CALCULATION REVIEW FORM

Calculation Number/File: PERY-03Q-301 Revision: 0

Review Method: ☑ Design Review ☐ Alternate Calc ☐ Other

Scope (PM)	Item	Review Attribute	Reviewer: G.A. MIESSI
✓	1	Were the inputs correctly selected and incorporated into the analysis? ☑ Yes ☐ No by/date:	GAM 9/26/03
✓	2	Are all assumptions necessary to perform the analysis reasonable and adequately described? ☑ Yes ☐ No by/date:	
✓	3	Are the applicable codes, standards, and regulatory documents and requirements, including edition and addenda, properly identified, and are their requirements met? ☑ Yes ☐ No by/date:	
✓	4	Is the output reasonable compared to the inputs? ☑ Yes ☐ No by/date:	
✓	5	Are correct material properties used in the analysis? ☑ Yes ☐ No by/date:	
✓	6	Are the acceptance criteria used in the analysis correct? ☑ Yes ☐ No by/date:	
✓	7	Are calculations numerically correct? ☑ Yes ☐ No by/date:	
✓	8	Are information and analysis results accurately transferred from underlying calculations or documents? ☑ Yes ☐ No by/date:	
✓	9	Are the analysis results complete? ☑ Yes ☐ No by/date:	
✓	10	Are known problems or limitations of the results adequately defined? ☑ Yes ☐ No by/date:	
✓	11	Were computer programs used in the analysis adequately identified, verified, tested, and controlled? ☑ Yes ☐ No by/date:	
✓	12	Is the output of computer programs compatible and reasonable compared with the input? ☑ Yes ☐ No by/date:	
✓	13	Are associated computer files correct, current, and available for archival? ☑ Yes ☐ No by/date:	GAM 9/26/03

Documentation Attached: ☑ Markup ☐ Memo ☐ Other

Comments (attach pages if necessary):

Markups on attached review copy -

Proposed Resolution (Preparer):

Comments incorporated.

Reviewer Acceptance*/Date: Miessi Al 9/26/03

The project manager's approval signature, below, also indicates that all design inputs used in the preparation of the attached calculation, and that are referenced in the attached calculation, were reviewed and approved for use by the PM, or his/hers designee.

Project Manager Approval/Date: Miessi Al 9/26/03

*Includes agreement that any computer files are current and available for archival

STRUCTURAL INTEGRITY Associates, Inc.	**CALCULATION PACKAGE**	**FILE No.: PERY-03Q-301** **PROJECT No.:** PERY-03Q

PROJECT NAME: Emergency Service Water System Pump Shaft Coupling Failure Analysis

CLIENT: First Energy Corporation

CALCULATION TITLE: Stress Comparison Between a Properly Centered Coupling and an Off-Centered Coupling

Document Revision	Affected Pages	Revision Description	Project Mgr. Approval Signature & Date	Preparer(s) & Checker(s) Signatures & Date
0	1-20 A1 Computer Files	Original Issue	GAM 9/26/03	FHK 09/26/03 GAM 9/26/03

1. OBJECTIVE

A coupling failure has been observed for the vertical pump shaft of the emergency service water system at Perry Nuclear Power Plant. The failed coupling was found to be have been vertically misaligned by 1". The objective of this calculation is to develop finite element models of the properly centered and off-centered pump shaft coupling assemblies, and then perform stress analyses to evaluate the impact of the misalignment on the coupling. The stress analysis results will also be used later to perform a fracture mechanics evaluation of the coupling.

2. FINITE ELEMENT MODEL

The finite element models (FEM) are developed using the 8-node structural solid (SOLID45) elements of the ANSYS software package [1]. The dimensions of the pump shaft coupling assembly, including the two shafts, two keys, and coupling, are obtained from References 2, 3, and 4. Note that the modeled length of each shaft, arbitrarily chosen as 5" from the end of the key slot, is enough to avoid boundary effects. The split rings are not modeled since their purpose is to transfer the down thrust axial loads, which do not contribute to the stresses on the coupling. The dimensions of the modeled geometry are summarized in Figure 1, and the finite element models are shown in Figures 2 through 5. The cross-sectional mesh for both models are identical (see Figure 6).

In order to model the interface between the different components, non-linear point-to-point contact (CONTAC52) elements are inserted between the contact surfaces between the coupling and the key, and the coupling and the shaft. The contact surfaces between the key and the shaft that are expected to be in compression due to the applied load are merged; this is acceptable as the detailed interactions between the key and the shaft is not the focus of this evaluation.

3. MATERIAL PROPERTIES

Reference 3 shows that the pump shaft, key, and coupling material is SA582 Type 416, which has a tested chemical composition of 13.5% Cr [5]. Therefore, the elastic modulus for the Type 416 stainless steel falls in the 13% Cr material group of the ASME Code [6], which is 29.2E+06 psi at 80 °F, while the Poisson's ratio is assumed to be 0.30. The material of the coupling assembly is martensitic in structure whether in the annealed or hardened and tempered condition. The ASM Handbook [7], which lists the room temperature Young's modulus of martensitic Stainless Steel Grades 410 and 416 at 29.0E+06 psi, states: "the modulus of elasticity is one of the most structure-insensitive of the mechanical properties. Generally, it is only slightly affected by alloying additions, heat treatment or cold work". This fact is corroborated by materials reference data sheets from various vendors that report the same room temperature Young's modulus of 29.0E+06 psi for martensitic Stainless Steel Grade 410 in different heat-treatment conditions [8].

4. ANALYSIS

Reference 3 states that the key is subjected to 42,000 in-lbs of torque, plus a shock factor of 1.1 for torsion. This load is converted to a force couple and applied at the top end of the upper shaft, while the bottom end of the lower shaft is fixed in order for the load to be appropriately transferred. In addition, one node pair between the key and the coupling and one node pair between the shaft and the coupling are coupled axially near the set screw locations to simulate them (the set screws are not modeled) for stability of the model (see Figures 3 and 5). The top end of the top shaft is held axially to prevent any off-axis rotation. The ANSYS input files for the analyses are listed in Appendix A.

5. RESULTS AND DISCUSSION

The deformed shapes, with the undeformed shapes outlined, of the shafts with the properly centered and off-centered couplings that subjected to the torque are shown in Figures 7 and 8, respectively. The overall hoop stress (SY) distribution on the model is shown in Figure 9. It should be noted that the highly localized maximum stresses seen on the shaft are simply due to the applied torque load at two points at the end of the shaft, which is far enough away from the coupling that it does not affect its stresses. Figure 10 presents the stresses in the shaft and illustrate the localization of the large stresses both in the centered and off-centered configurations.

5.1 Stress Comparison Between Configurations

The radial (SX), hoop (SY), and axial (SZ) stresses on the properly centered and off-centered couplings are shown in Figures 11 through 13. Since the primary objective of this analysis is to investigate the root cause of the cracking in the pump shaft coupling, only tensile stresses are of importance. The results demonstrate that all three stress components peak at the edge of the keyway on the couplings, and all of the component stresses on the off-centered coupling are higher than that for the centered coupling. The comparison between the maximum component stresses is summarized in Table 5-1.

Table 5-1: Pump Shaft Coupling Peak Stress Comparison

Coupling	Radial Stress (SX), ksi	Hoop Stress (SY), ksi	Axial Stress (SZ), ksi
Centered	48.0	114.4	37.6
Off-Centered	65.1	154.9	49.8
% Difference	35.6%	35.4%	32.4%

The above comparisons demonstrate that the off-centered coupling is clearly more susceptible to cracking and failure than the properly centered coupling.

5.2 Primary Stress Comparison to Allowables

In the original design analysis of the vertical pump [3], the lineshaft coupling assembly was qualified based on the average primary stresses and allowable stresses presented in Table 5-2:

Table 5-2: Pump Shaft Assembly Original Report Primary and Allowable Stresses

Component	Primary Stress (psi)	Allowable Stress (psi)
Split Ring	Axial Stress = 21,580	30,000
Key	Shear Stress = 12,491	20,000
Shaft	Shearing Stress = 13,051	Not applicable
	Stress Intensity = 29,155	30,000
Coupling	Stress Intensity < 29,155 [1]	30,000

[1] The coupling stress were not explicitly calculated but were determined to be lower than those of the shaft based on a comparison of section properties.

The dimensions used in this evaluation are nearly identical to the dimensions used in the original analysis except for the smaller, corroded shaft diameter used in the latter. Thus, for the same operating loads, the design analysis should remain valid.

In order to verify the primary stresses in the coupling assembly, the through-wall stresses from the finite element analysis are linearized at some locations to extract the membrane and bending stresses in the structure. The linearization option is available in ANSYS to allow a separation of stresses across the thickness of the section under consideration into membrane (constant, average value) and bending (linear, variable) stresses. First, the section is defined by a path consisting of two end points, which are at free surfaces, and 47 intermediate points (automatically determined by linear interpolation in the active display coordinate system). Then, the stress results are mapped onto that path and the membrane and bending stresses are extracted. The stress paths for the key and shaft are illustrated in Figures 14 and the paths for the coupling are shown in Figure 15. To obtain the primary stresses, which do not include peak stresses, the stress paths must be taken away from geometric discontinuities of the coupling assembly. Thus, the stress path for the shaft is taken halfway between the end of the shaft and the bottom of the keyway. For the coupling and the keys, the paths are taken at the centerline of each of the component.

