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Resistance Weld Qualifcation Analysis for Radioactive Waste Canisters (U)

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N. K. Gupta

Westinghouse Savannah River Company
Savannah River Site
Aiken, South Carolina 29808

C. Gong
Westinghouse Savannah River Company
SC USA

MASTER

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N. K. Gupta and Chung Gong
Westinghouse Savannah River Co.
Aiken, SC 29808

ABSTRACT

High level radioactive waste canisters are sealed by resistance upset welding to ensure leak tight closures. Resistance welding is fast, uniform, and can be performed remotely to minimize radiation exposure to the operators. Canisters are constructed in accordance with ASME B&PV Code, Section VIII, Division 1, however, the resistance welds are not used in Section VIII. The resistance welds are qualified by analysis using material properties obtained from the test coupons. Burst tests are performed on canister welds to meet ASME Section IX welder qualification requirements. Since burst tests are not used in Section IX for resistance weld qualification, finite element results of canister resistance welds are compared with the finite element analysis results of resistance weld tests in ASME Section IX, QW-196 to establish similarity between the two weld tests. Detailed analyses show that the primary mode of failure in both the tests is shear and, therefore, the use of burst test in place of shear test is acceptable. It is believed that the detailed analyses and results could help in establishing acceptance criteria for resistance upset welding in ASME B&PV Code, Sections VIII, and IX.

INTRODUCTION

The Defense Waste Processing Facility (DWPF) at Savannah River Site will vitrify high level radioactive waste. The vitrified waste will be stored in stainless steel canisters which are sealed by welding a plug into the canister nozzle by resistance upset welding. The canisters are cylinders approximately 2 ft in diameter and 10 ft tall fabricated from 0.375" thick plate with forged bottom and nozzle joined to the cylinder by girth welds. All components are fabricated from Type 304L stainless steel. The plug is 0.5" thick and 5" in diameter, slightly oversized for the nozzle opening (interference fit). Figure 1 shows a schematic of the DWPF canister, canister nozzle, and the plug arrangement.

The canisters are fabricated in accordance with ASME B&PV Code, Section VIII, Division 1 [1]. However, the seal welds using resistance upset welding are not addressed in Section VIII of the ASME Code. ASME Code, Section IX [2] gives the requirements for qualifying the welding procedures, welding equipment, and the welding operators for resistance welding. Section IX requirements for resistance welding are geared towards thin plate and sheet metal components generally not used in the design of pressure vessels. Resistance weld qualification tests are called shear tests and are given in Section IX, paragraph QW-196 [2].

In the design of seal welds for the DWPF canisters, burst tests are used to qualify the seal welds to meet the Section IX requirements. In using the burst tests, rather than the shear tests as called out in Section IX, it is felt that burst tests are a better indicator of the structural integrity of the seal welds and are also easier to implement than the shear tests for this application.

The analysis in this investigation will show the similarity of the state of strain in both tests. Neverthless, no attempt is made to evaluate the soundness (structural integrity) of the welding in the two processes.

Resistance Upset Welding

Resistance upset welding provides a reliable means of sealing the canisters and is well suited for use in the DWPF environment where its simplicity lends itself to remote, automatic operation. It is generally a solid-state process (no melting) using high temperature and force to bond materials over a very short time period (< 2.5 seconds in this case). These short times at elevated temperature minimize the formation of heat affected zone in the material surrounding the weld. Bonding occurs due to the grain growth across the interface during high temperature deformation. Plastic deformation is, therefore, a key factor in the formation of these solid welds. Solid-state welds thus formed are less susceptible to volumetric defects such as porosity from solubility changes during solidification of fusion welds.

MECHANICAL PROPERTIES

Base Metal

Mechanical properties of solution-annealed Type 304L stainless steel are obtained from Reference 3. True plastic strains are used for input into the finite element structural models. Table 1 gives the stress strain data used in the analyses.

Weld Metal

Mechanical properties of the metal at the weld interface change. Hardness values of the weld metal were determined from the actual samples of the canister weld. It is found that the hardness of the metal at the interface increases from the hardness of the annealed 304L hardness [4, 5]. An increase of 7% to 8% was found in Reference 4. No tensile tests were performed to obtain stress strain data for the weld metal. Since an increase in hardness increases the tensile strength in general, annealed 304L stress values were increased by this amount to obtain the weld material properties. Table 1 gives the stress strain data used in the analyses.

