

Model 1 : Rigid Linkage Method

Model 2 : Equivalent Adhesive Joining Element Method

Table 2 . Comparison of Maximum Stress Distribution
Between the two Method.

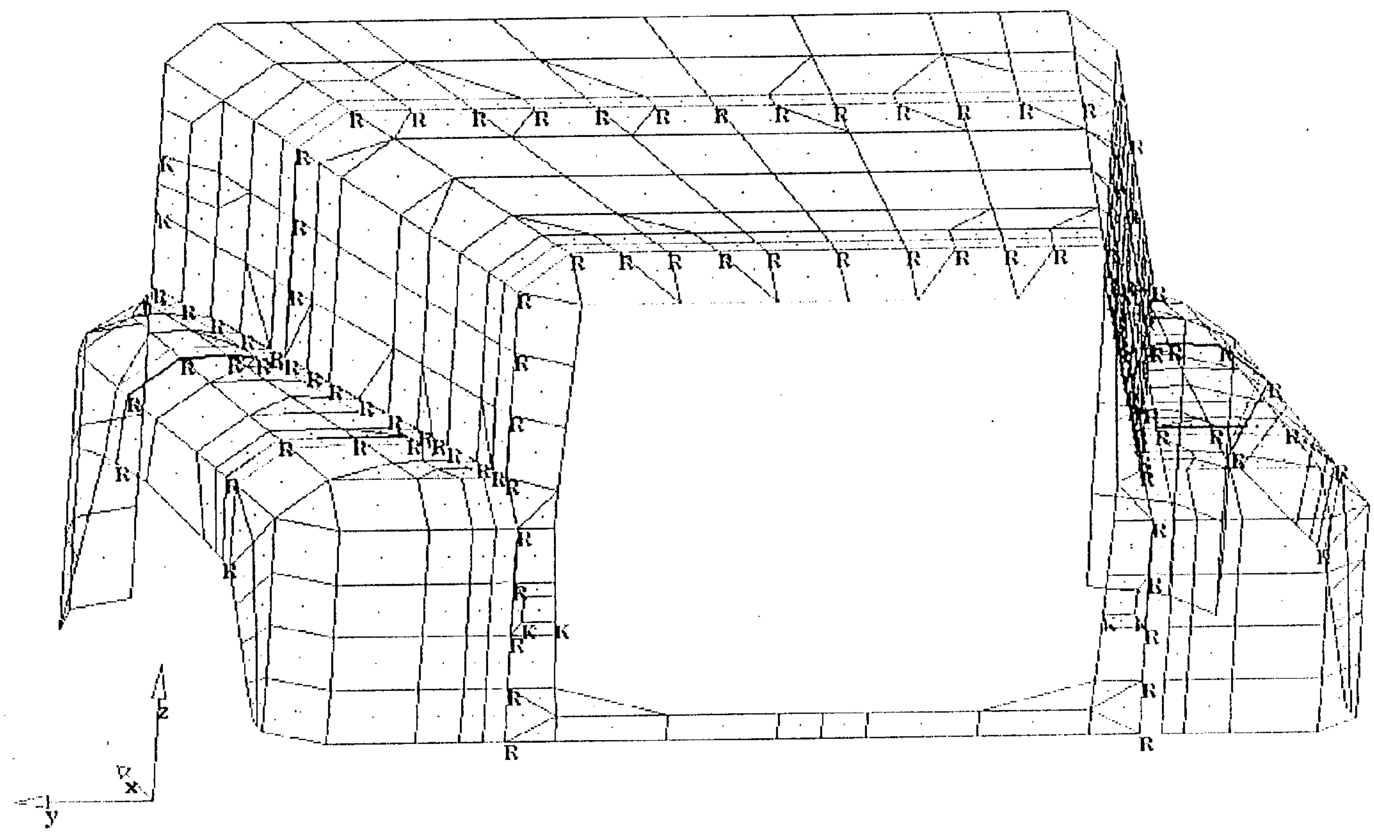

Figure 1. FEA Model 1 Utilizing Rigid Beam Element (RBE2) for the Rigid Linkage Modeling of Adhesive Joining.