The stress intensity calculated for the shaft in the original report includes bending and deadweight contributions, which are not considered in this analysis. Hence, only the maximum primary shearing stresses obtained from the finite element analyses are presented in Table 5-3 and compared to the values calculated in the original report. As expected, for the centered configuration, the stresses are almost equal or less than the stresses calculated in the original report. The off-centered configuration produces nearly identical primary shearing stresses in the shaft and coupling but 33% higher stresses in the top key and slightly lower stresses in the bottom key. This 33% increase in primary shear stress is in agreement with the fact that only ¾ of the top key is engaged. Therefore, the finite element analysis primary stresses compare well with the original report.

Table 5-3: Pump Shaft Assembly Primary Stress Comparison

Component	Shearing Stress (psi)		
	Original Analysis	Finite Element Analysis	
		Centered	Off-Centered
Top Key [1]	12,491	12,670	16,830
Bottom Key		12,660	11,790
Shaft	13,051	12,990	13,110
Coupling	< 13,051	5,574	5,733

[1] Only ¾ of the top key is engaged in the off-centered configuration.

The ANSYS post-processing result files for are listed in Appendix A.

6. CONCLUSION

The stress analysis of the ESW pump coupling assembly demonstrates that very high hoop stresses are generated in the localized regions near the geometric discontinuities of the keyway under normal operating conditions. Figure 12 shows that the maximum hoop stresses are at the keyway groove, the exact location where the coupling cracking was reported [5]. Such high stresses in a crevice-like location, coupled with a susceptible material in a stress corrosion tolerant environment, can lead to intergranular stress corrosion cracking. Moreover, the stress analyses indicate that the improper installation of the coupling on the shafts increases the hoop stresses at the keyway by 35%, further augmenting the possibility of cracking.

7. REFERENCES

1. ANSYS/Mechanical, Release 6.1 (w/ Service Packs 2 and 3), ANSYS Inc., April 2002.
2. Pace Energy Drawing No. SMAC30393, Rev. 1, "Coupling," SI File No. PERY-03Q-201.
3. McDonald Engineering Report No. ME-454 (Dated 07/20/1982), "Seismic Analysis of Vertical Pump," Including Addendum No. 1 (Dated 04/03/1984), SI File No. PERY-03Q-202.
4. E-Mail and Accompanying Attachments from C. Flensburg (First Energy) to A. Miessi (SI), "Pump Shaft Dimensions Rev. 1," Dated 09/11/2003, SI File No. PERY-03Q-201.
5. BETA Laboratory Report No. M-03284, "Failure Analysis Report," Dated 09/19/2003, SI File No. PERY-03Q-203.
6. ASME Boiler and Pressure Vessel Code, Section II, Part D – Properties, 1998 Edition, No Addenda.
7. ASM Handbook, Ninth Edition, Volume 3, "Properties and Selection" and Volume 8 "Mechanical Testing".
8. Materials Reference Data Sheets from:
   - BodyCote Materials Testing, "Stainless Steel – Grade 410", www.azom.com
   - AK Steel Corporation, "410 Stainless Steel Product Data Sheet", www.aksteel.com
   - Ferguson Metals, Inc., "Technical Data Stainless Steel Martensitic Type 410 UNS(S41000)", www.fergusonmetals.com
   - Allegheny Ludlum Corporation, "Technical Data Blue Sheet, Martensitic Stainless Steel Types 410, 420, 425 Mod, and 440A", www.alleghenyludlum.com

   SI File No. PERY-03Q-204.

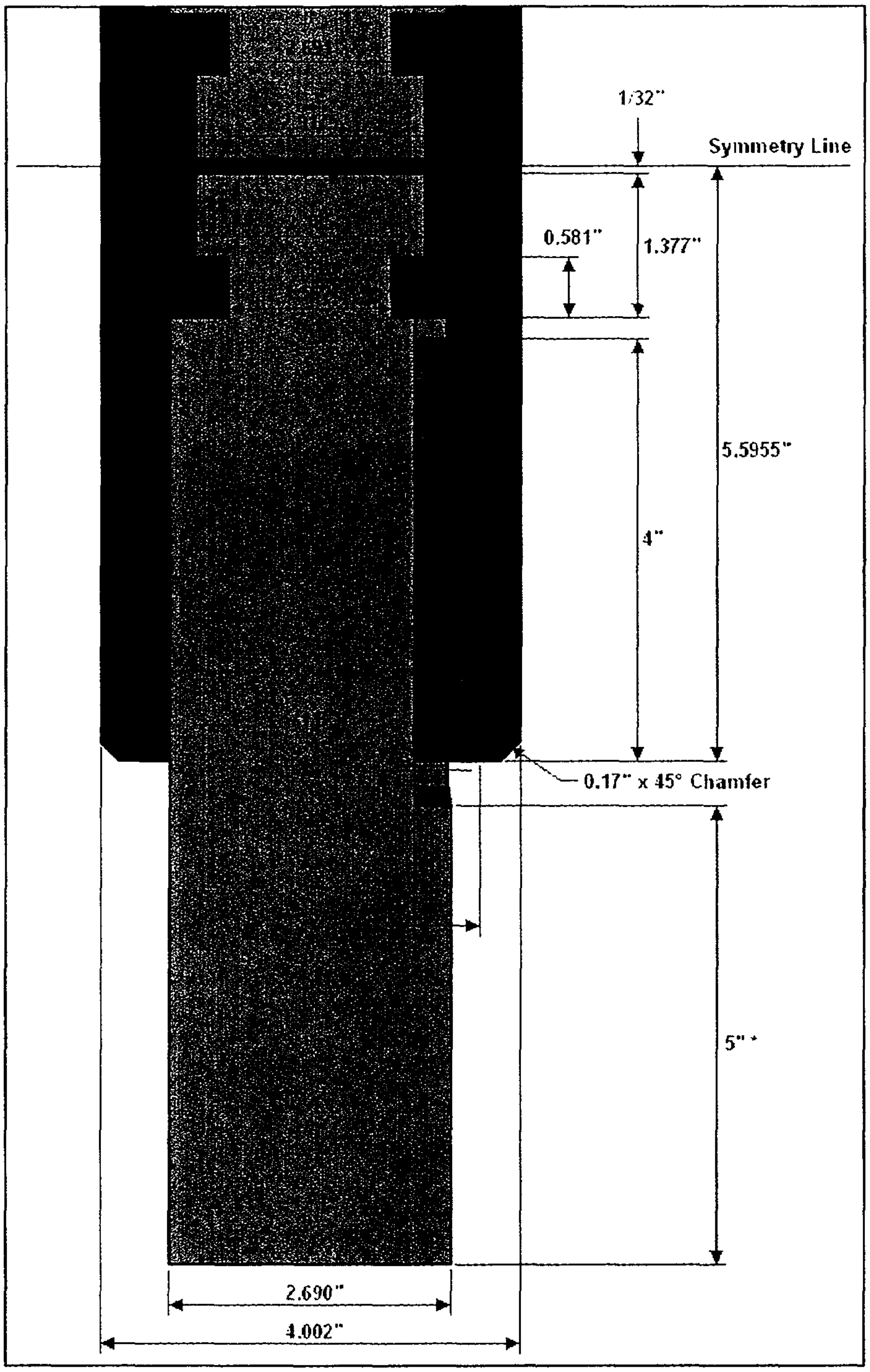

Figure 1: Dimensions of the Pump Shaft Coupling Assembly

(* indicates assumed dimensions; all other dimensions are obtained from References 2, 3, and 4)

