NASA Technical Memorandum 108463

Finite Element Analysis of a Composite Wheelchair Wheel Design

Rene Ortega
Marshall Space Flight Center • MSFC, Alabama

Structures and Dynamics Laboratory
Science and Engineering Directorate

National Aeronautics and Space Administration
Marshall Space Flight Center • MSFC, Alabama 35812

August 1994

TABLE OF CONTENTS

PRECEDING PAGE BLANK NOT FILMED

LIST OF ILLUSTRATIONS

LIST OF TABLES

TECHNICAL MEMORANDUM

FINITE ELEMENT ANALYSIS OF A COMPOSITE WHEELCHAIR WHEEL DESIGN

I. INTRODUCTION

This report documents the results of a finite element analysis of an innovative design for a wheelchair wheel as shown in figure 1. The designer's[1] intent is to soften the riding feeling by incorporating a mechanism attaching the wheel rim to the spokes that would allow considerable deflection upon compressive loads. The compressive loads on the wheel are created when the total weight is reacted by the ground. Upon loading, the wheel should locally flatten at the ground while maintaining round proportions everywhere else. A half of a single mechanism is shown in figure 2. This mechanism consists of a continuous Kevlar™ cloth sandwiched between glued aluminum blocks. The three pivot points shown in the figure allow the compressive deflections, while the aluminum blocks act as stops when the mechanism is loaded in tension.

Several structural areas need to be investigated in order to ensure proper and safe operation of this wheelchair design. Considerable deflection incurred by the reaction to the ground should be ensured. Also, the relative local deflection incurred by a constant weight should remain the same while the wheel is spinning in order to ensure a smooth ride. The stresses are to be low enough to prevent yielding in the metals and provide adequate fatigue life in the structure. Glued bonds are to be strong enough to prevent peeling effects. The angular deflection caused by torsional loads is to be kept to a minimum. The wheel should be rigid enough to sustain loads applied perpendicularly to the wheel face. Finally, the composite material is to be strong in tension, pliable, and resistant to potential unraveling under fatigue. The work documented here addresses some of these areas.

II. FINITE ELEMENT MODELING

The wheel shown in figure 1 was modeled using the ANSYS 5.0A[2] finite element program. A two-dimensional (2–D) finite element model was built and is shown in figure 3. A close-up of the composite mechanism and rim section is shown in figure 4. The spokes were assumed to be stiff as compared to the composite mechanism and rim, therefore, they were not modeled. The model has a total of 27,456 nodes and 30,816 elements. Each node has two degrees of freedom, ux and uy. Two ANSYS element types were used: A four-noded 2–D structural solid (PLANE42) under plane stress with thickness input, and a 2–D Point-to-Surface Contact Element (CONTAC48). The element types are pictured in figure 5 and the break up of the elements per component and corresponding material is shown in table 1.

The material properties used in the model are given in table 2. The 304 stainless steel and the aluminum 6061 T6 properties were obtained from a Rockwell International Rocketdyne Division Material Properties Manual[3] and were used directly in the model. The properties for the composite cloth were derived from composites theory. Actual properties from the manufacturer (Fibrite) were not available. Therefore, Kevlar 49™ fiber properties obtained from course material taught by Dr. Robert M. Hackett[4] were used in conjunction with a computer program called "Microdeb" developed by Dr. Hackett to calculate the properties for a uniaxial layer of a transversely isotropic composite. The values obtained from "Microdeb" were used with a "Mic-Mac Engine"[5] spreadsheet program, developed by Dr. Stephen W. Tsai of Stanford University, to obtain the matrix of elasticity constants used in the finite element model. The thickness of the cloth was specified as a nominal 20 mils by the manufacturer. Therefore, the cloth was assumed to be composed of four plies stacked at 0° and 90° since Kevlar 49™ fibers have a nominal 5-mils diameter. The assumption that the cloth is composed of plies stacked at various angles is somewhat in error because in reality the cloth is a weaved fabric. The Kevlar™ fiber volume fraction was assumed as 0.7. Table 3 shows a matrix of elastic constants for various values of fiber volume fraction. All of the above assumptions affect the model displacement and stress results. Due to the above-mentioned assumptions the model should be anchored by actual testing of a prototype wheel. It is important to note that the properties are used equally in tension and compression by the finite element code. The Kevlar 49™ cloth provides significant stiffness in tension, while none in compression. Therefore, this behavior was achieved by first running the full model under loads. The areas indicating the composite mechanism under compression were identified and the model was then run without the elements and nodes associated with those areas.

Fixed boundary conditions were imposed on the nodes where the composite mechanism would attach to the spokes. Two load cases were explored as shown in figure 3. The first load case was a force applied to the rim next to both sides of the loop where the composite mechanism is attached. The total magnitude of the load was 180 lb. The second load case consisted of the 180-lb force applied to the rim at the midpoint between two loops. This was done to test whether displacement continuity was maintained as the load is being transferred around the rim.

III. RESULTS AND DISCUSSION

The displacement and stress results for the two load cases with various configurations for the composite mechanism under compression are presented in this section.

Figures 6 and 7 show the displacement and stress results for the first load case with one missing composite mechanism that is assumed to behave under compression. The maximum displacement is only about 0.4 in. In addition, the maximum stresses denoted by A and B in figure 7 exceed yield and ultimate values. Assuming that a single missing composite mechanism is an overly stiff configuration, the results of a second analysis is shown in figures 8 and 9 where the legs denoted by Z of adjacent composite mechanisms are removed. This increased the maximum deflection to about 0.73 in causing a further increase in the stresses. A final configuration was attempted in which three composite mechanisms are missing. As shown in figures 10 and 11, displacements were in the order of 0.74 in with no alleviation of the very high stresses. It is important to note that the desired displacements were to be between 1.5 to 2 in causing stresses less than the endurance limits shown in table 2.

For the sake of completeness, three similar configurations as those discussed above were analyzed using the second load step. Additional parts of a composite mechanism are removed in each successive configuration. This second batch of finite element runs was done to investigate whether the smoothness in the deflections is maintained as the load is transferred around the rim. Results are displayed in figures 12 through 17. In each case, the deflections increased and the stresses decreased as compared to the load step I results. However, stresses are still above yield and ultimate. In addition, it is inconclusive whether the actual "ride feeling" is affected by the second load step, because an additional number of composite mechanism sections are removed as compared to the first load step.

At the request of the designer, a final set of analyses was conducted by modifying the existing model. The modifications consisted of adding an additional rim loop at the midpoint between composite mechanisms as shown in figures 18 and 20. The goal was to redistribute stresses among loops and increase maximum deflections. Only the first load step with a single composite mechanism removed was pursued. As shown in figures 18 and 19, deflections increased only marginally and stresses remained very high. For the case shown in figures 20 and 21, the deflections doubled but the stresses were still unacceptable.

Very little can be said with certainty about the durability of the composite mechanism, except for a high potential for debonding of the aluminum blocks from the Kevlar™ cloth. The reasons for this uncertainty are the numerous assumptions used to model the cloth as discussed in section II. However, the stiffness offered by the modeled composite mechanism under tension loads is expected to be reasonable.

IV. CONCLUSIONS

A finite element analysis of a composite wheelchair wheel was conducted. Results indicate that a metal rim would not be able to sustain operating loads due to the large deflections incurred. In the best of scenarios and if a high strength superalloy was used for the rim, a fatigue problem would remain. Therefore, it is recommended that an alternate nonmetallic and flexible material rim design be pursued for this application.

The main purpose of the composite cloth is to provide flexibility under compression. This is achieved at the three pivot points shown in figure 2. Due to the high potential of debonding between the Kevlar™ cloth and the aluminum blocks, it is recommended that the cloth be restricted to the joints attaching solid aluminum blocks. This could be achieved by using a pin and clevis type of joint. Also, manufacturing costs would be reduced by eliminating gluing operations.

In a recent article[6] by Machine Design Magazine, a nonpneumatic tire with shock-absorbing qualities was described. The tire was designed for caster wheel use by Uniroyal Goodrich Tire Co. This is an all rubber tire which might be applicable for use in a wheelchair wheel.

Table 1. Finite element model description.

Model Section	Element Type	Number of Elements	Material Type
Rim	Plane 42	2,304	304 Stainless
Aluminum Blocks	Plane 42	14,592	6061-T6 Aluminum
Composite Mechanism	Plane 42	8,800	Kevlar 49™ Cloth
Contact Areas	Contact 48	5,120	———

Table 2. Material properties.

Property	304 Stainless (Global Coordinates)	6061 T6 Aluminum (Global Coordinates)	Kevlar 49™ Cloth (Element Axis Coordinates)
Young's Modulus-E_x (Msi)	29	10	6.3
Young's Modulus-E_y (Msi)	29	10	6.3
Young's Modulus-E_z (Msi)	29	10	6.3
Poisson's Ratio-ν_{xy}	0.28	0.33	6.46e-7
Poisson's Ratio-ν_{xz}	0.28	0.33	6.46e-7
Poisson's Ratio-ν_{yz}	0.28	0.33	0.3
Shear Modulus-G_{xy} (Msi)	11.3	3.76	6.095e-6
Shear Modulus-G_{xz} (Msi)	11.3	3.76	6.095e-6
Shear Modulus-G_{yz} (Msi)	11.3	3.76	2.42
Yield Strength (Msi)	30	35	
Ultimate Strength (Msi)	75	42	
Endurance (Msi)	17-34	20	

Table 3. Kevlar 49™ cloth computed material properties.

Fiber Volume Fraction - x is longitudinal axis z is transverse axis Using Model Coord. System	0.4	0.5	0.6	0.7 (Used in FEM Model)
Young's Modulus-$E_{11} = E_x$ (Msi)	3.6	4.5	5.4	6.3
Poisson's Ratio-$\nu_{12} = \nu_{xy}$	2.46e-6	1.59e-6	1.03e-6	6.46e-7
Shear Modulus-$E_{66} = G_{xy}$ (lb/in^2)	13.71	10.93	8.41	6.095
G_{yz} (Msi) ($\nu_{yz} = 0.3$)	1.38	1.73	2.08	2.42
G_{yz} (Msi) ($\nu_{yz} = 0.5$ -not used)	1.2	1.5	1.8	2.1
Assumptions: Fiber Data: $E_{xx} = 18e6$ $E_{zz} = 0.8e6$ Fictitious matrix: $E = 100$ $\nu = 0.34$	$E_z = E_y = E_x$ $\nu_{xz} = 0.32$	$\nu_{xy} = \nu_{xz}$ $\nu_{zz} = 0.35$	$G_{xy} = G_{xz}$ $G_{xz} = 0.4e6$	$G_{zz} = 0.296e6$