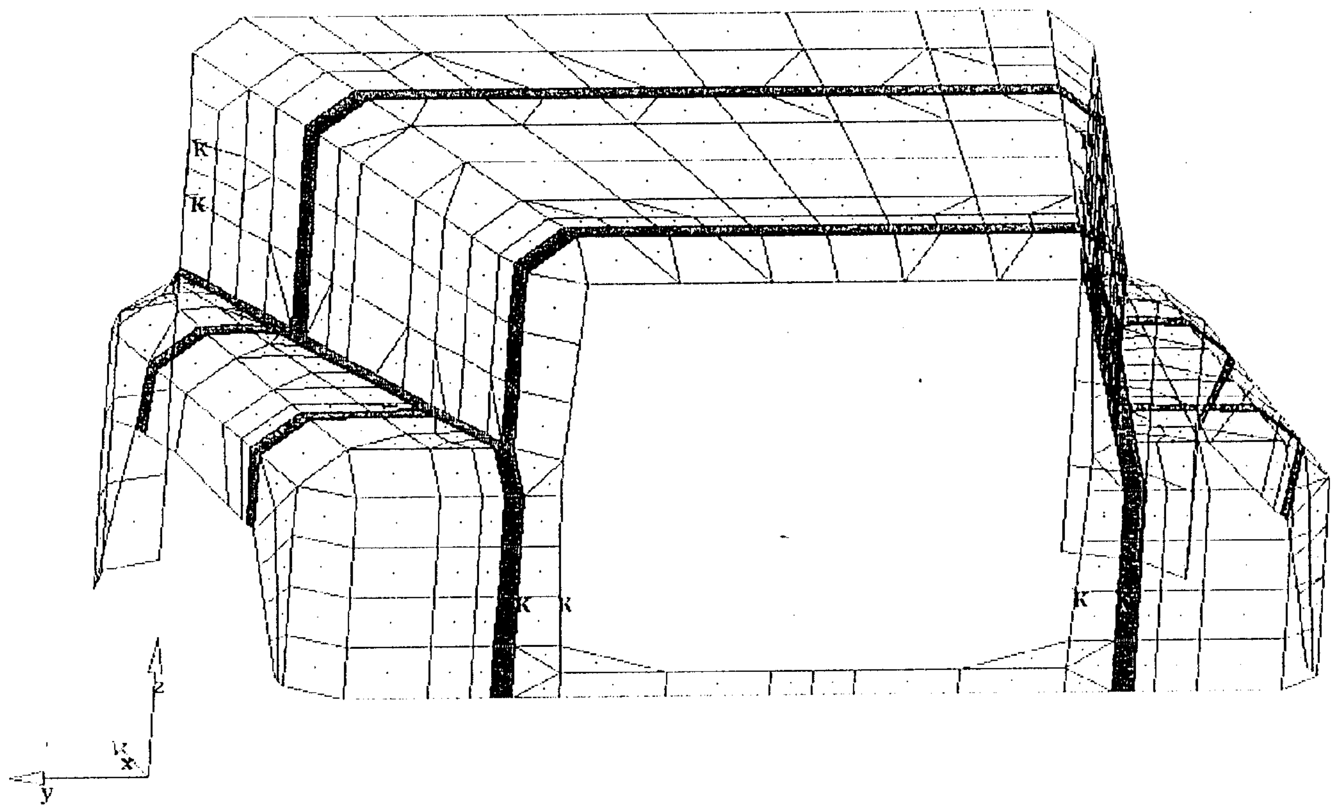

Figure 2. FEA Model 2 Utilizing Equivalent Adhesive Elements for the Modeling of Adhesive Joining.