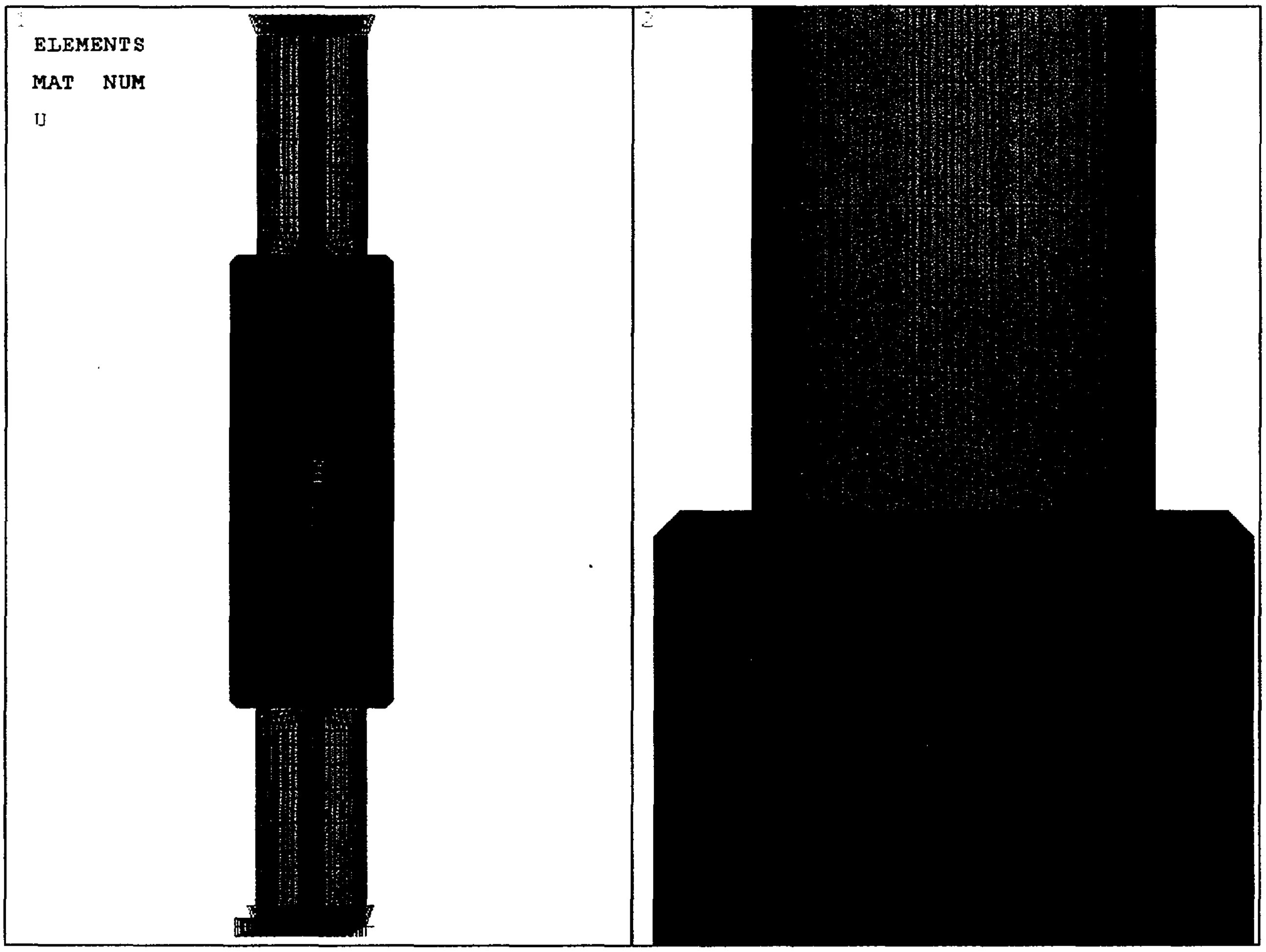

Figure 2: Top View of the Finite Element Model of the Shaft with a Properly Centered Coupling

(Blue color represents applied displacement constraints: top shaft end is axially held, bottom shaft end is fixed in all translational degrees-of-freedom)

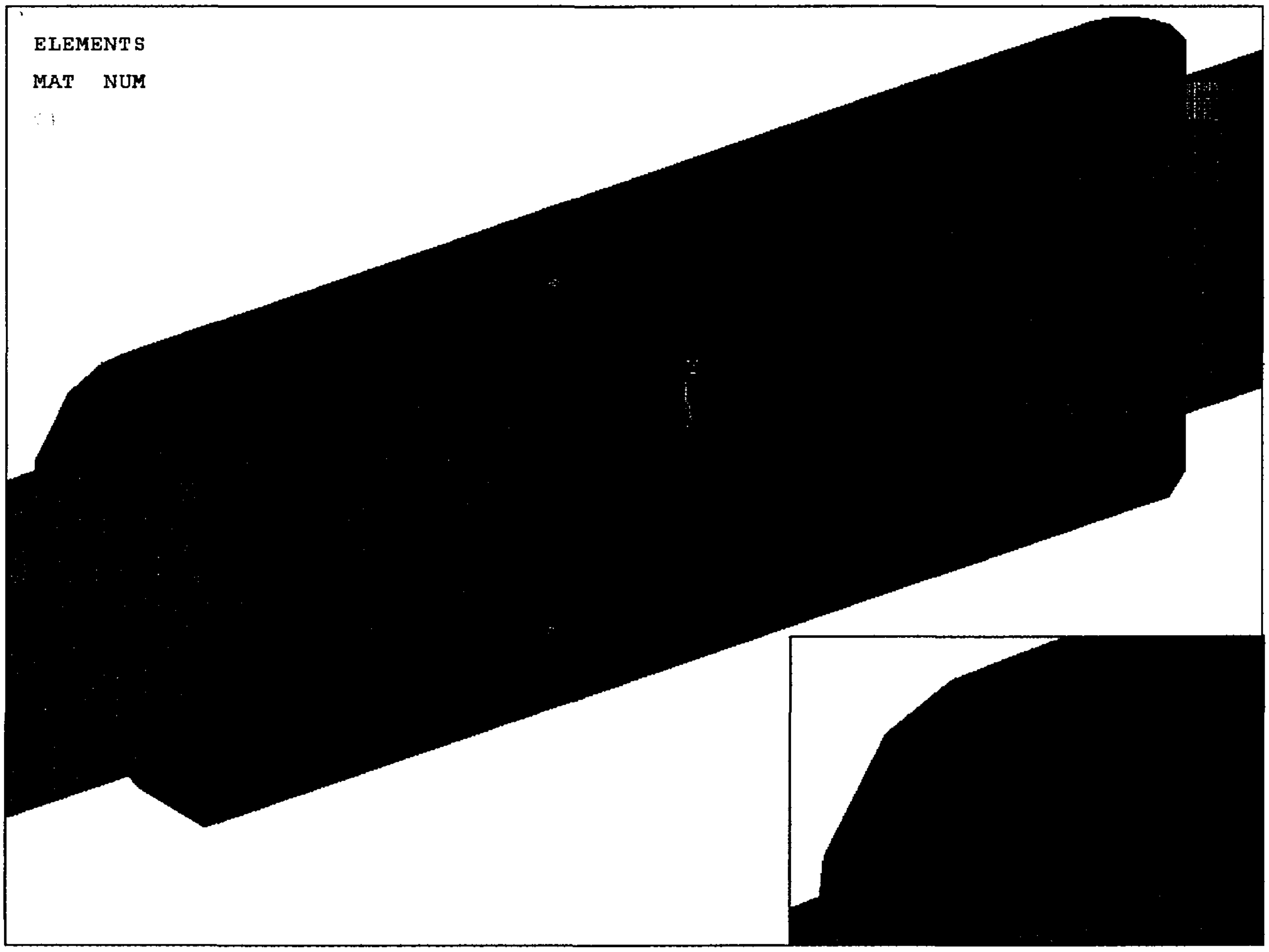

Figure 3: Half-Sectional View of the Centered Coupling Model

(Green color represents applied axial couples simulating the set-screws)