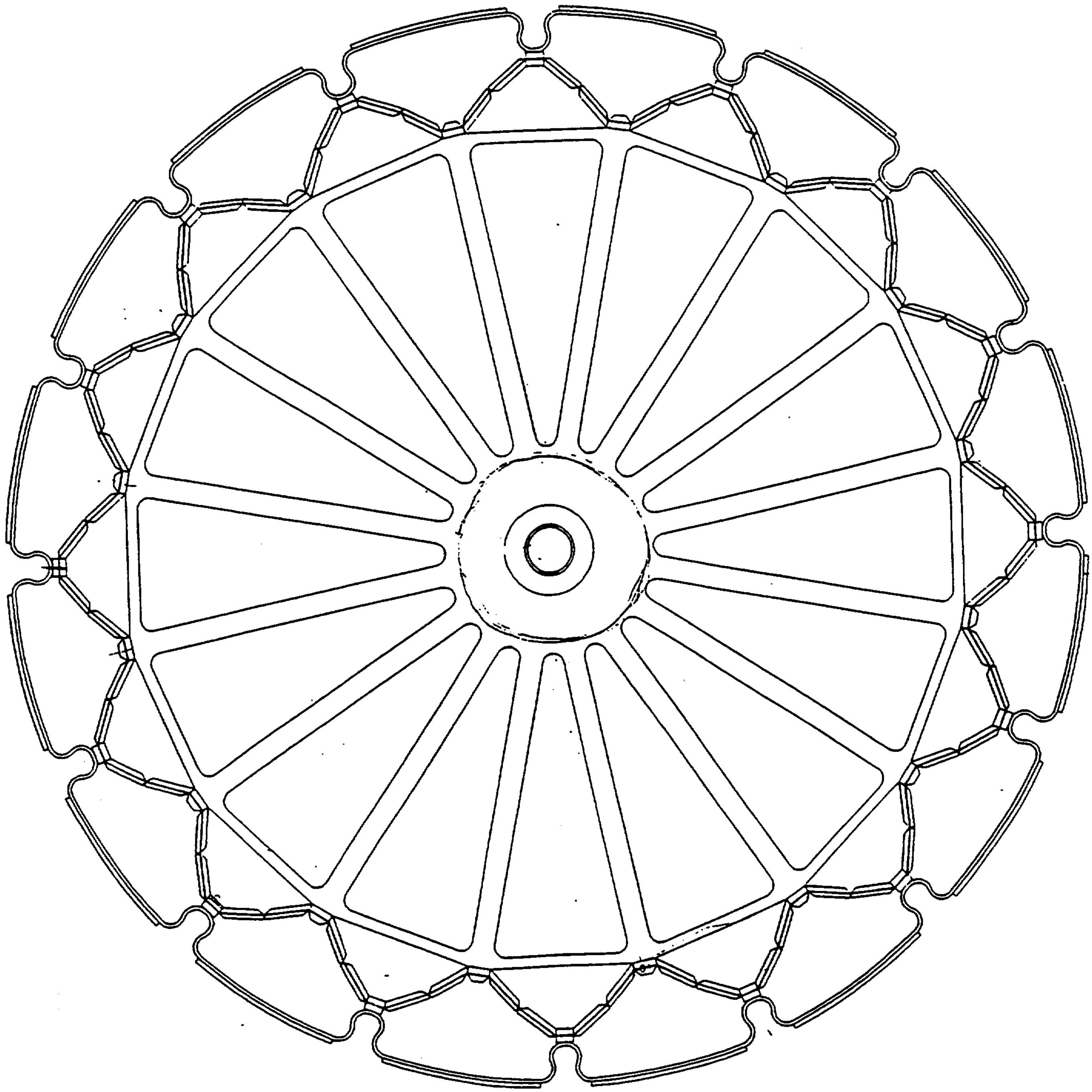


Figure 1. Composite wheelchair wheel design.

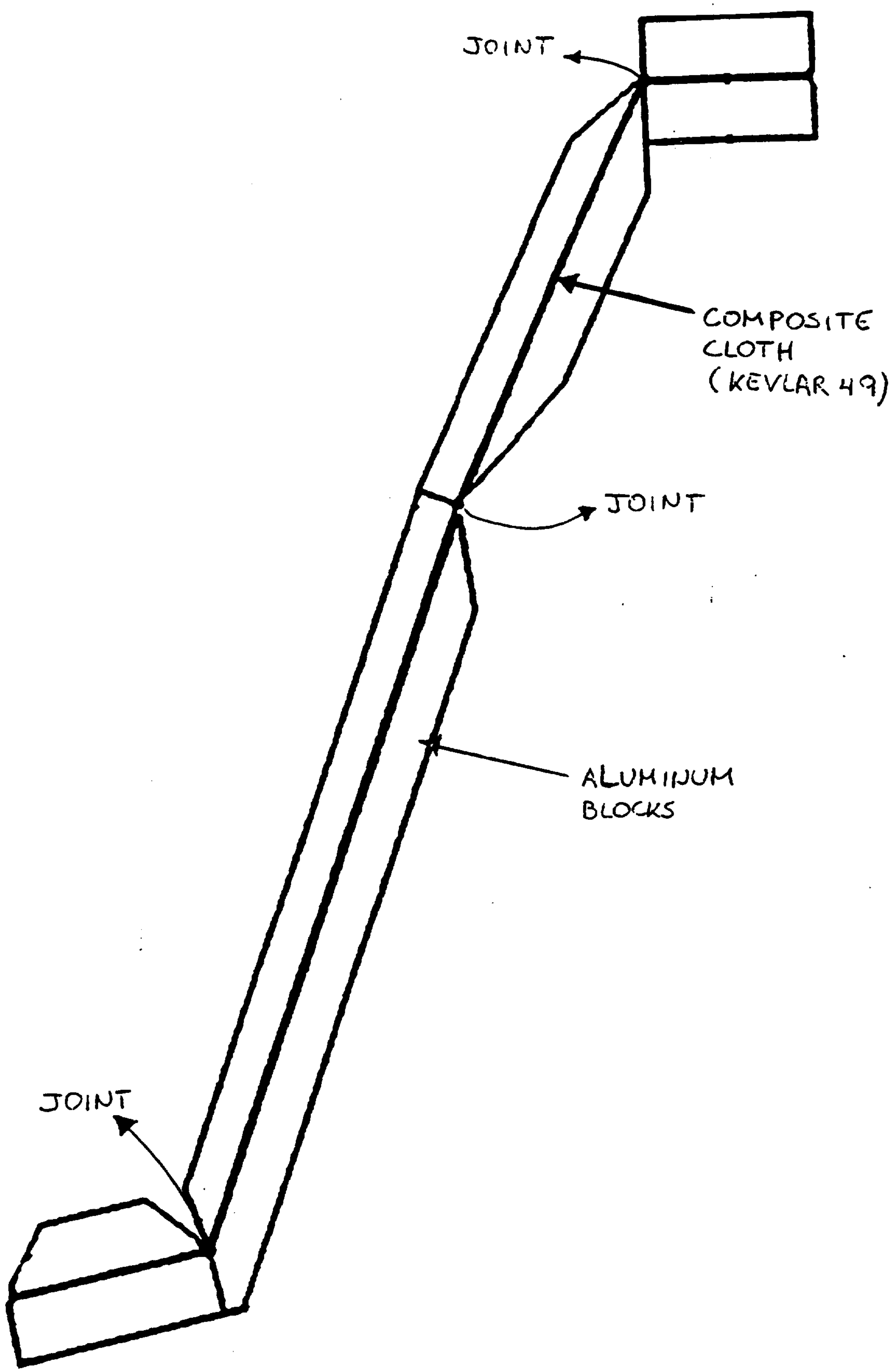


Figure 2. Left half of one composite mechanism.

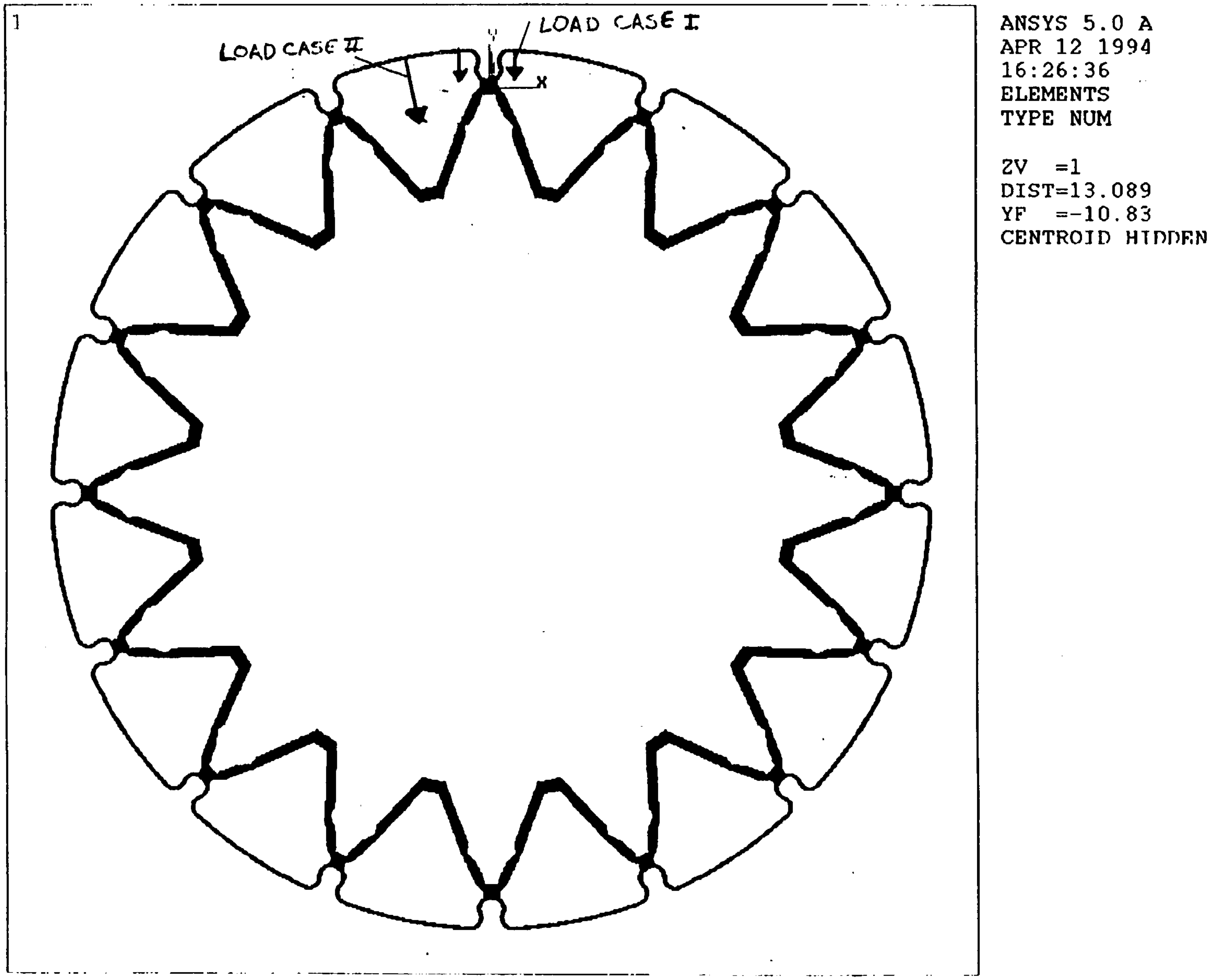


Figure 3. Finite element model of composite wheel.