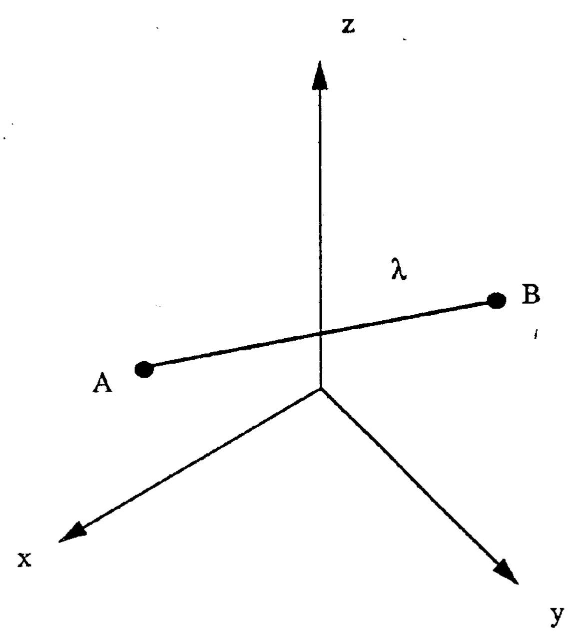

Figure 3. Schematics of General Rigid Linkage.

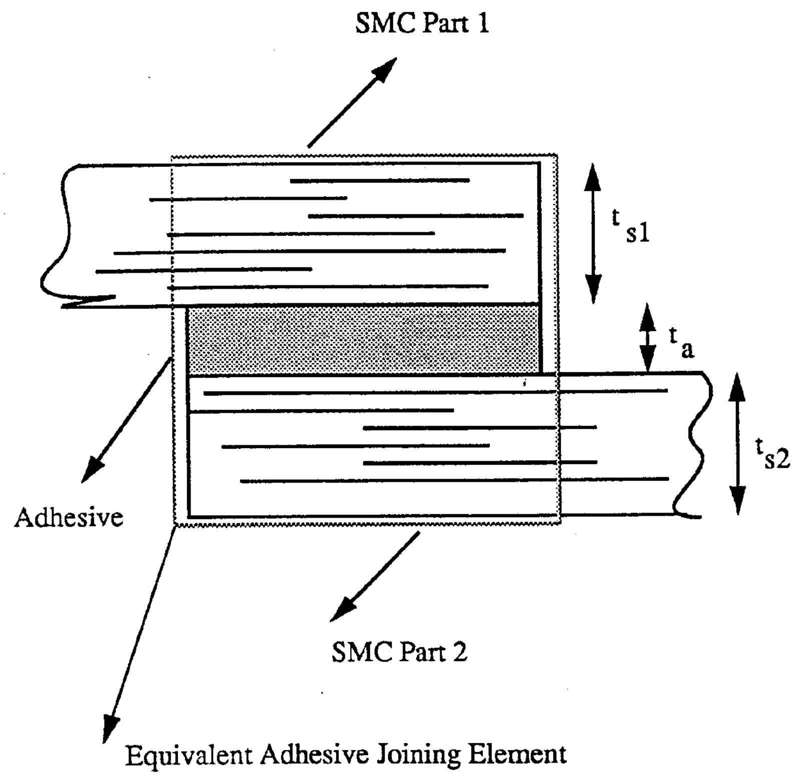

Figure 4. Schematic of Side View of Equilivalent Adhesive Element for the Modeling of Adhesive Joining.