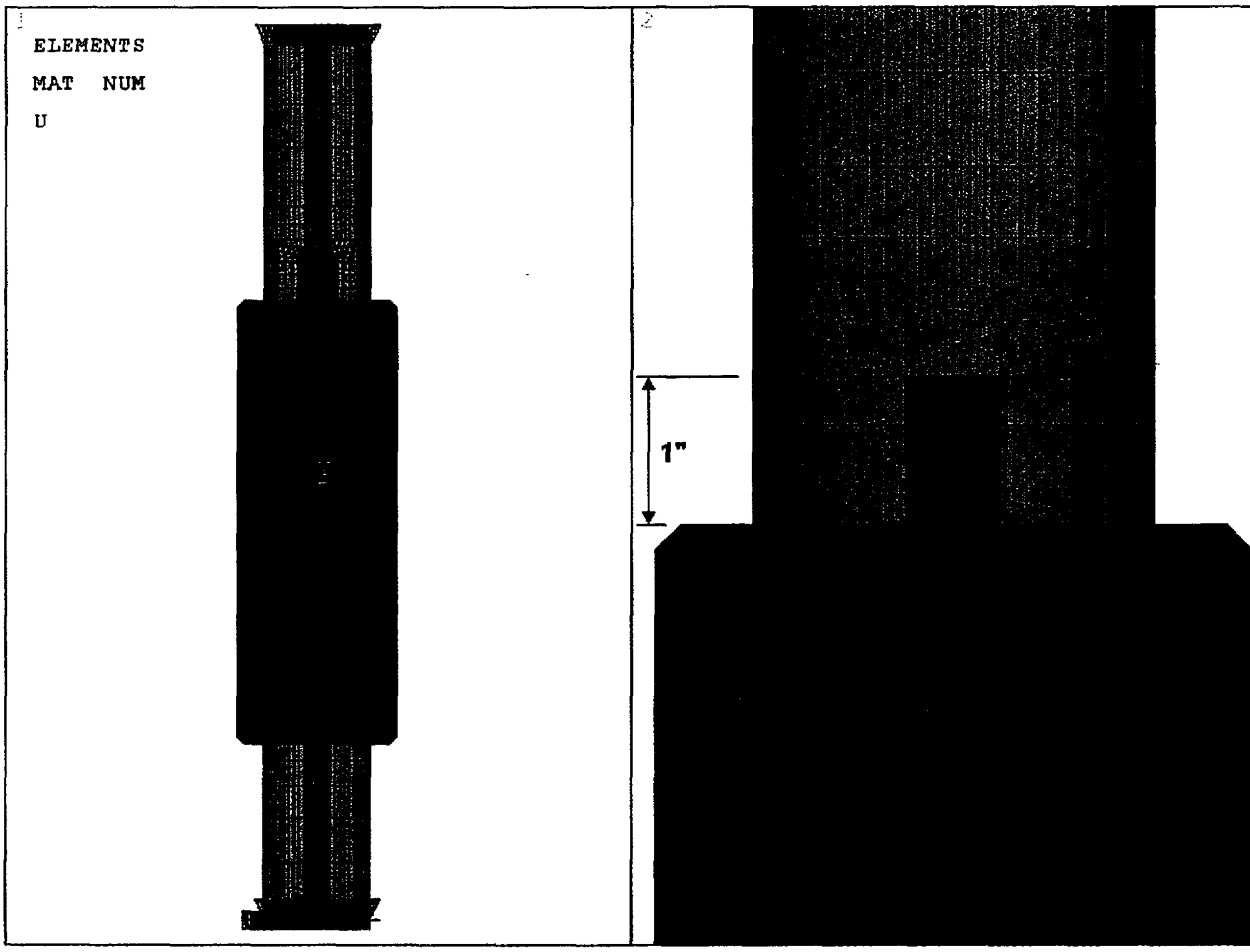

Figure 4: Top View of the Finite Element Model of the Shaft with an Off-Centered Coupling

(Blue color represents applied displacement constraints: top shaft end is axially held, bottom shaft end is fixed in all translational degrees-of-freedom. The coupling is 1" below its center position.)

Revision	0			
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Checker/Date	GAM 09/26/03			

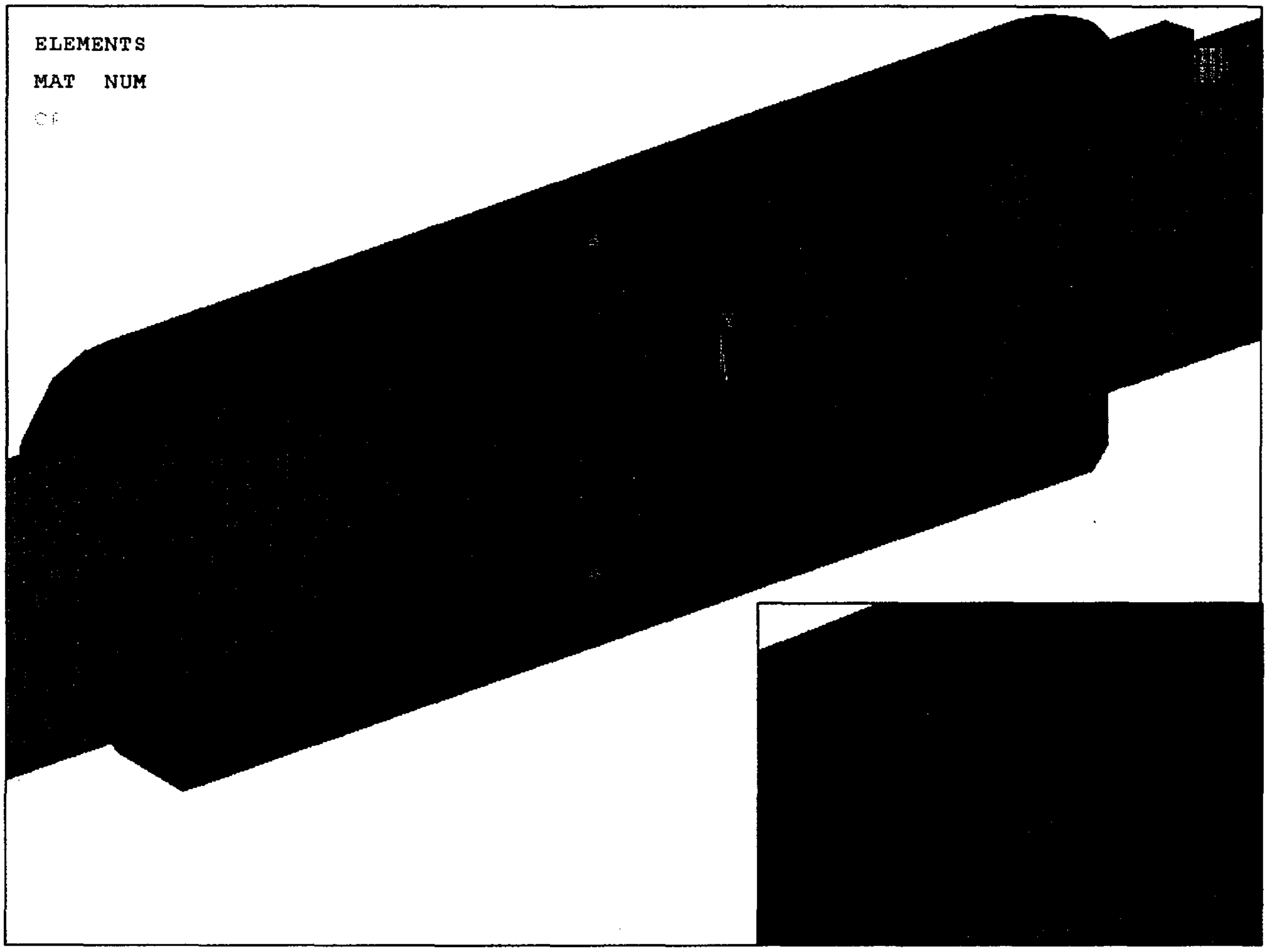


Figure 5: Half-Sectional View of the Off-Centered Coupling Model

(Green color represents applied axial couples simulating the set-screws)

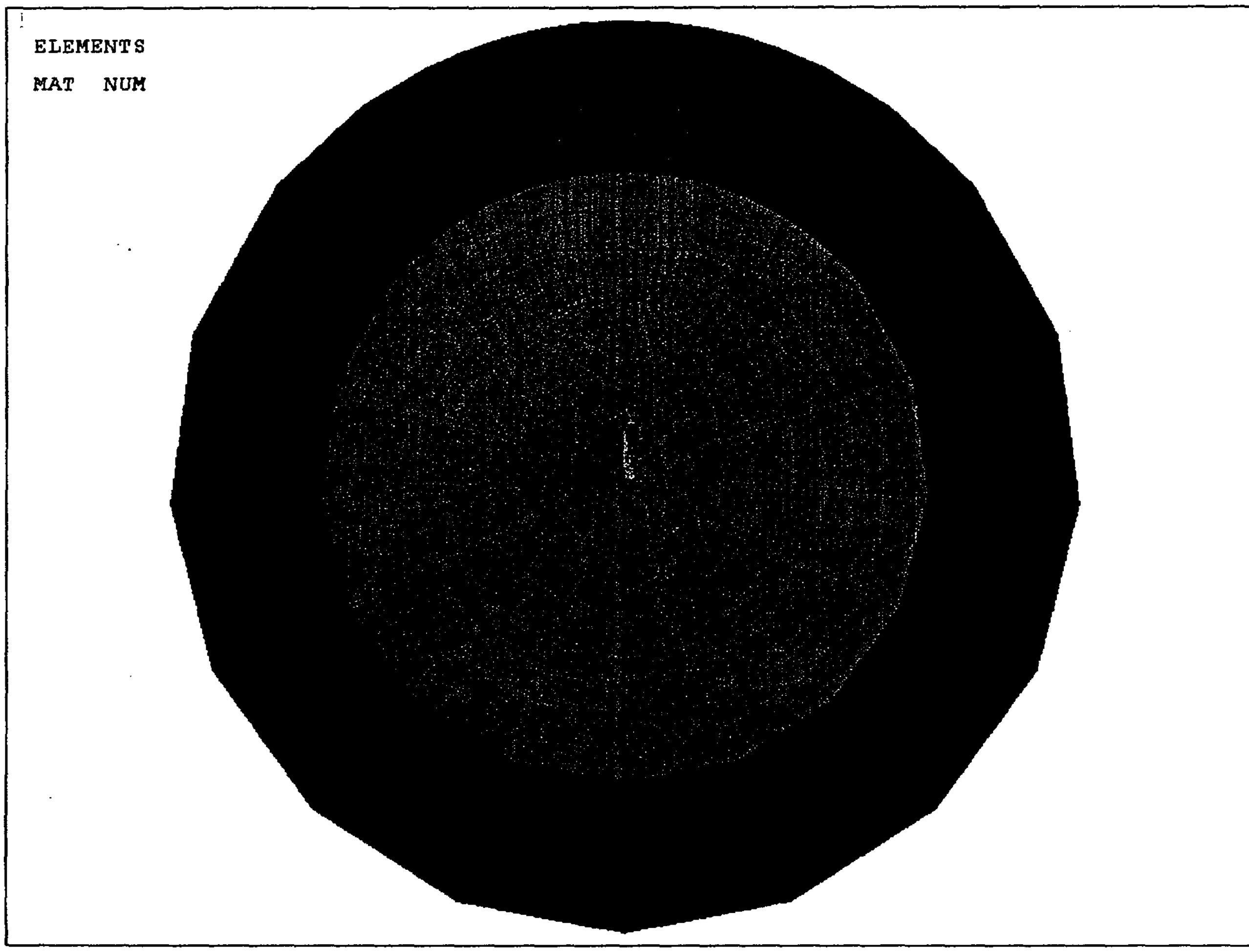


Figure 6: Front View of the Model Showing the Cross-Sectional Mesh

(Both models have identical cross-sectional mesh)