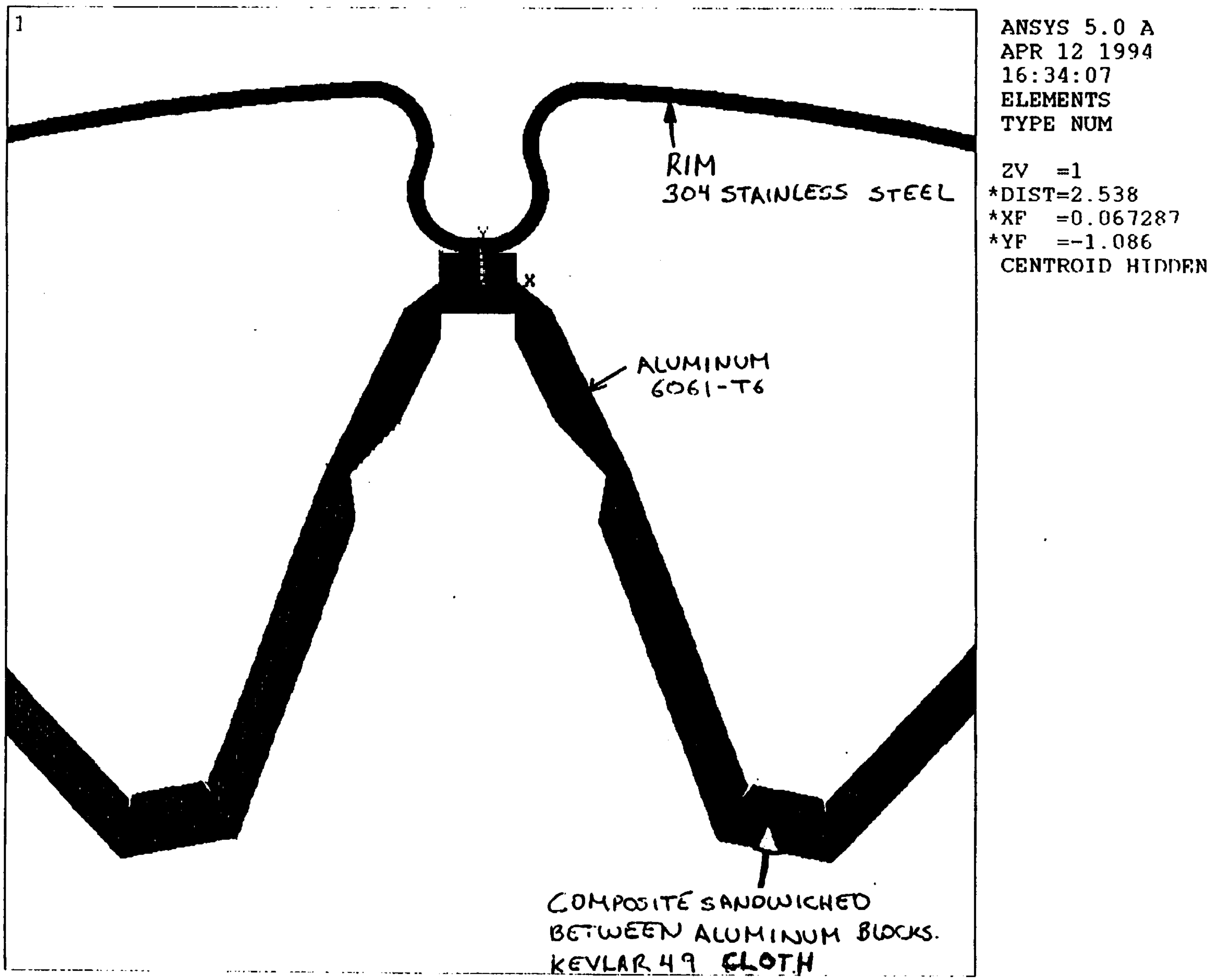
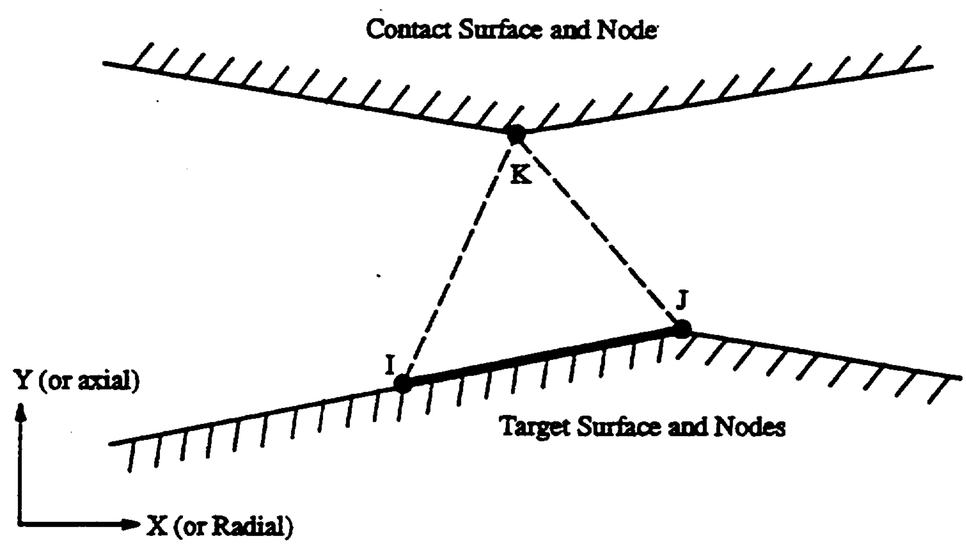
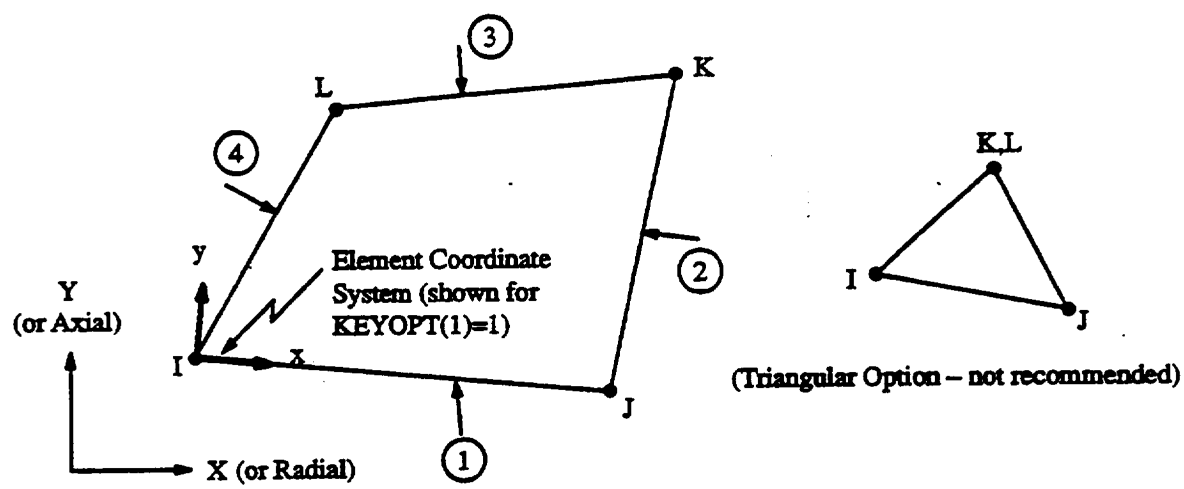


Figure 4. Close-up of composite mechanisms and rim section of model.



A. Contac48 2–D point-to-surface contact element.



B. Plane42 2–D structural solid.

Figure 5. Finite element types representation.

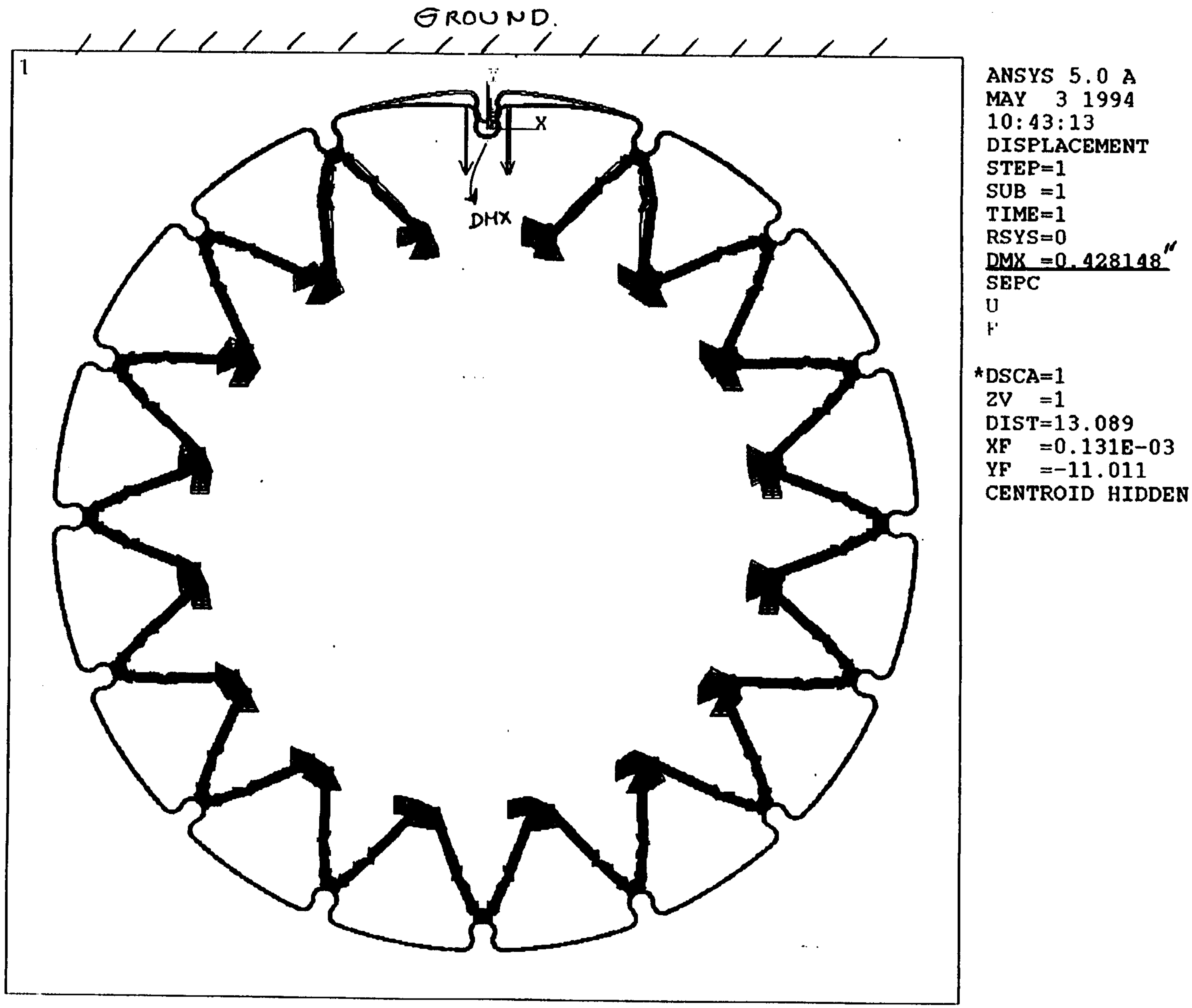


Figure 6. Displacement results—first load step and one missing mechanism.