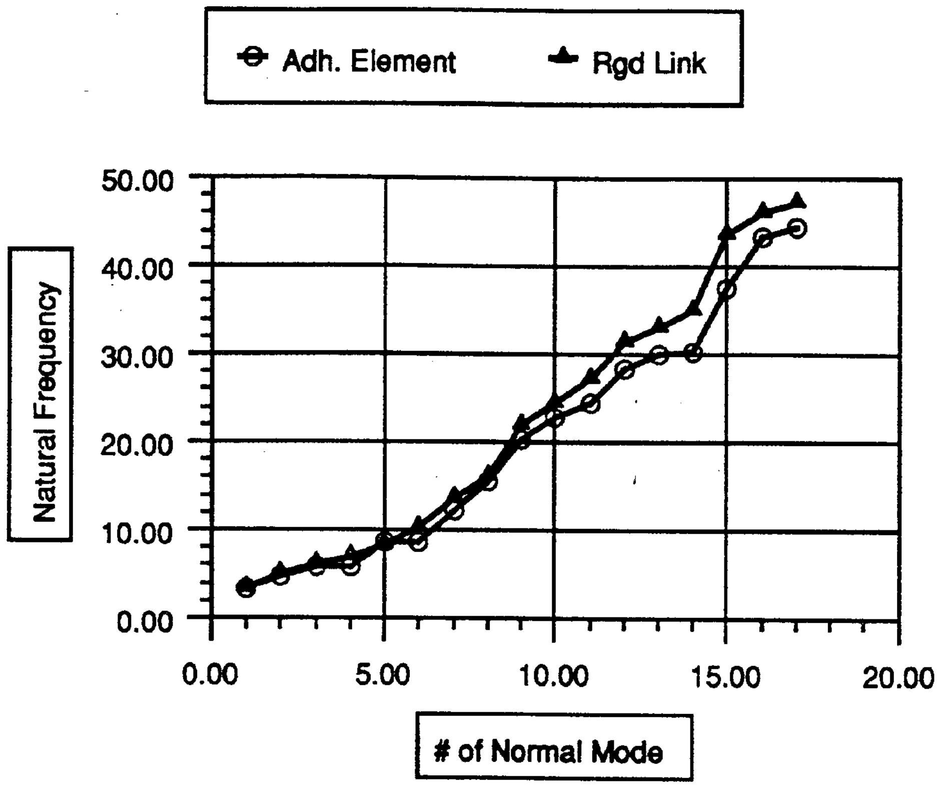

Figure 5. Comparison of Normal Mode Frequency Difference Between Two Models.

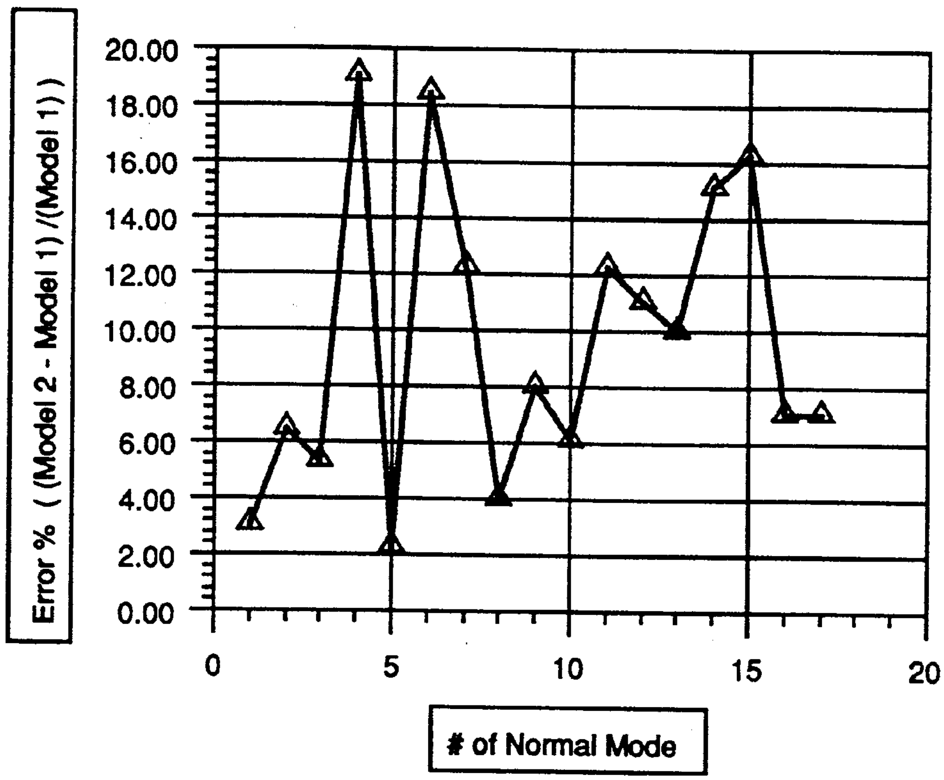

Figure 6. % Difference of Normal Mode Frequencies Below 50 Hz in Two Models.