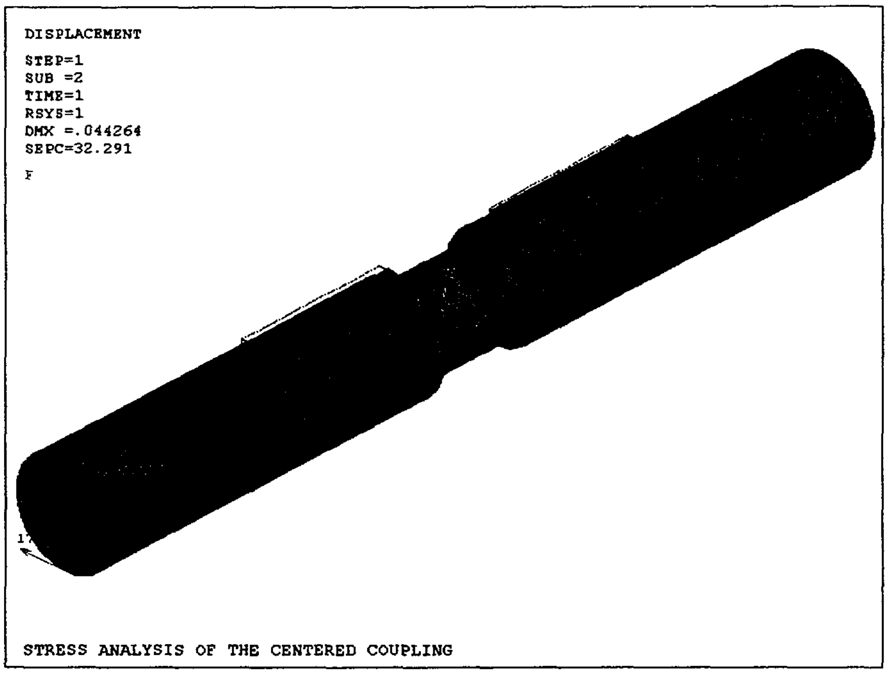


Figure 7: Deformed Shape of the Shaft with a Properly Centered Coupling

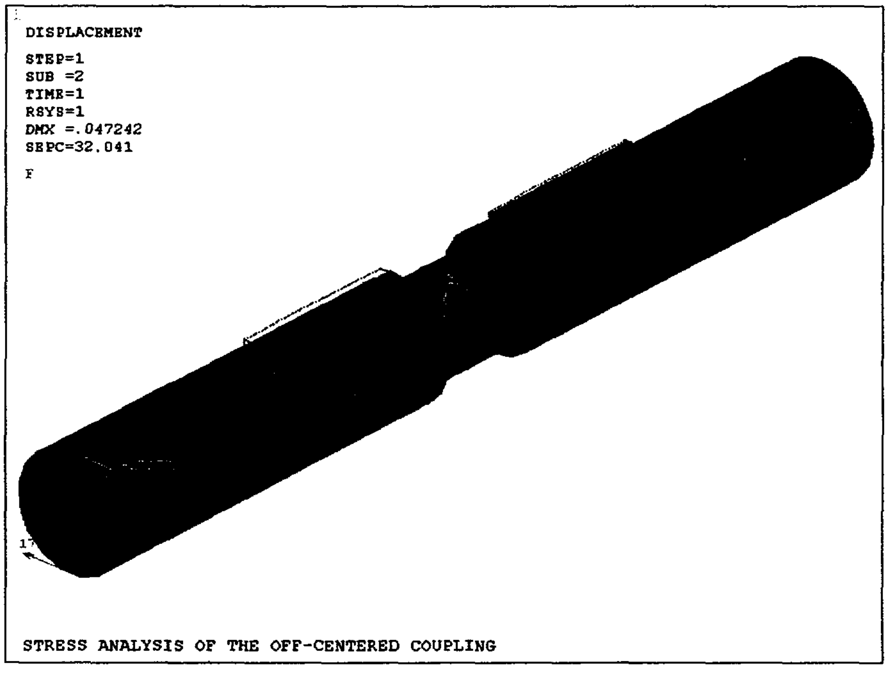
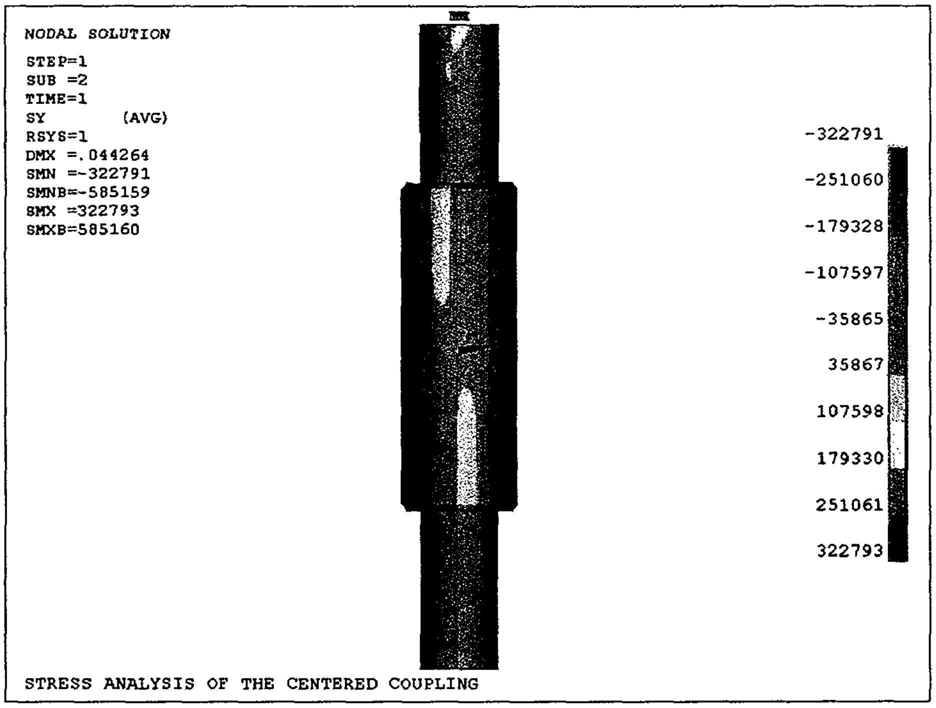
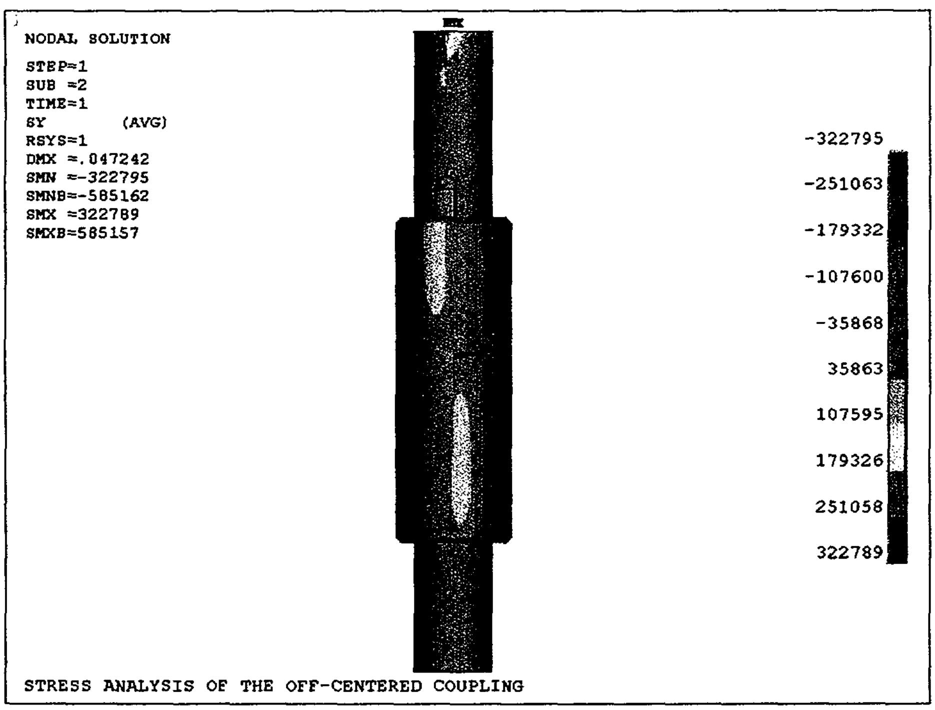