STRUCTURAL ANALYSIS

Basic Assumptions

The following assumptions are made in the analyses.

1. The canister resistance weld is free of cracks or other fabrication flaws. *This is confirmed from the metallography of the welds [4] where no voids or other flaws are observed.*
2. The canister weld is vertical and lies at the interface of the nozzle and the plug. *The interface is distorted during the welding process. However, small geometrical deviations in the analysis model will not affect the results significantly in this study.*
3. There are no significant residual stresses at the interface. It is expected that due to very thin interface where the metal flows during the welding process, any residual stresses are highly localized and will act like peak stresses with minimal distortion. *This assumption appears to be acceptable since failure during burst tests occur in the base metal and away from the weld interface.*
4. For the shear test on the weld between two plates, reduction in thickness at the spot or projection weld is negligible.

Methodology

The finite element methodology was used to evaluate the response of the canister-plug weld and the shear test at failure loads. Since the strains are large at failure loads, nonlinear analyses are necessary to obtain the correct response. The general purpose structural analysis computer code ABAQUS [6] was used to perform the analyses.

Acceptance Criteria

1. For the canister weld, the burst pressure is equal to or greater than 2600 psig [7].
2. For the shear test, the weld strength meets the requirements given in the ASME Code, Section IX, QW- 462.10 [2].
3. Failure strain for the stainless steel is 40% [3].

Applied Loads

The canister-plug weld is subjected to pressure loading. No other loading such as thermal or seismic is considered important for the overall integrity of the canister weld. The shear test is subjected to tension loading only at the free ends of the plates.

FINITE ELEMENT MODEL

Canister-Plug Weld

The basic dimensions for generating the FE model are given in Figure 1. Since the canister-plug weld geometry is axisymmetric, axisymmetric solid elements CAX4 in the ABAQUS computer code were utilized. A total of 2370 elements were modeled to capture the detailed deformation patterns.

A review of the weld geometry shows that a crevice (see Figure 3 in Reference 4) is formed at the bottom of the plug during the welding operation. This crevice results in lack of bonding at the very bottom of the plug . This lack of bonding acts as stress concentration point. The finite element model is modified to reflect this lack of bonding. Figure 2 shows the finite element mesh of the model.

Shear Test Model

The basic dimensions (Fig. 1) for generating the FE model were taken from drawing details of the shear test in the ASME Code, Section IX, QW-462.9 [2]. Solid continuum elements C3D8R were used to capture the response for large deformation. Five elements were used through the thickness of each plate to get a fine mesh necessary for the large deformation problem. Figure 3 shows the finite element mesh of the model.

ASME Code, Section IX, QW-196 [2] requires that the spot weld size be at least $0.9\sqrt{t}$, where "t" is the thickness of the thinner plate. For a 1/8 inch thick plate, this is equal to a spot weld of 0.3182" diameter. A rectangular weld area of 0.3125" x 0.375" was modeled in the finite element model. A rectangular weld area in lieu of a circular area was modeled for simplicity. A total of 6000 solid 8 noded elements were used.

Boundary Conditions

<u>Canister-Plug Weld Model.</u> For the canister weld model, the lower end of the nozzle was restrained in the axial direction. This restraint was considered sufficient since it was far away from the weld area. Coding of exact boundary conditions to reflect connection of the nozzle to the canister body will have insignificant effect on the results in the weld area.

Shear Test Model. For the shear test model, one end of the lower plate (Plate 1 in Fig. 3) was fixed. The free end of the upper plate (Plate 2) was restrained in all directions except the longitudinal pull direction. This simulates the end being held in a vise and pulled in the longitudinal pull direction.

ANALYSIS RESULTS

Failure load is calculated as the load when the maximum equivalent plastic strain reaches approximately 40% for any element. Equivalent plastic strain is listed as the PEEQ value in the ABAQUS output results. The results are tabulated in the tables given below. Actual failure loads from burst tests for the canister weld and minimum failure loads from the ASME Code, Section IX, QW-462.10 [2] for the shear test are also listed.