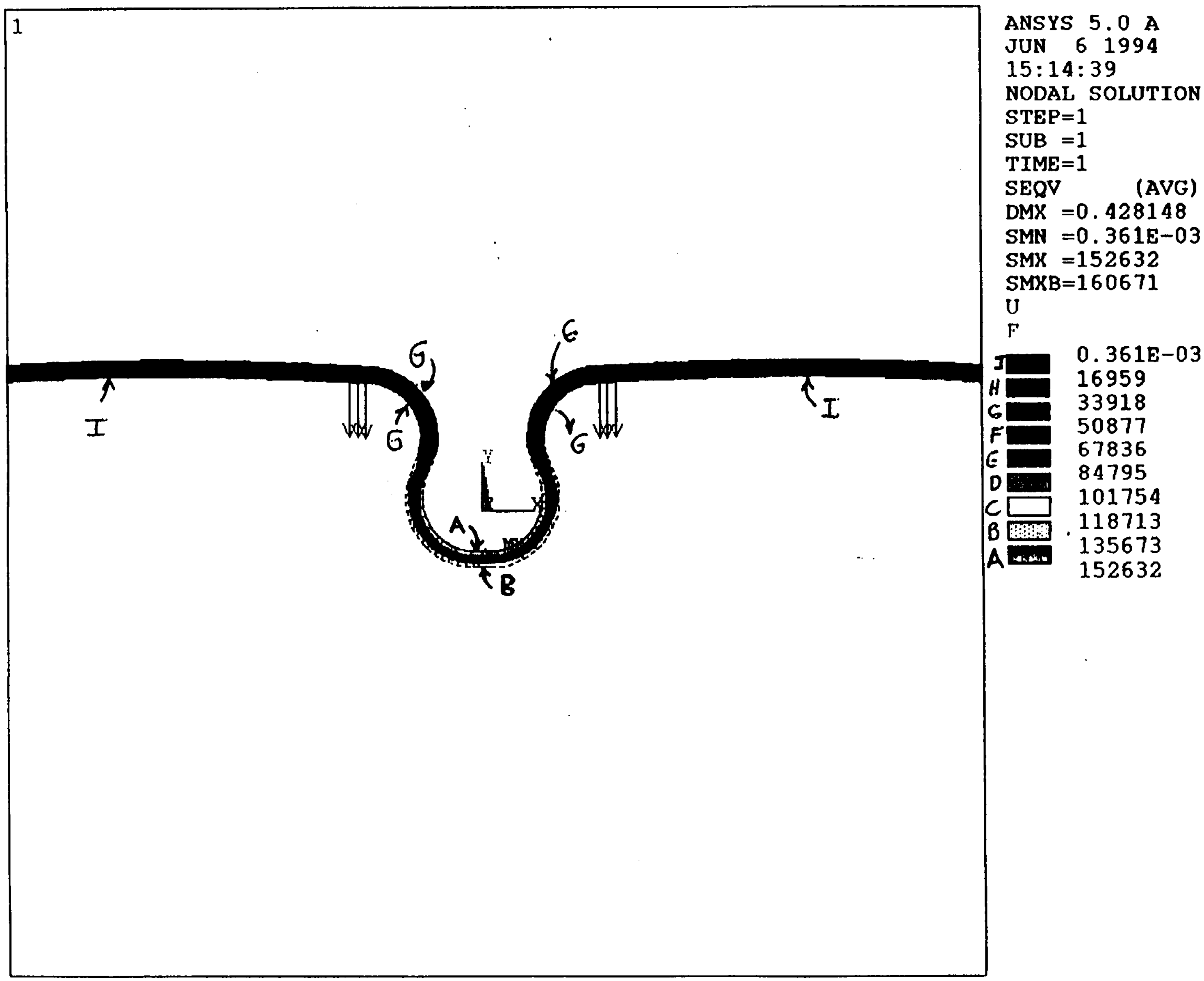


Figure 7. Stress results—first load step and one missing mechanism.

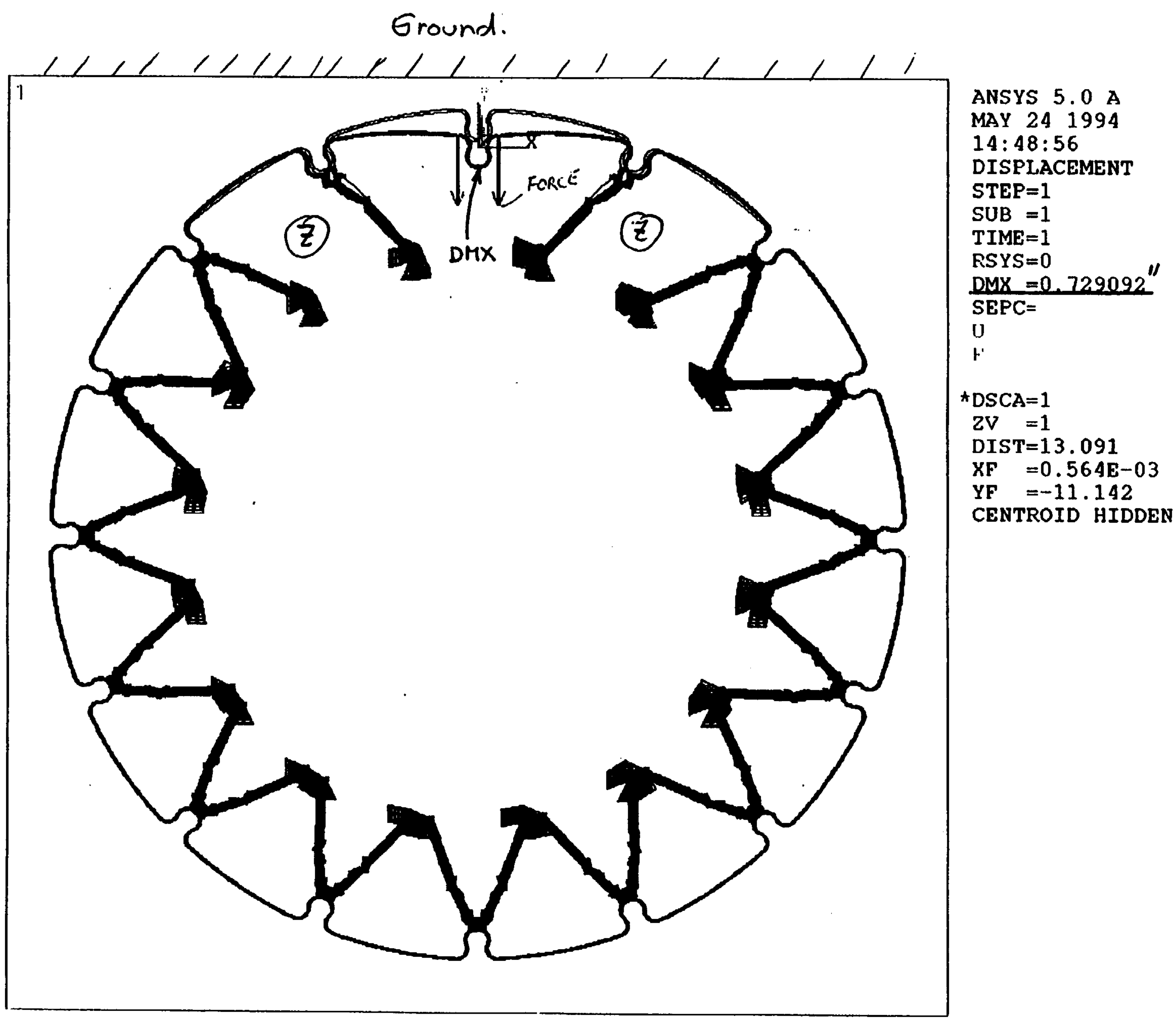


Figure 8. Displacement results—first load step and 1+Z missing mechanisms.

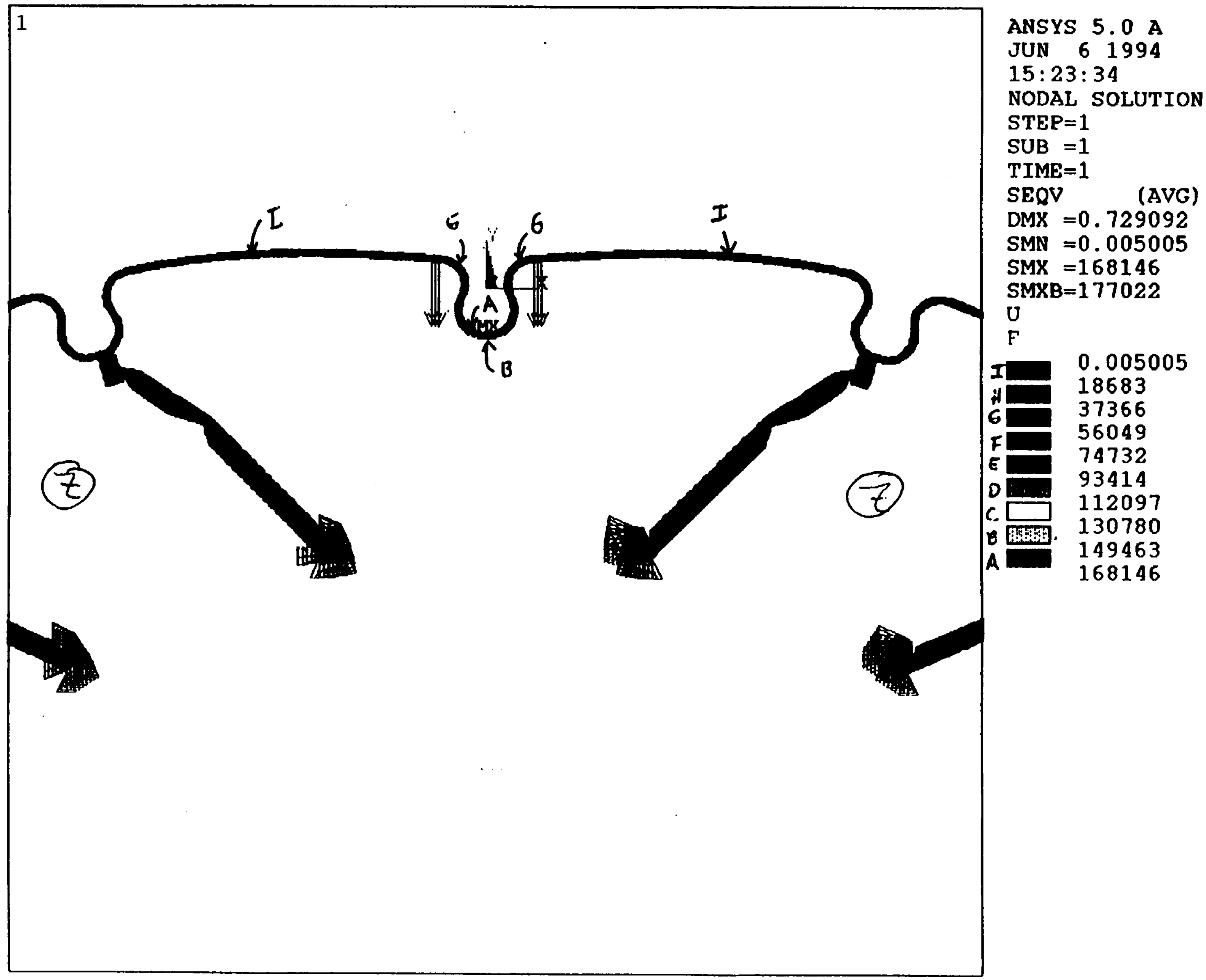


Figure 9. Stress results—first load step and 1+Z missing mechanisms.