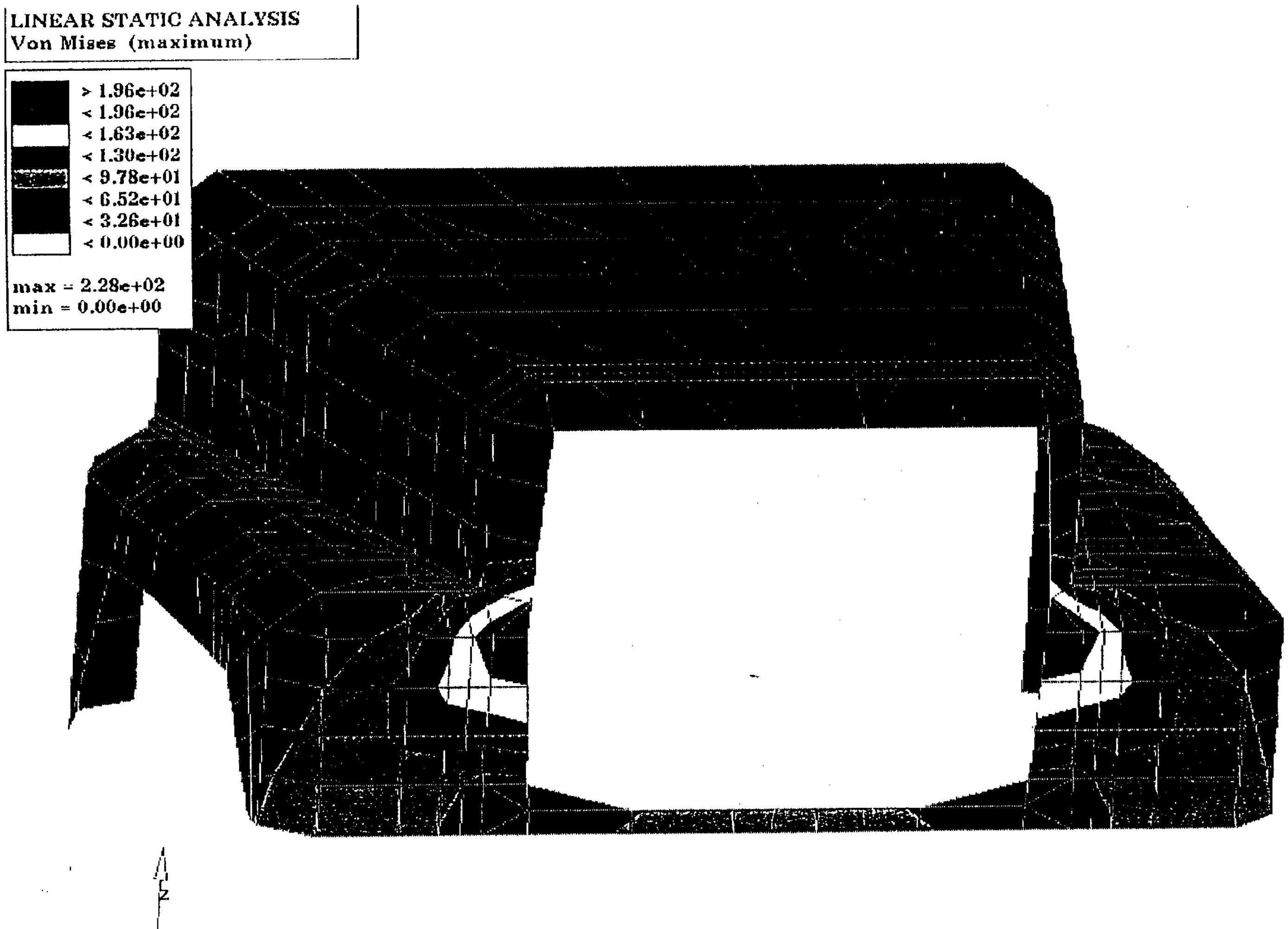

Figure 7. Maximum Von Mises Distribution in Model 1.