Figure 8: Deformed Shape of the Shaft with an Off-Centered Coupling

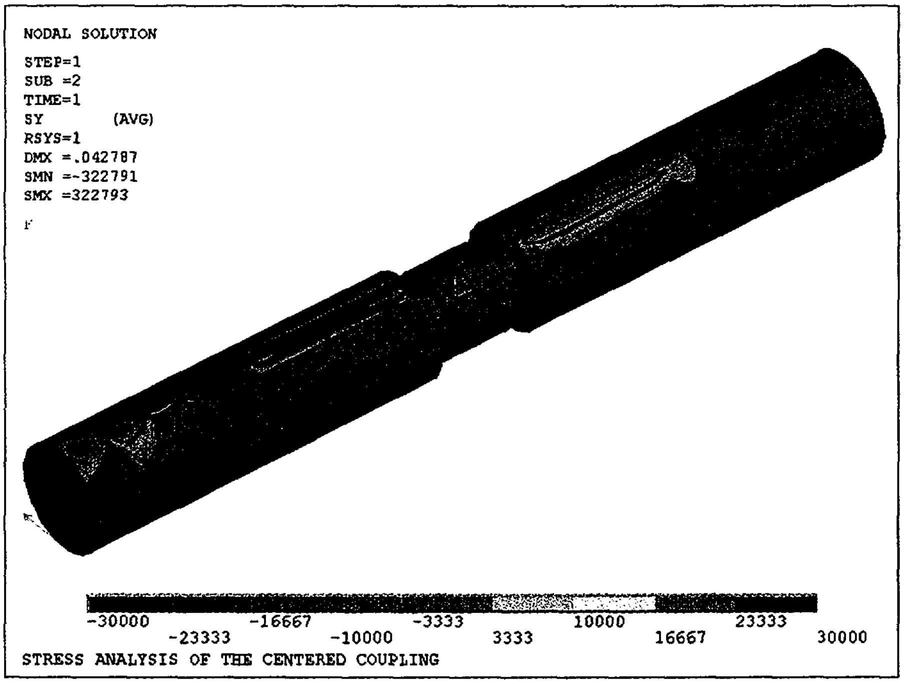


a) Centered Coupling

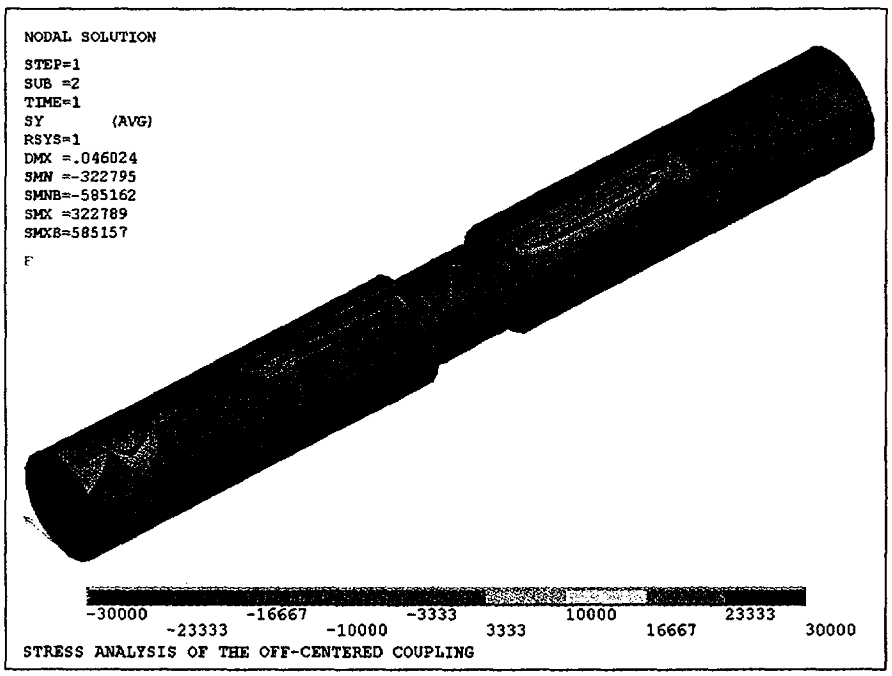


b) Off-Centered Coupling

Figure 9: Overall Hoop Stress Distribution on the Models

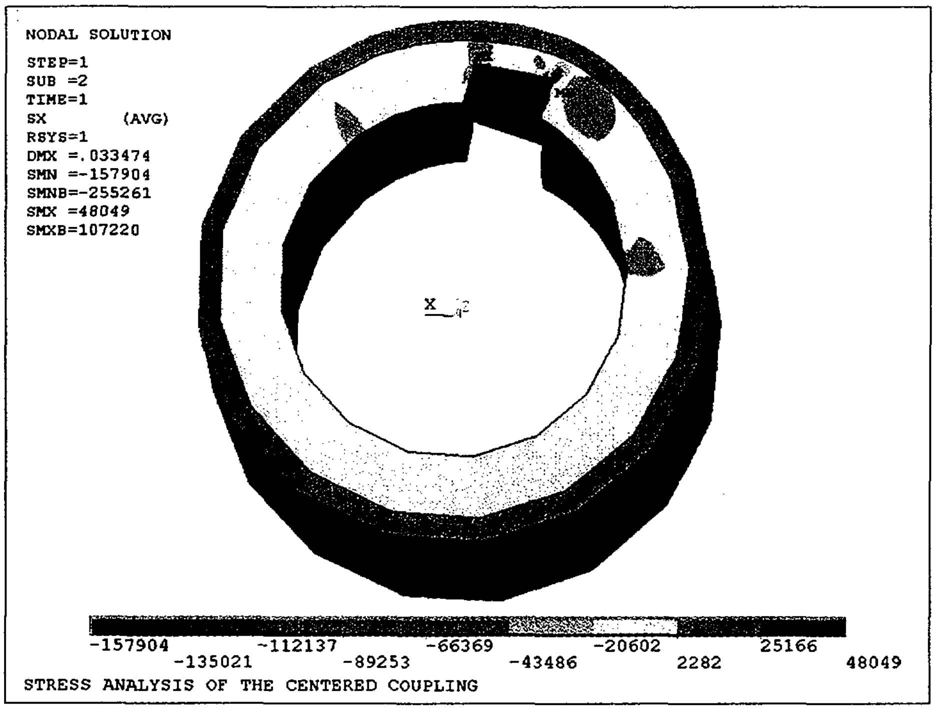


a) Centered Coupling

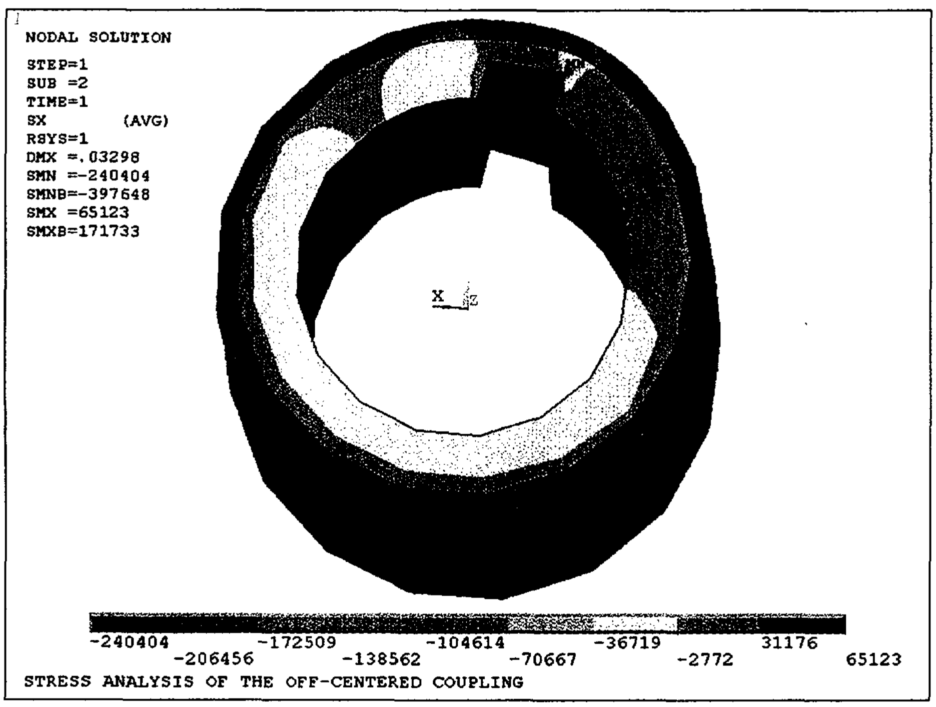


b) Off-Centered Coupling

Figure 10: Overall Hoop Stress Distribution on the Models
(Gray color represents areas where the stress is beyond the range in the legend)