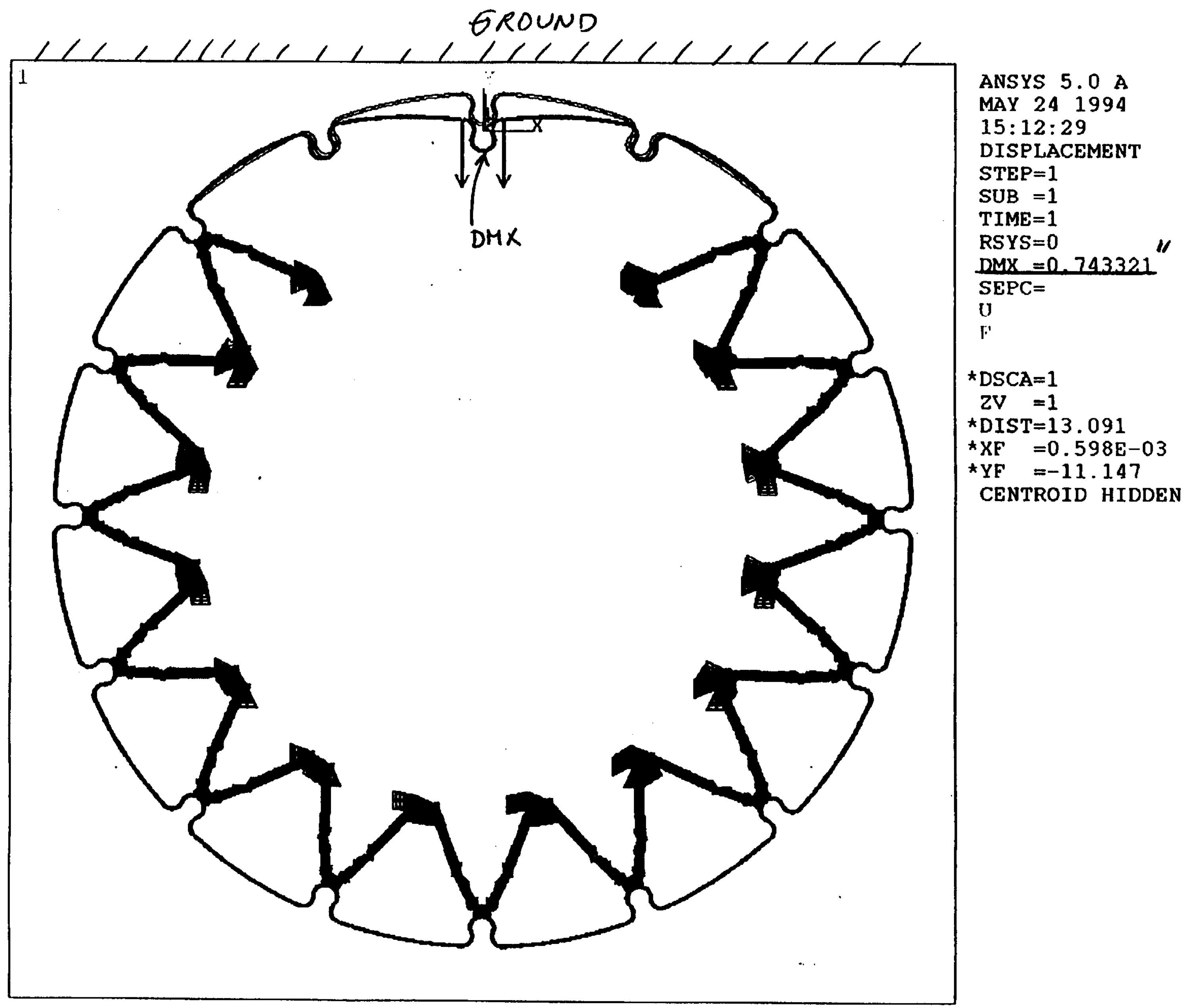


Figure 10. Displacement results—first load step and three missing mechanisms.

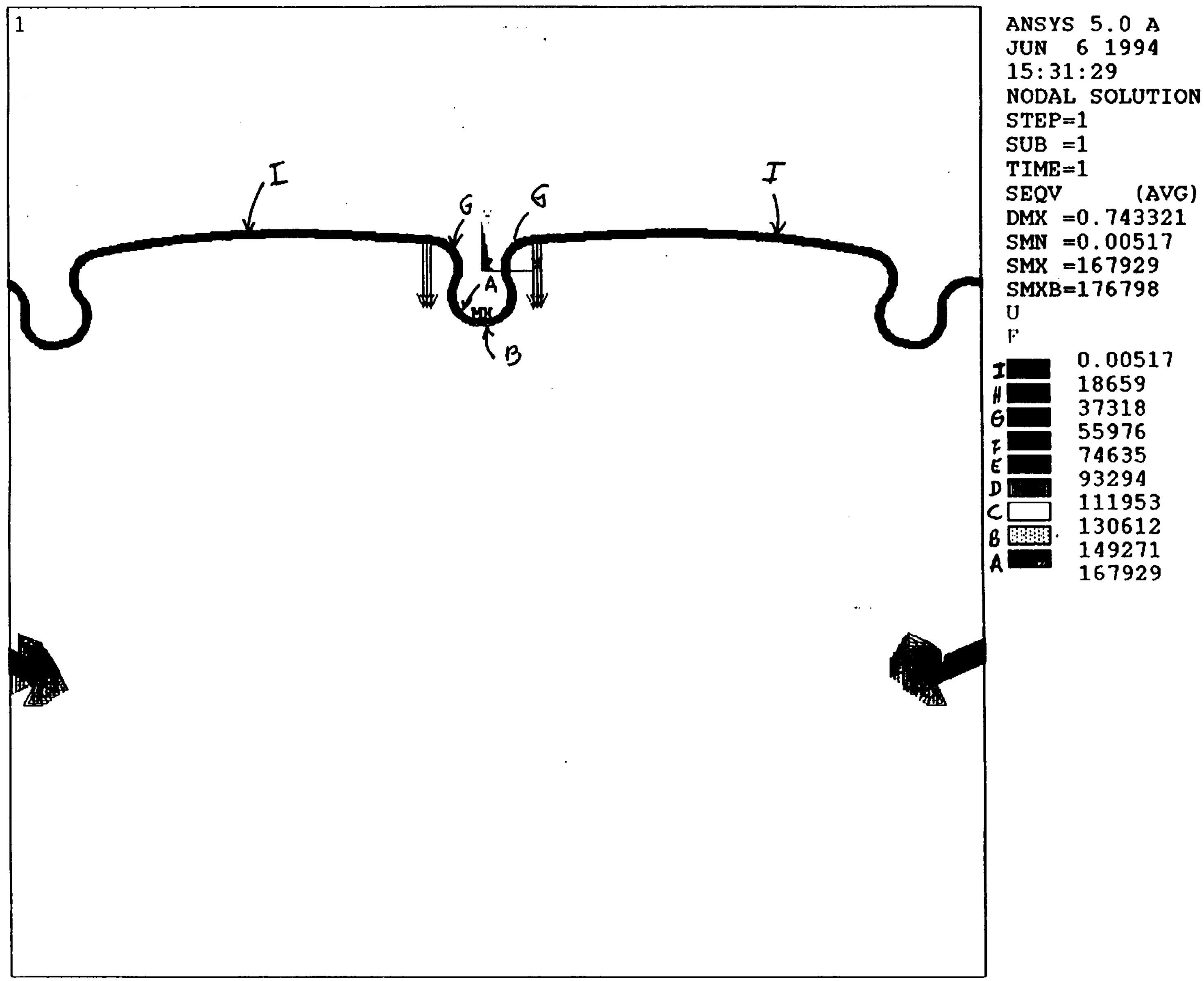


Figure 11. Stress results—first load step and three missing mechanisms.

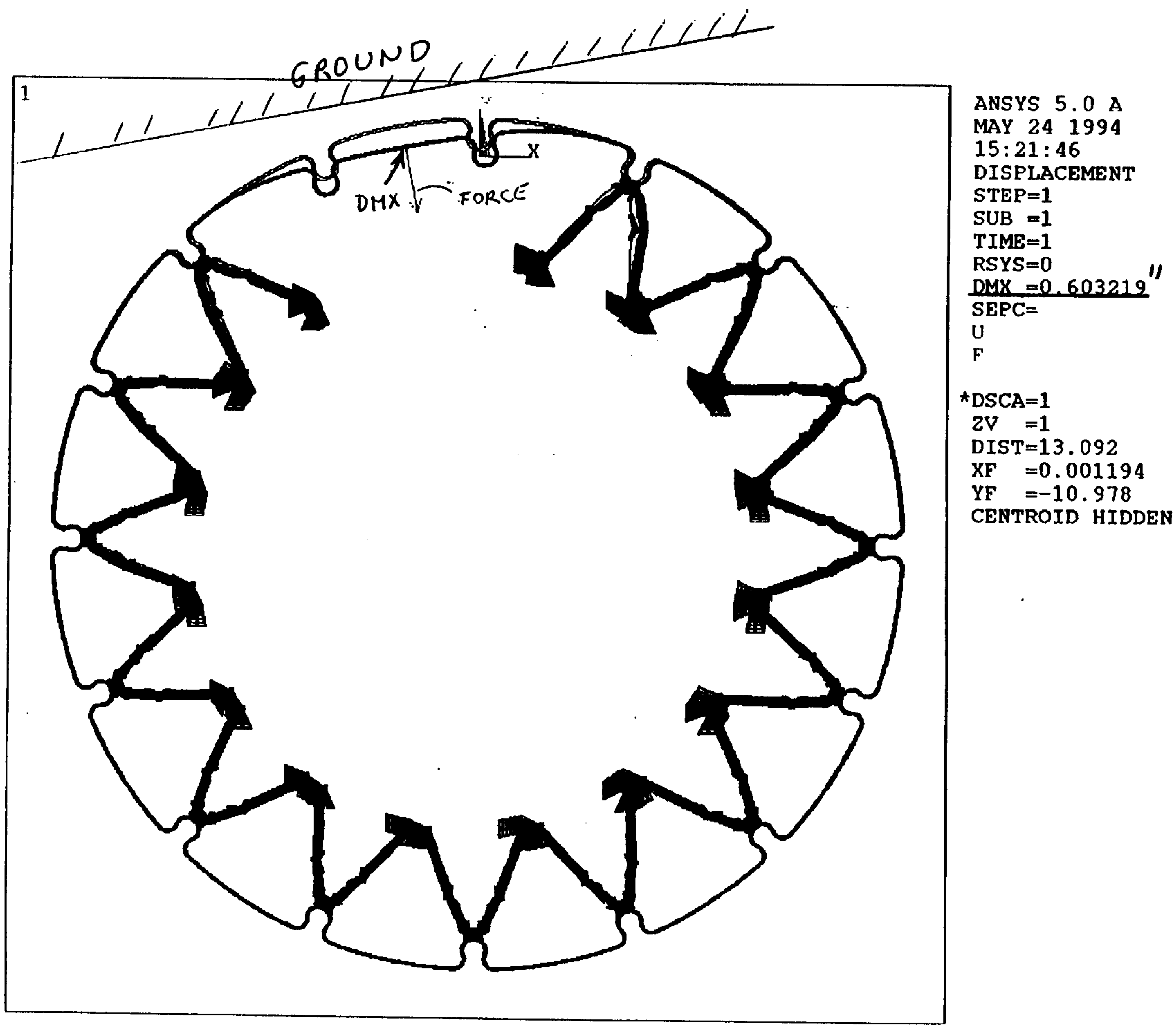


Figure 12. Displacement results—second load step and two missing mechanisms.