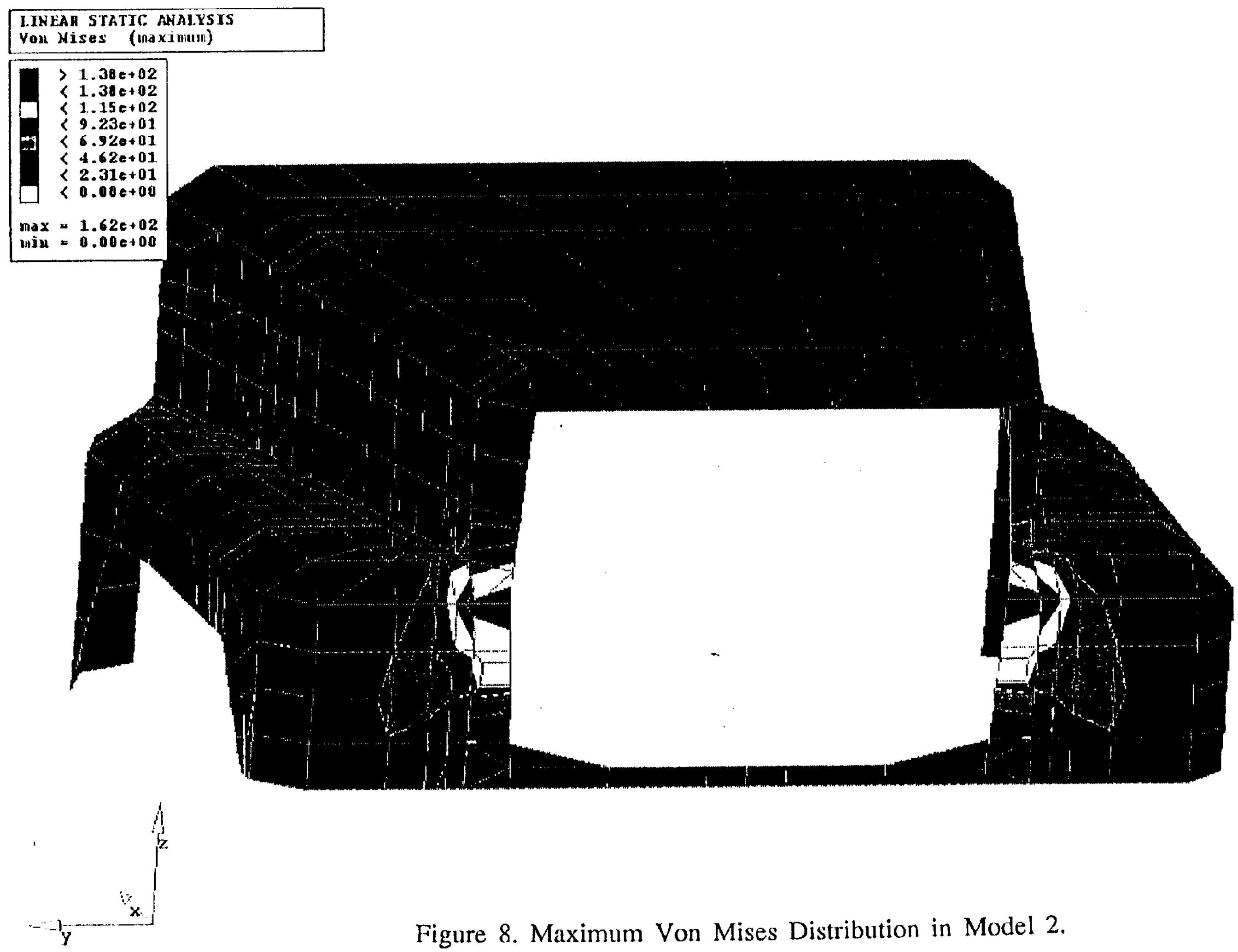

Figure 8. Maximum Von Mises Distribution in Model 2.