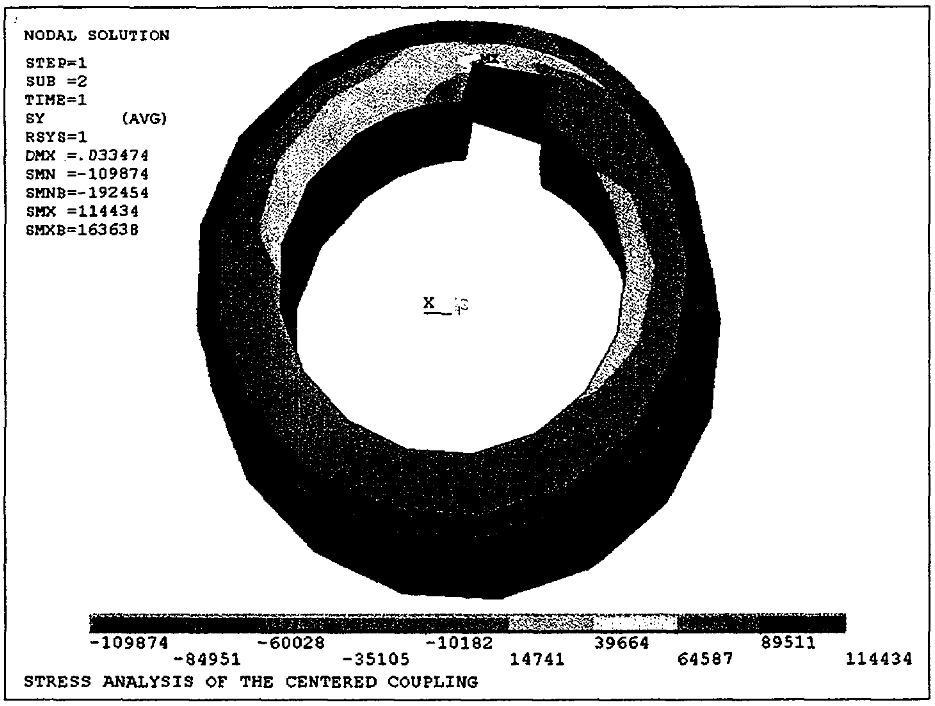


a) Centered Coupling

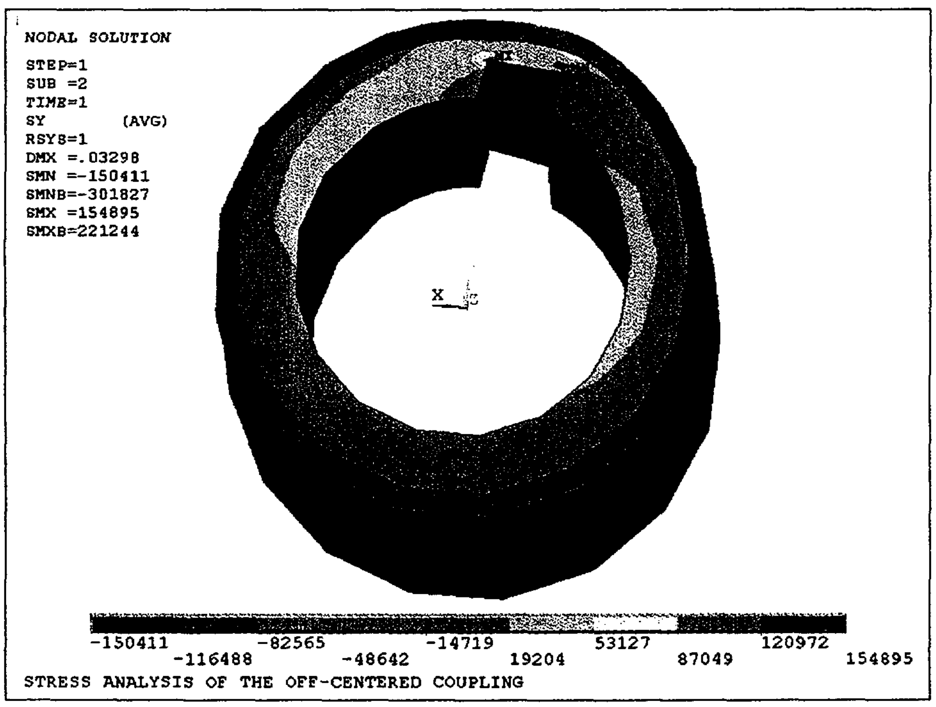


b) Off-Centered Coupling

Figure 11: Radial Stress Distribution on the Couplings, SX

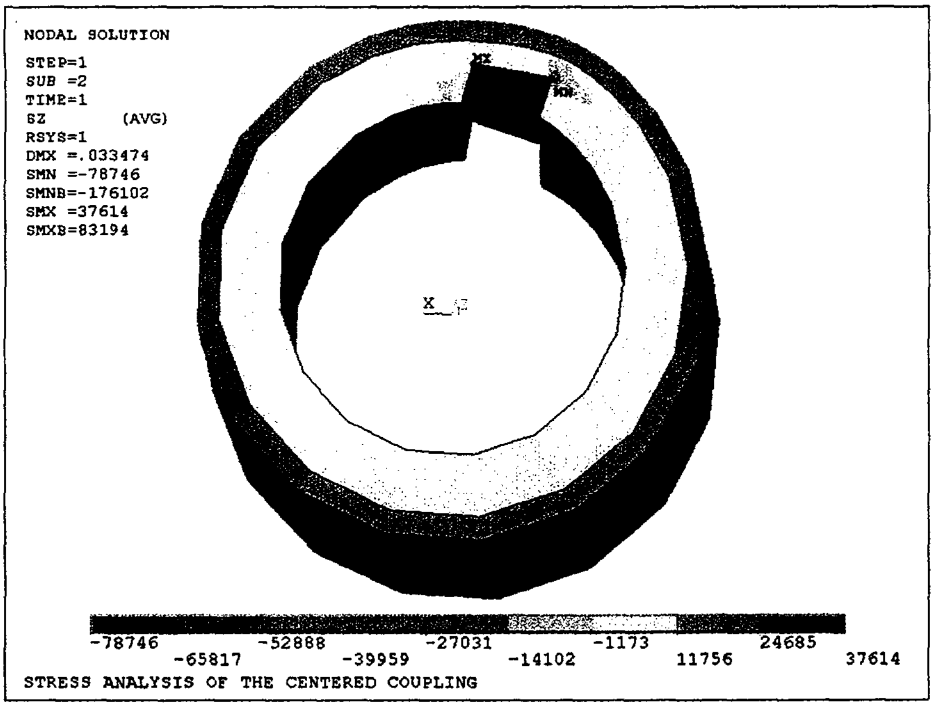


a) Centered Coupling

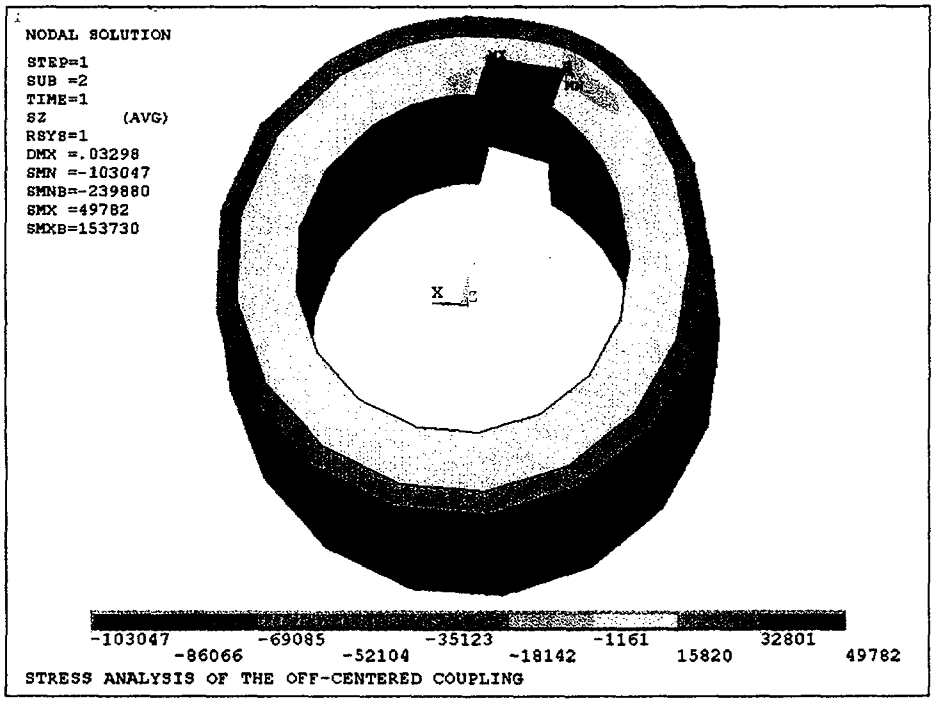


b) Off-Centered Coupling

Figure 12: Hoop Stress Distribution on the Couplings, SY

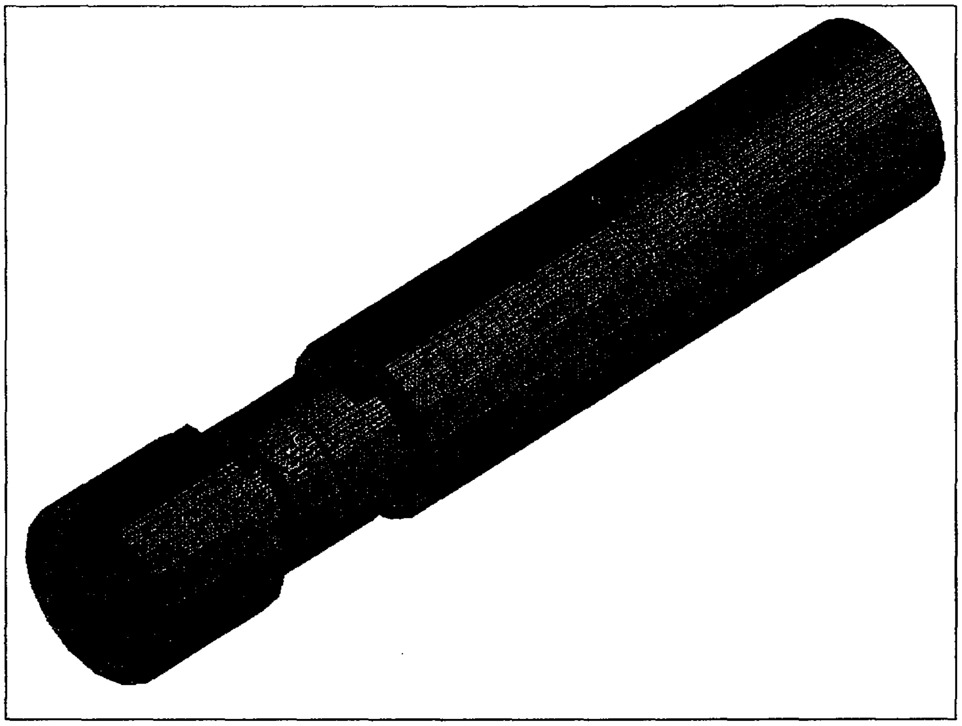


a) Centered Coupling

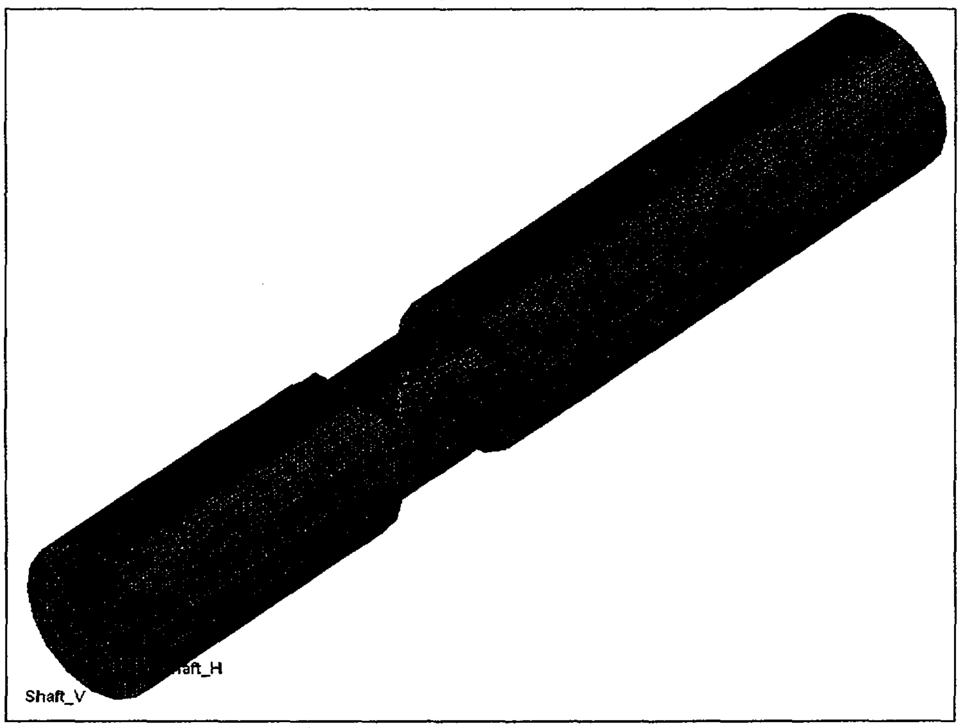


b) Off-Centered Coupling

Figure 13: Axial Stress Distribution on the Couplings, SZ



a) In the Key



b) In the Shaft

Figure 14: Stress Linearization Paths in the Key and Shaft