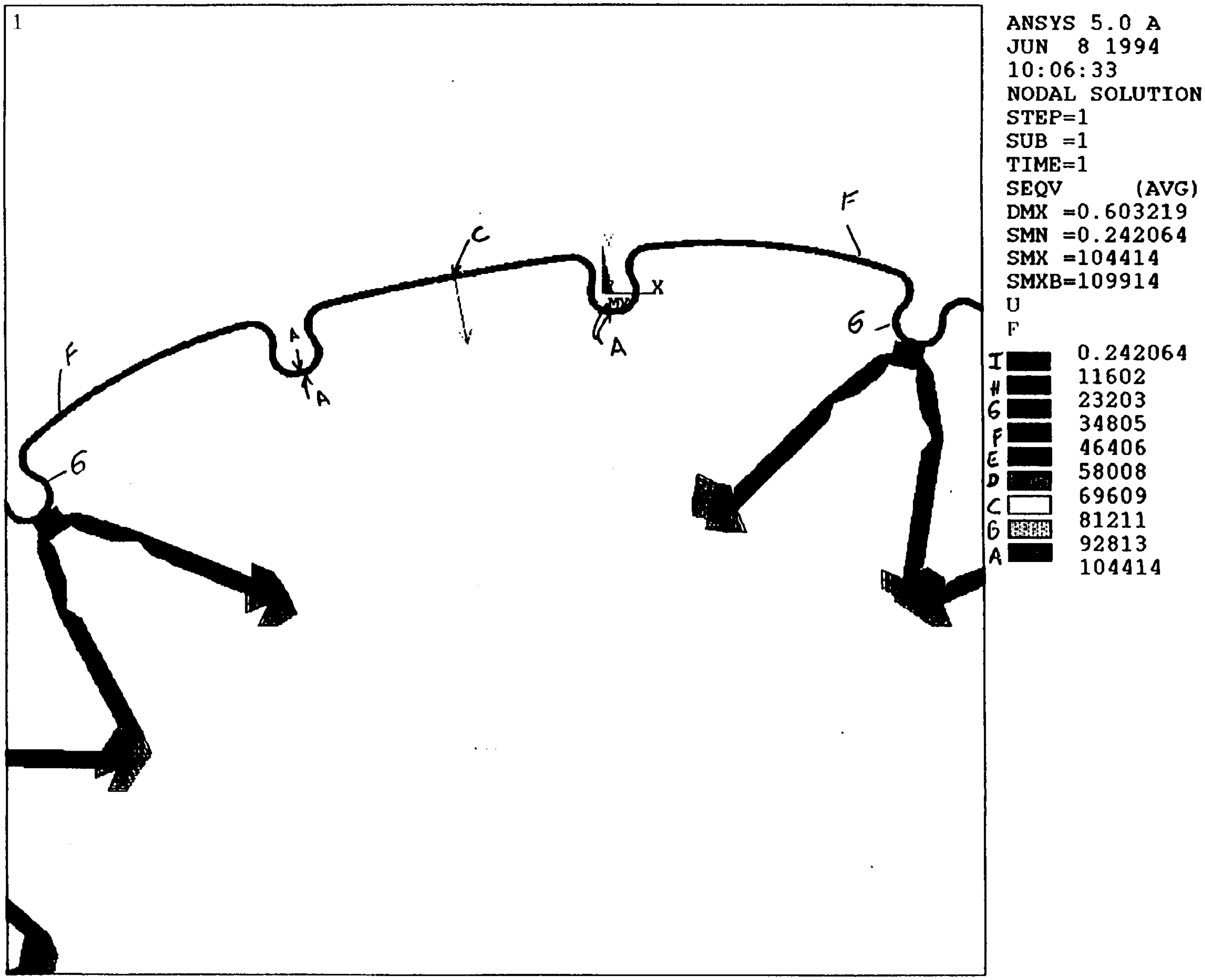


Figure 13. Stress results—second load step and two missing mechanisms.

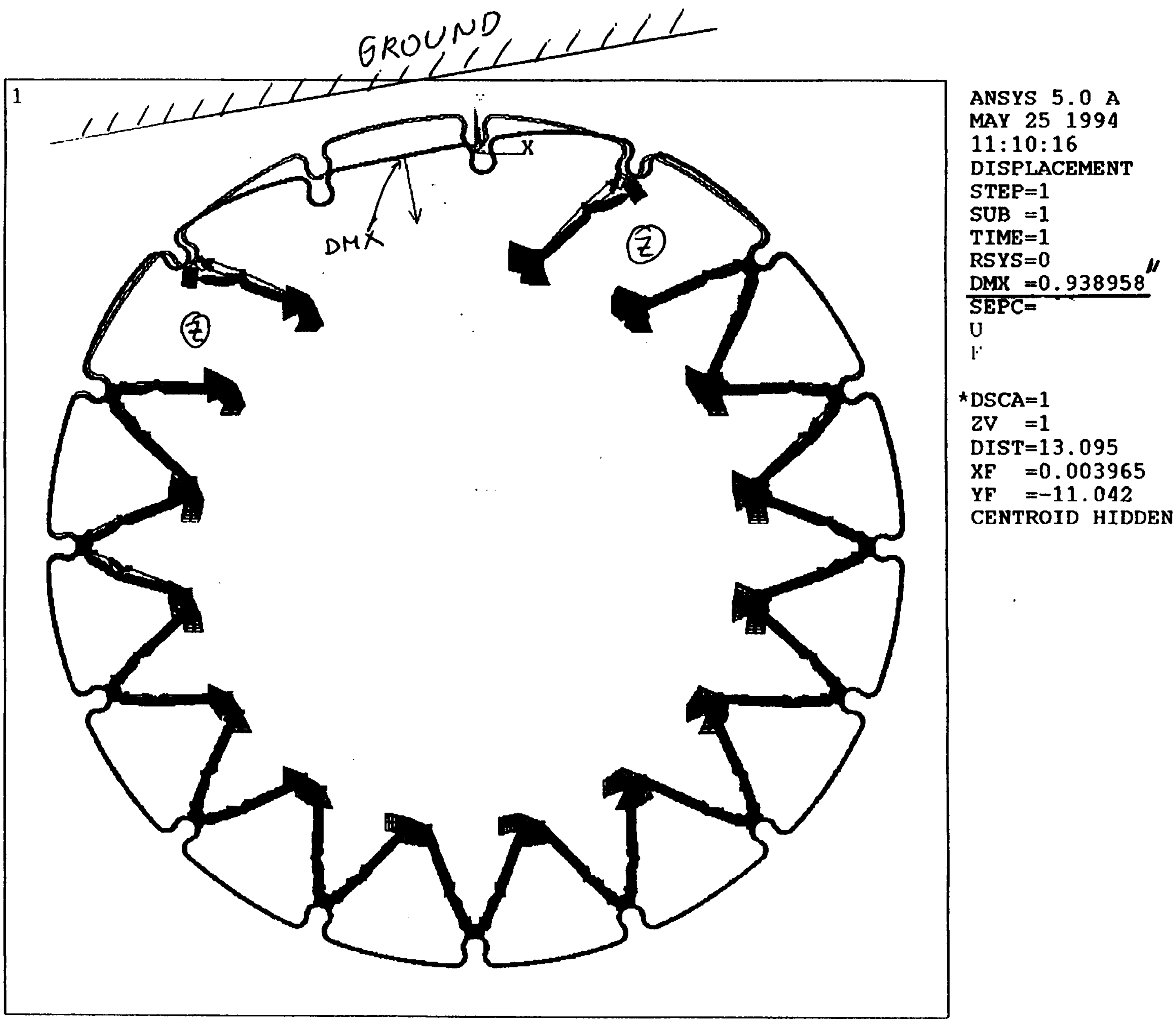


Figure 14. Displacement results—second load step and 2+Z missing mechanisms.

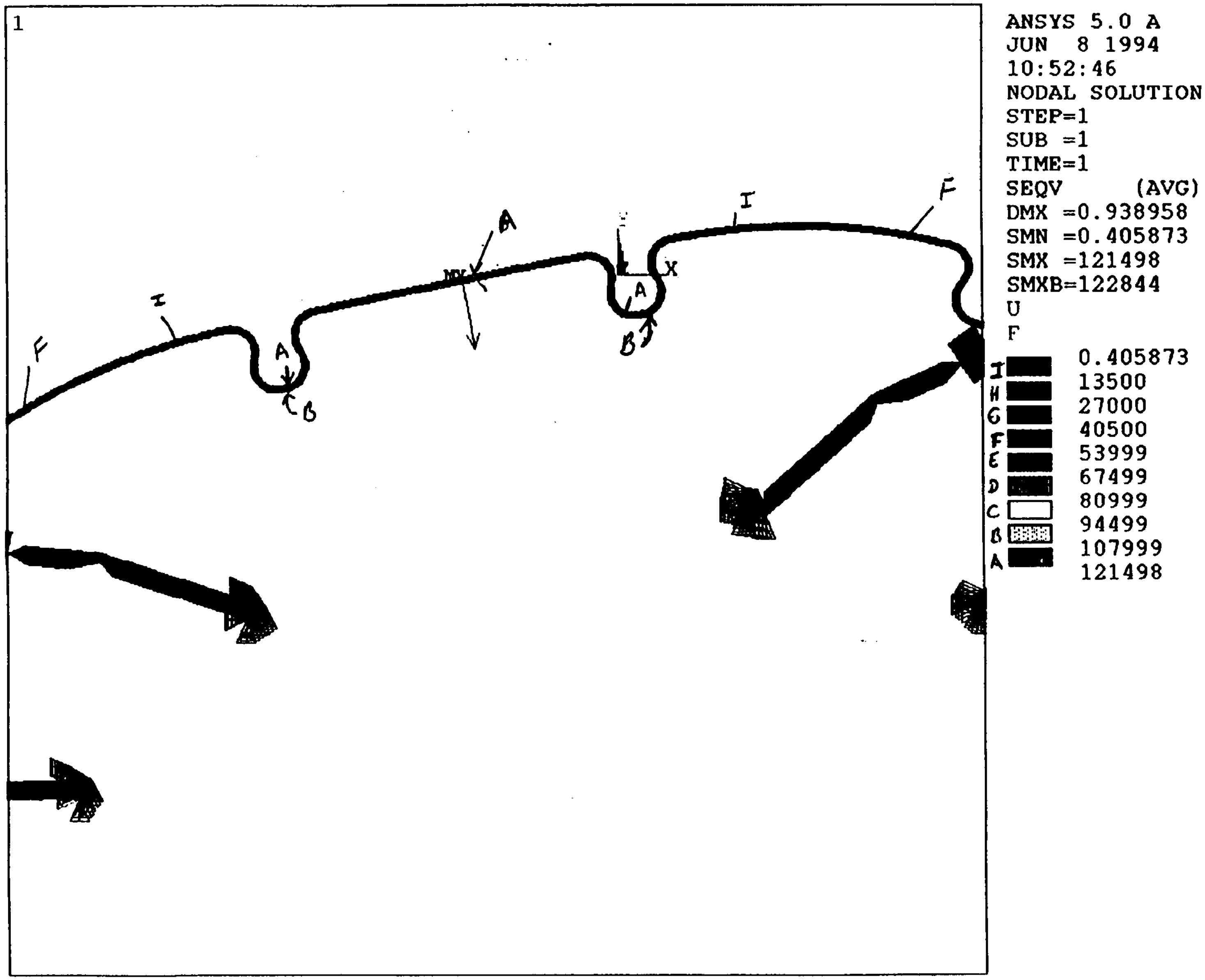


Figure 15. Stress results—second load step and 2+Z missing mechanisms.