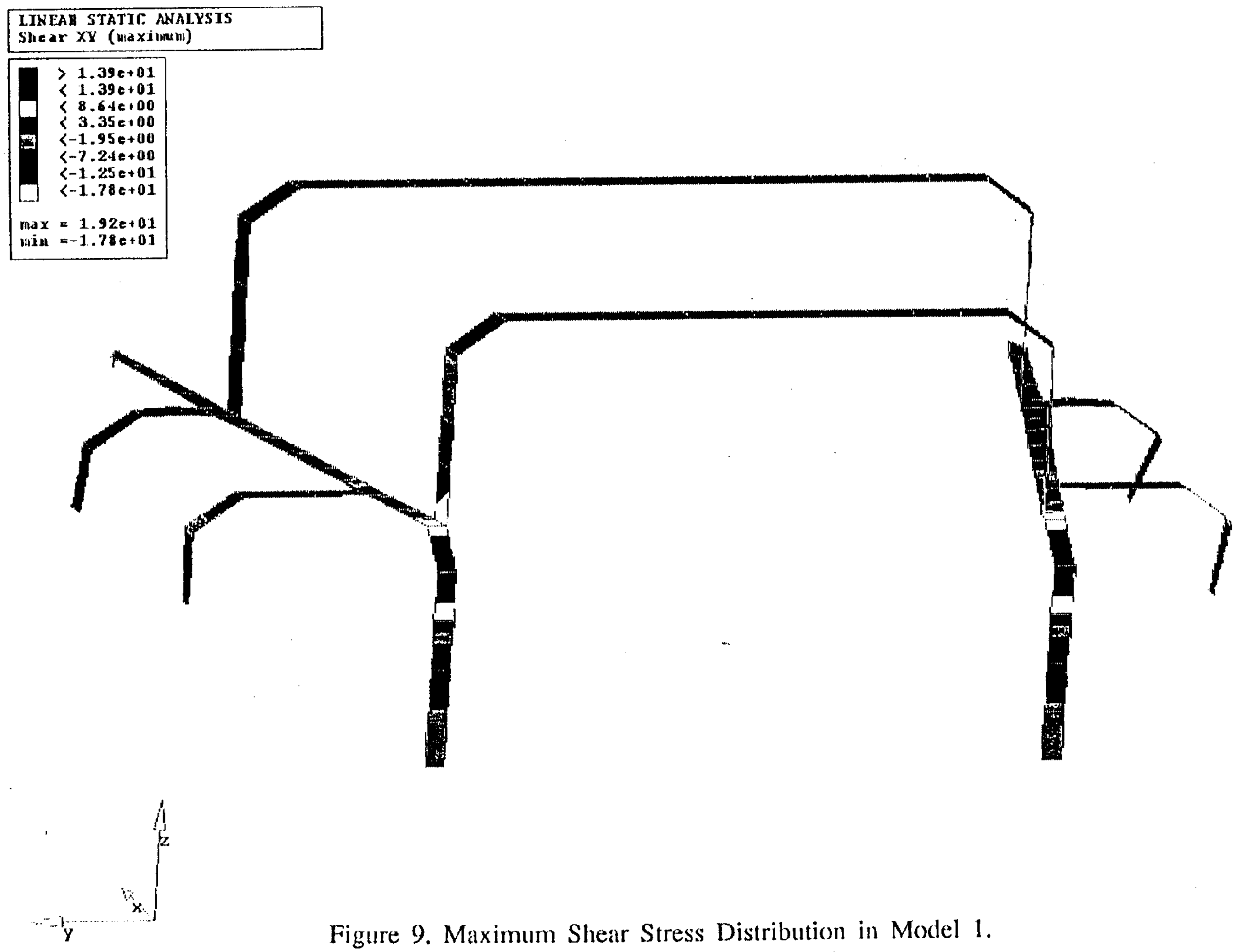

Figure 9. Maximum Shear Stress Distribution in Model 1.