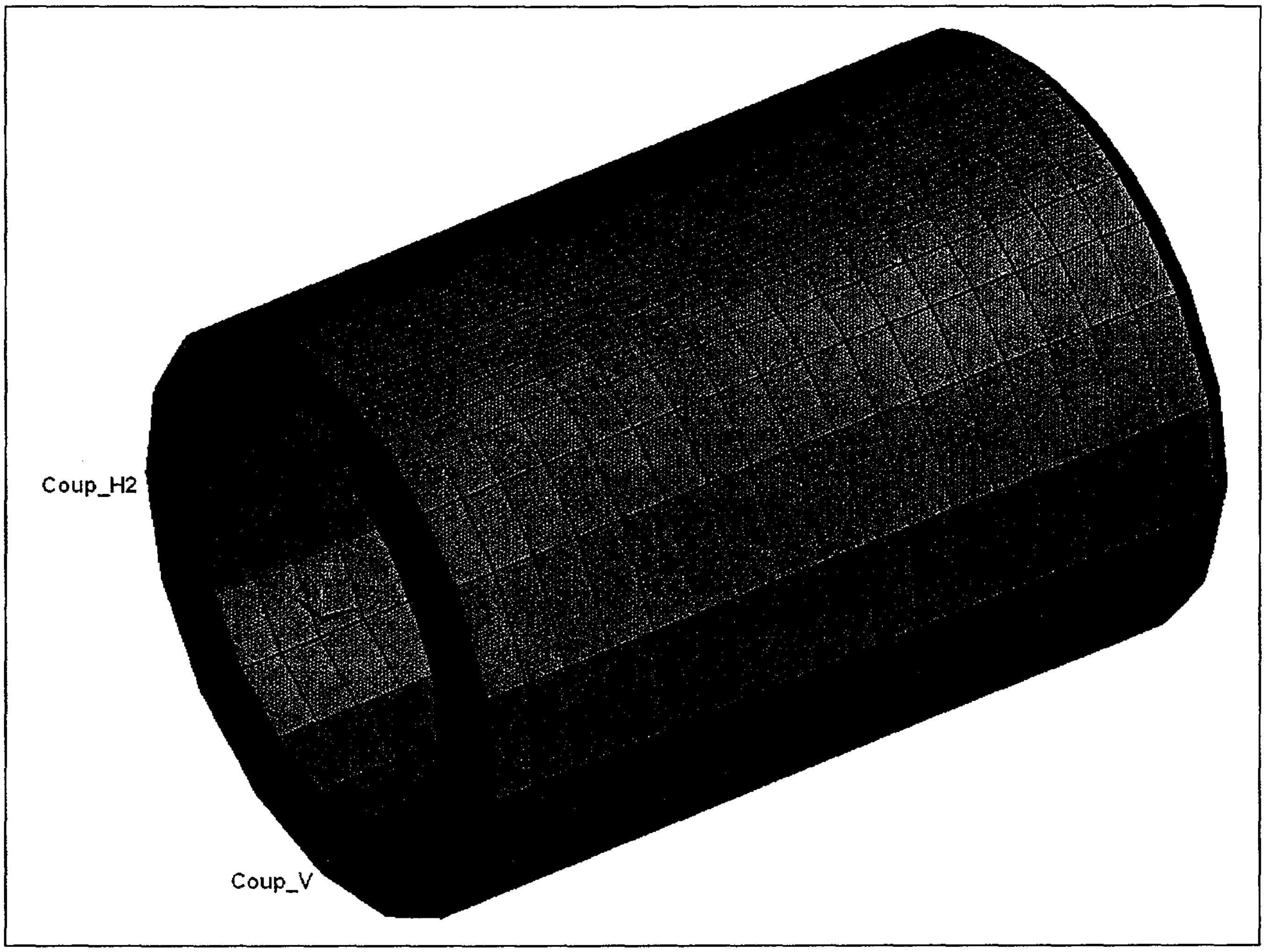


Figure 15: Stress Linearization Paths in the Coupling

APPENDIX A – ANSYS INPUT AND OUTPUT FILES DESCRIPTION

Input File	Description
SHAFT_CENTER.INP	Finite element model geometry for the properly centered coupling
SHAFT_OFF.INP	Finite element model geometry for the off-centered coupling
STR_CENTER.INP	Stress analysis of the centered coupling model
STR_OFFINP	Stress analysis of the off-centered coupling model
LINEARIZE.INP	Post-processing file to extract linearized stresses

Output File	Description
LINEARIZE_CTR.OUT	Linearized stress output for centered coupling analysis
LINEARIZE_OFF.OUT	Linearized stress output for off-centered coupling analysis