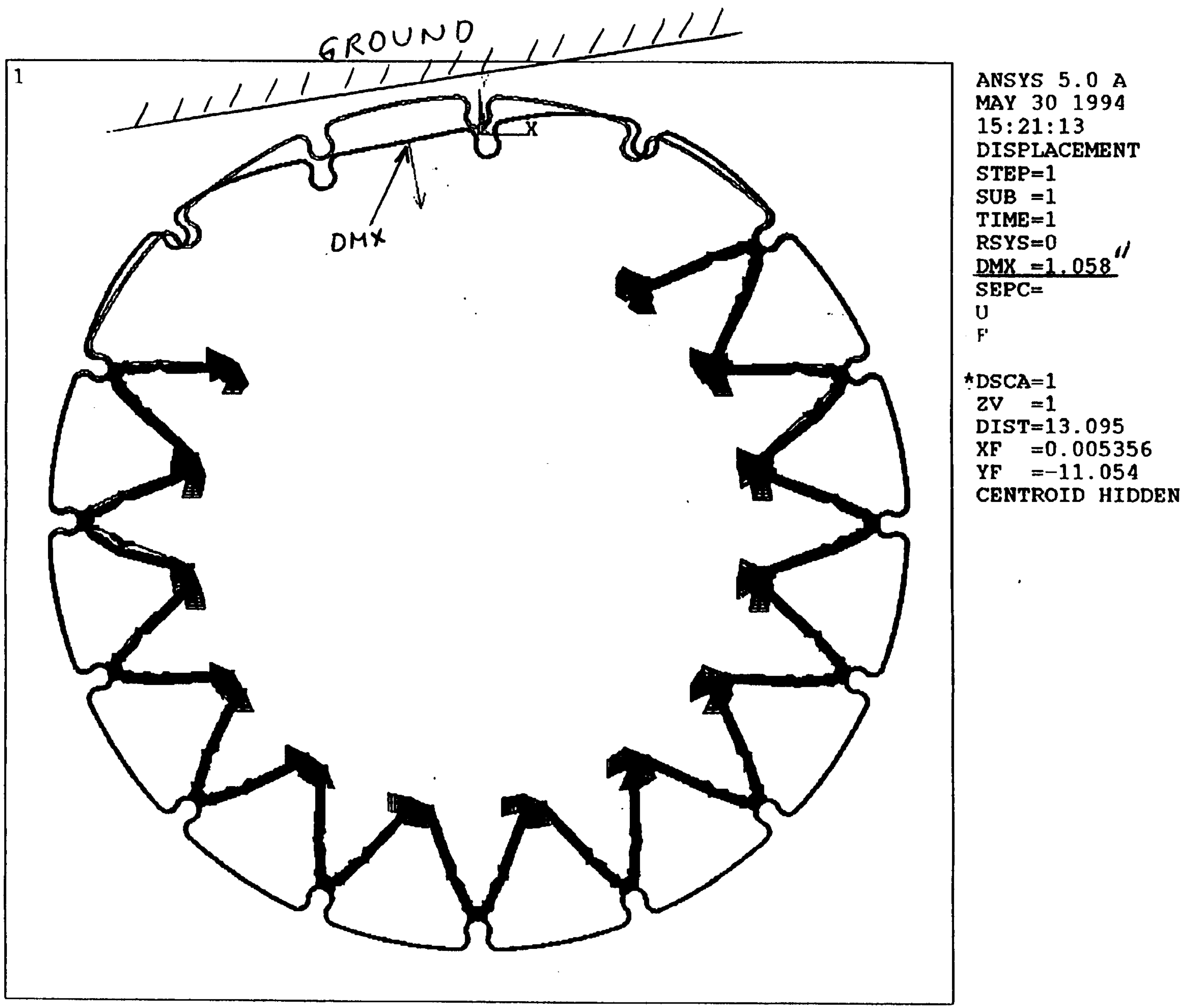


Figure 16. Displacement results—second load step and four missing mechanisms.

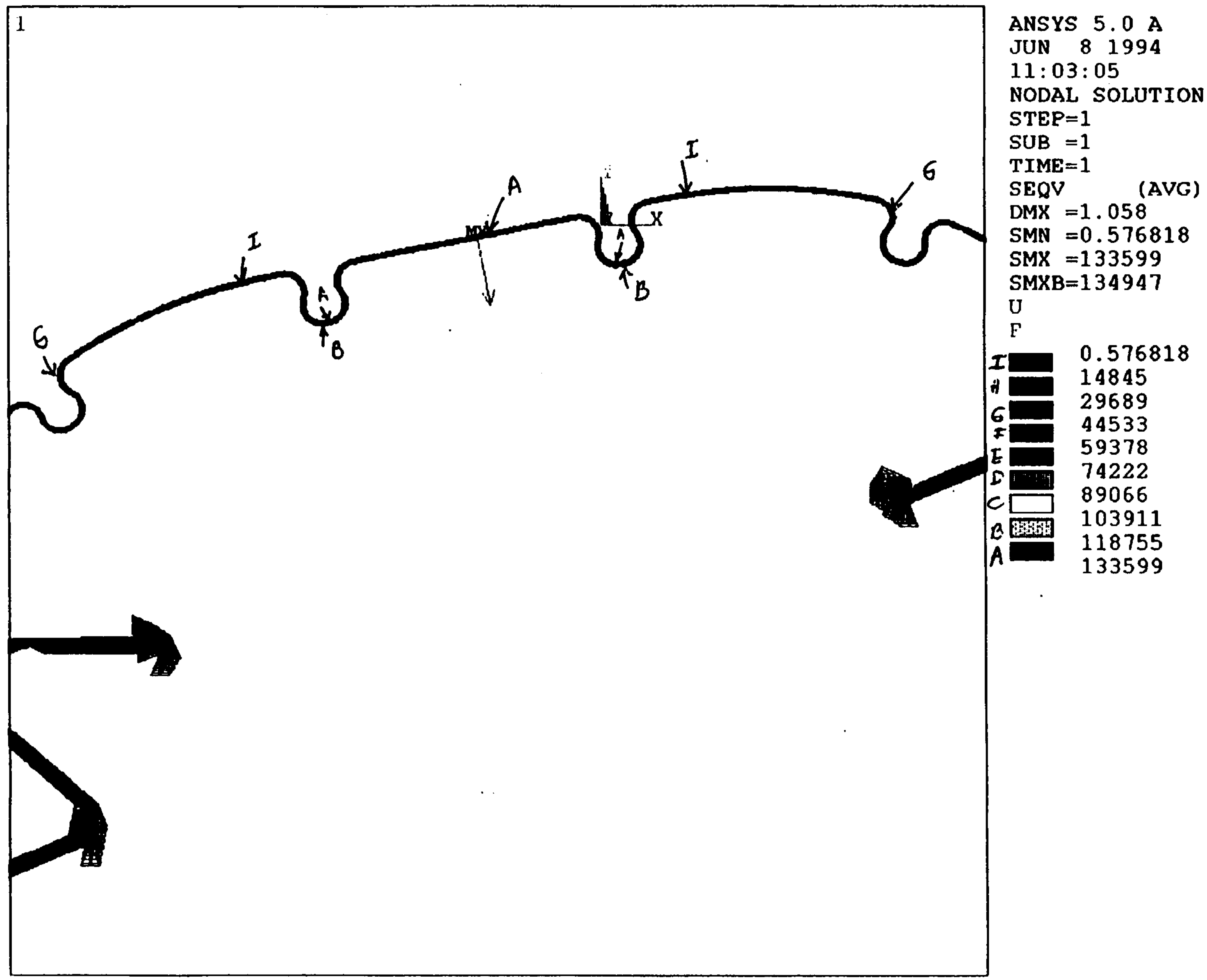


Figure 17. Stress results—second load step and four missing mechanisms.

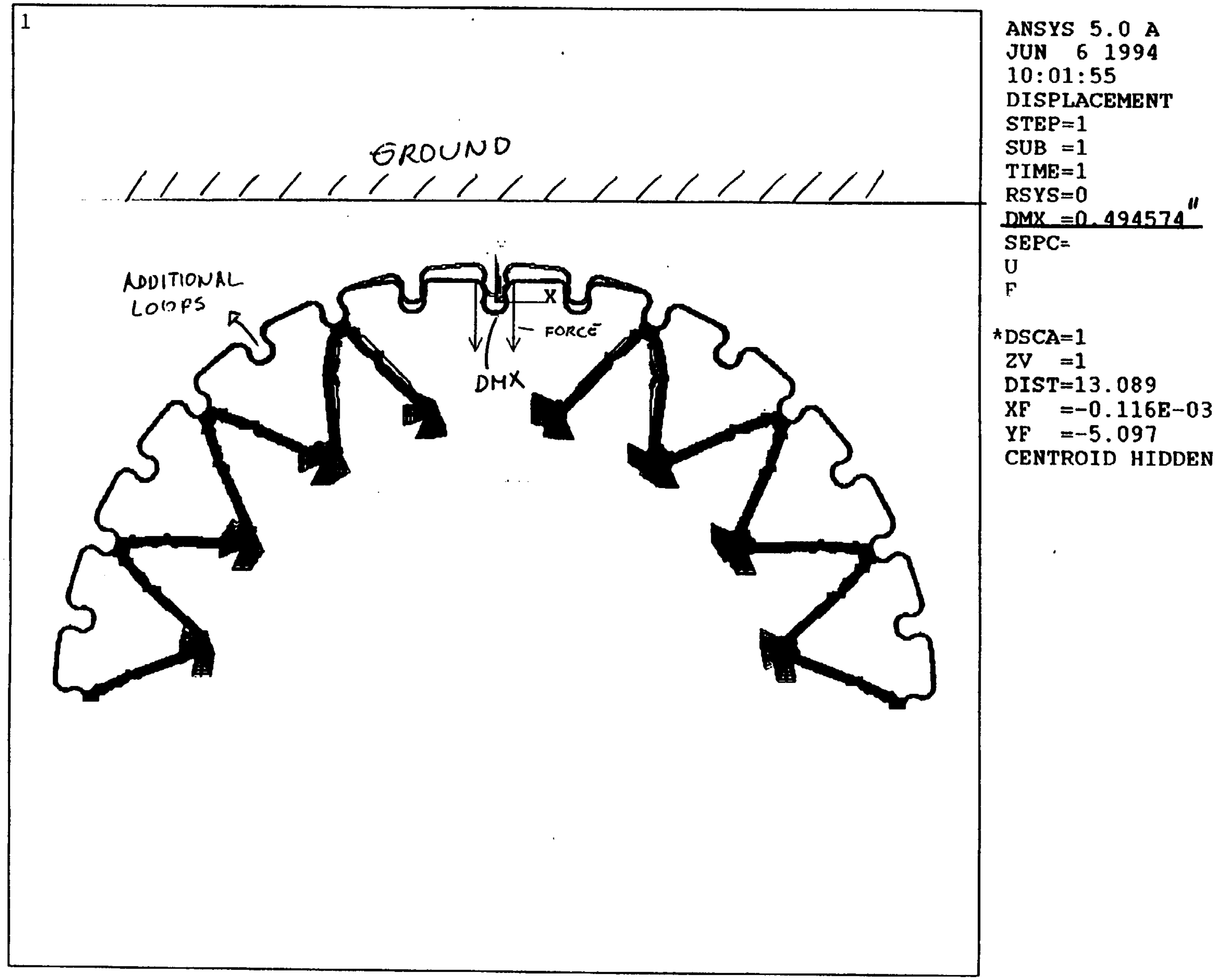


Figure 18. Displacement results—first mod. model—first load step and one missing mechanism.