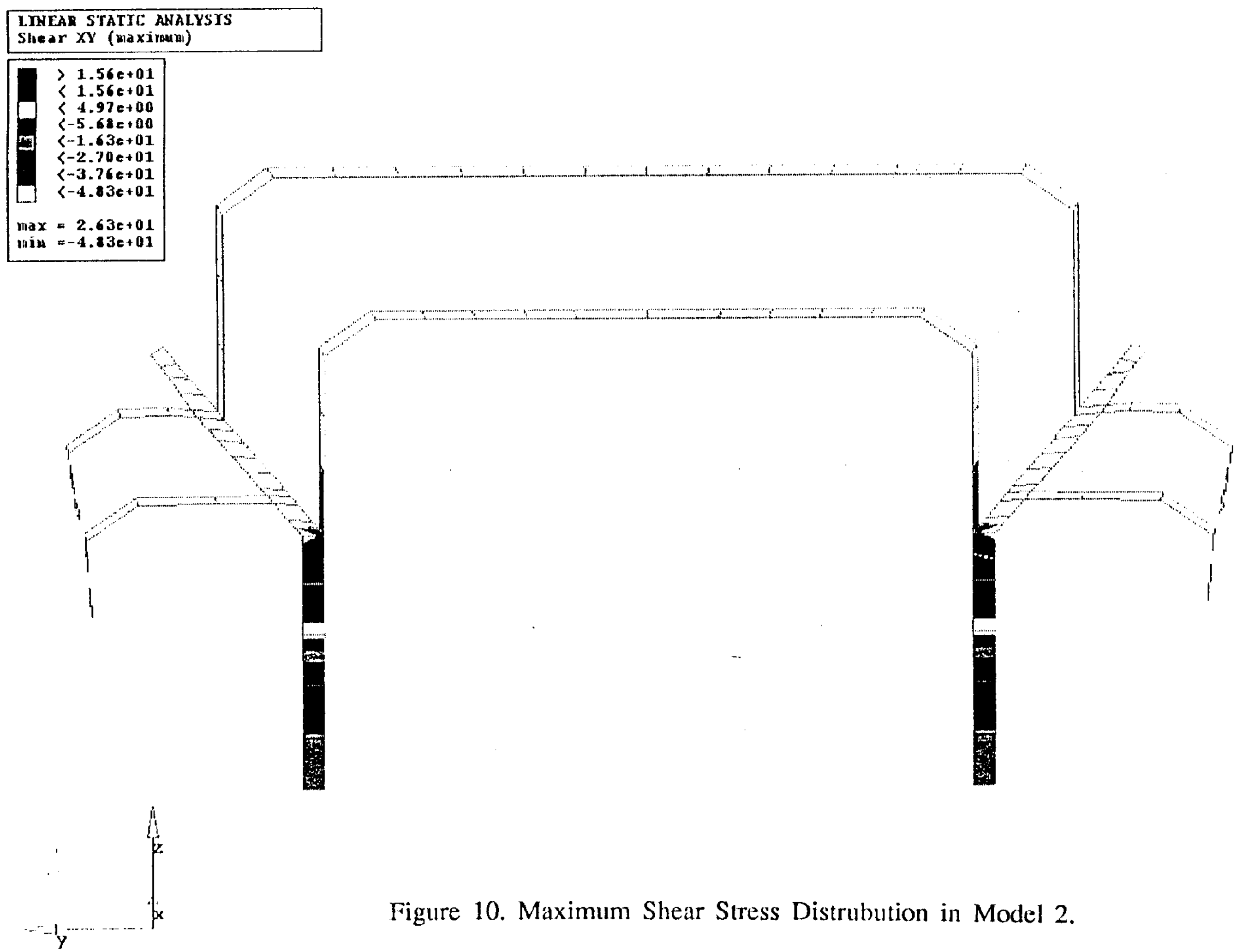

Figure 10. Maximum Shear Stress Distrubution in Model 2.