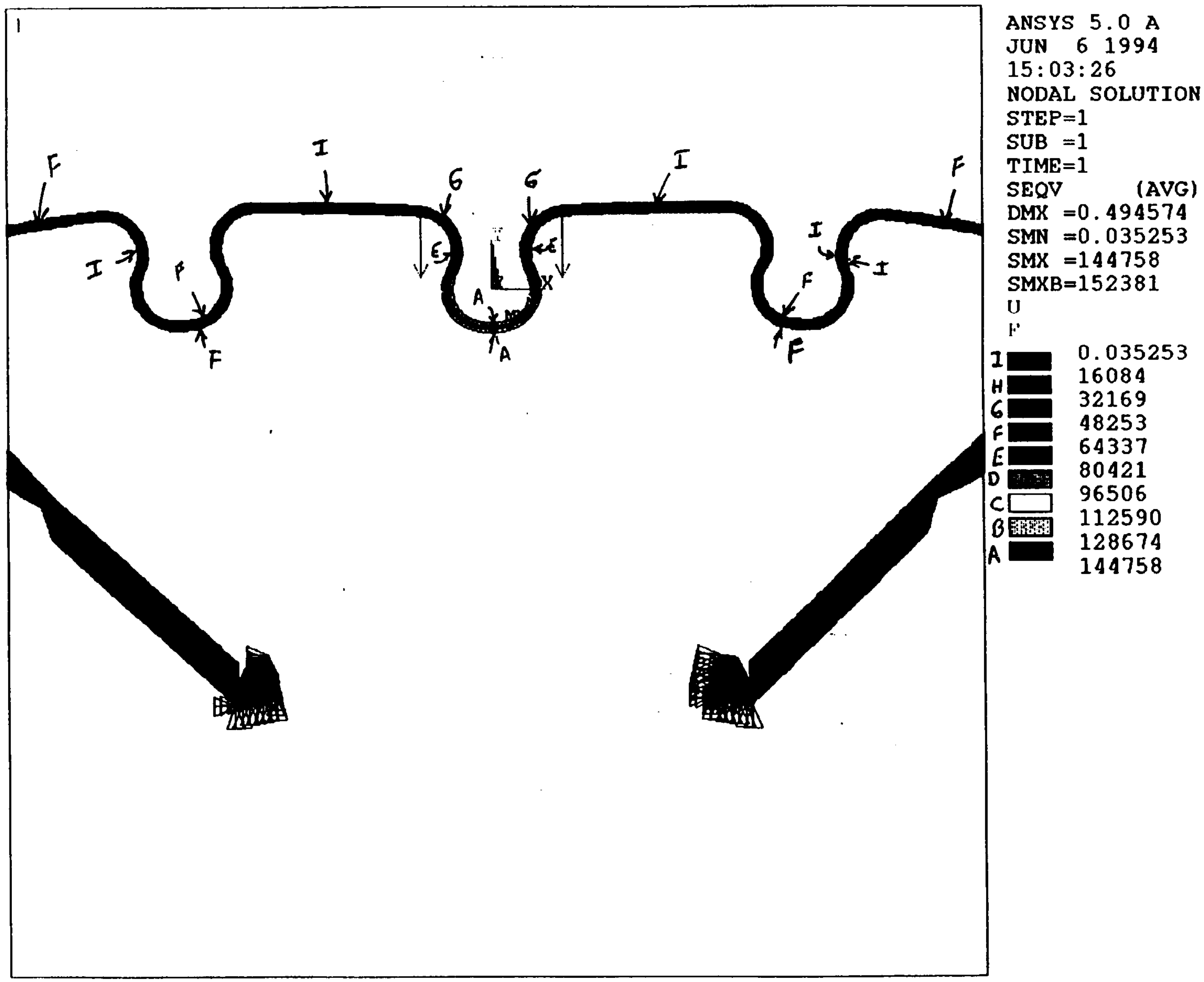


Figure 19. Stress results—first mod. model—first load step and one missing mechanism.

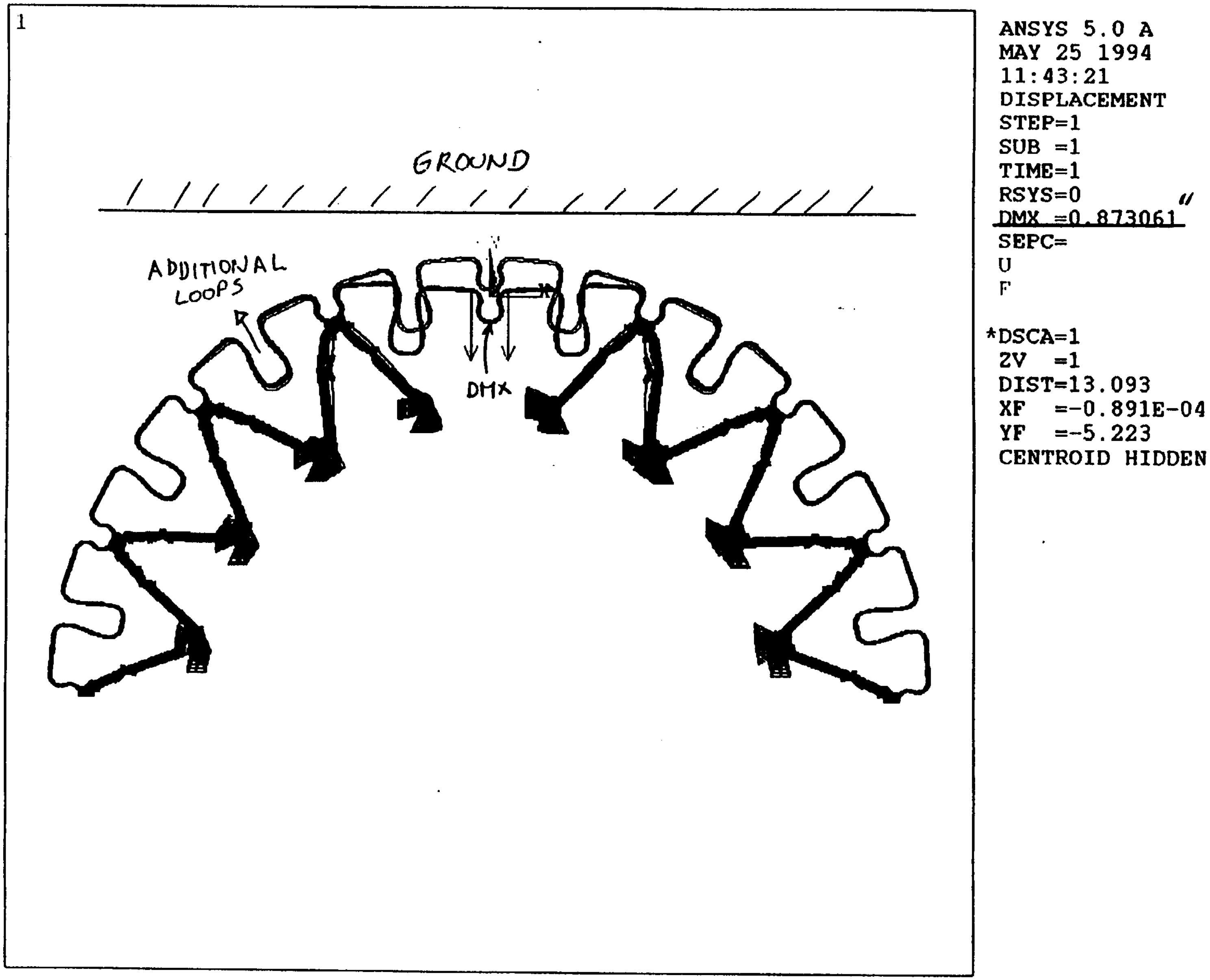


Figure 20. Displacement results—second mod. model—first load step and one missing mechanism.

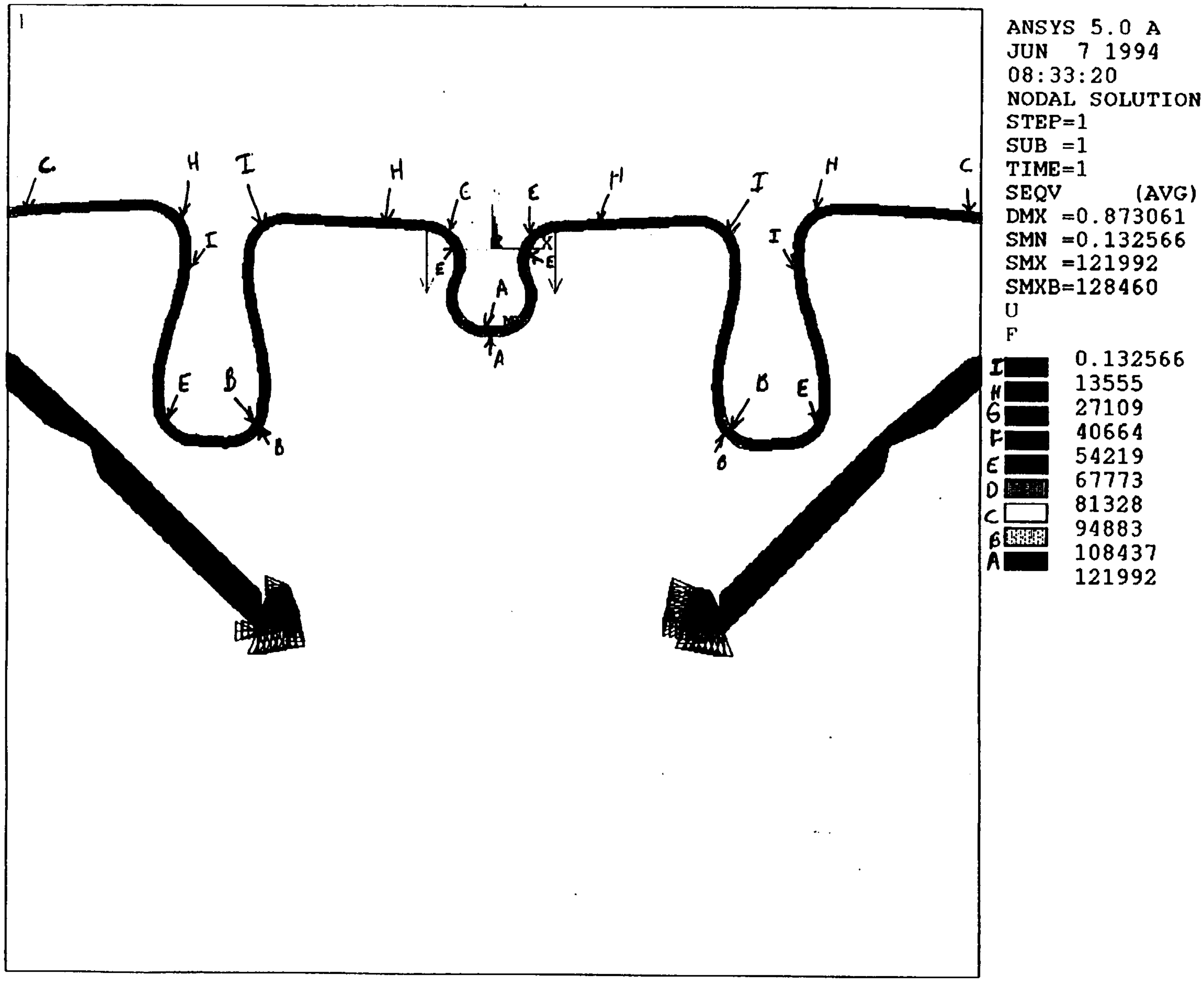


Figure 21. Stress results—second mod. model—first load step and one missing mechanism.

REFERENCES

1. Weddendorf, B.C.: Composite Wheelchair Wheel Designer.

2. ANSYS Engineering Analysis System User's Manual: Vs. 5.0A, Swanson Analysis System Inc., vols. I to IV, 1992.

3. Rockwell International Rocketdyne Division: Material Properties Manual, Prepared by Materials Engineering and Technology, vols. I to III, fourth ed., 1986.

4. Hackett, R.M.: "A Course on Advanced Composite Material Systems." Marshall Space Flight Center, AL, 1993.

5. Tsai, S.W.: "Theory of Composites Design." Think Composites, Dayton, OH, 1992.

6. "Tire Rides Without Air," *News Trends*, Machine Design Magazine, vol. 66, No. 10, May 23, 1994, pp. 16.

APPROVAL

FINITE ELEMENT ANALYSIS OF A COMPOSITE WHEELCHAIR WHEEL DESIGN

By R. Ortega

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

J.C. BLAIR
Director, Structures and Dynamics Laboratory

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1994	Technical Memorandum

4. TITLE AND SUBTITLE
Finite Element Analysis of a Composite Wheelchair Wheel Design

5. FUNDING NUMBERS

6. AUTHOR(S)
R. Ortega

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM - 108463

11. SUPPLEMENTARY NOTES
Prepared by Structures and Dynamics Laboratory, Science and Engineering Directorate.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified—Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The finite element analysis of a composite wheelchair wheel design is presented. The design is the result of a technology utilization request. The designer's intent is to soften the riding feeling by incorporating a mechanism attaching the wheel rim to the spokes that would allow considerable deflection upon compressive loads. A finite element analysis was conducted to verify proper structural function. Displacement and stress results are presented and conclusions are provided.

14. SUBJECT TERMS
finite element analysis, composite materials, wheelchair wheels

15. NUMBER OF PAGES
32

16. PRICE CODE
NTIS

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102