Canister-Plug Weld Results

Loading Condition	Failure Pressure from Analysis (psig)	Actual Failure Pressure from Burst Test(psig)	Maximum Plastic Strain, PEEQ [6] (%)
Pressure	9000	≈7000	24

For the canister-plug weld it was found that the maximum plastic strain was only approximately 24% at 9000 psig internal pressure. The analysis was stopped at this stage since a safety margin > 3 (9000/2600 = 3.46) exists at 9000 psig. A safety margin of 3 is considered adequate for evaluation by detailed analysis. The difference in the failure pessure values from analysis and burst test stems from the lack of actual stress strain data for the 304L and the weld metal, and the approximate geometry in the FE model. Weld build-up (a stress riser) at the top of the plug-nozzle interface or shift in the weld interface were not modeled in the FE model for simplicity. Figure 4 shows the deformed shape of the canister-plug model.

Shear Test Spot Weld Results

Loading Condition	Failure Load from Analysis (lbs)	Minimum Failure Load from QW-462.10 [2] (lbs)	Maximum Plastic Strain, PEEQ [6] (%)
Tension	4713	5065	40

The load calculation in the table above is based on a **minimum** spot weld of 0.3182" diameter as required in the paragraph QW-462.10 of the ASME Code, Section IX [2]. The difference in the failure load obtained in the analysis and the Section IX requirements can be explained from the lack of correct stress strain data for the plate material. However, the calculated load from the analysis gives good confidence in the finite element model to predict the failure mode for the shear test. Figure 5 shows the deformed shape of the shear model.

BURST TEST AND SHEAR TEST SIMILARITY

Due to the significant differences in the nature of the two tests, the similarity can be shown only qualitatively. Stress and strain magnitude and orientation are highly dependent on the geometry, type of loading, and the boundary conditions and as such a numerical comparison is difficult. However, some strain comparisons can be made at the elements which experience large deformation to determine the failure mode i.e. shear, tension, or compression. Relative principal strains will be calculated at integration points of those elements which experience large deformations. It is expected that these relative strain values will exhibit some dominant failure mode.

Table 2 gives the principal strain values (Lep's) in the order of their magnitudes at all integration points for the elements (at the resistance weld interface) which undergo large deformation during the canister weld model. From the principal strains, relative principal strain values are calculated by dividing the principal strains by magnitude of total strain to assess the state of strain. The magnitude of total strain is calculated as the square root of the sum of the squares (vector sum) of Lep's.

$$\text{Magnitude of total starin} = \sqrt{\text{Lep1}^2 + \text{Lep2}^2 + \text{Lep3}^2}$$

Table 3 gives the values of magnitude of strain and the the relative values of strains. Table 4 gives the principal strain values, magnitude of total strain, and the relative values of strains for the shear test model.

A review of the strain values in the state of strain columns shows that minimum and maximum strains are approximately equal and opposite in magnitude. The third strain is negligible in magnitude as compared to the other two strains. A review of the Mohr circle shows that the shear strain is maximum when the principal strains are approximately equal and opposite in magnitude. This state of strain clearly indicates that a shear dominant failure mode exists. This trend exists in both the tests and, therefore, it can be concluded that the failure mode in both the tests is shear. On this basis, the two tests are similar in nature.

CONCLUSIONS

1) Based on the detailed structural analyses of the burst test for the canister-plug weld and the shear test as required in the ASME Code, Section IX, QW-196 [2], it is found that the dominant failure mode for the two tests is shear. On this basis, the use of burst test for the canister weld in lieu of shear test is acceptable.

2) Based on the realistic material properties of 304L stainless steel and the weld metal, it is found that the canister-plug weld is structurally sound and can safely withstand 2600 psig of internal pressure.

ACKNOWLEDGEMENT

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REFERENCES

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[5] Kanne Jr., W. R., Solid State Resistance Welding of Cylinders and Spheres, Welding Journal, May 1986 pp 33-38.

[6] ABAQUS, Version 5-3, Hibbitt, Karlsson, & Sorensen, Inc., Pawtucket, Rhode Island, 1994.

[7] SRT-SPS-940066, Qualification of Resistance Welding Processes in the Defense Waste Processing Facility (U), Westinghouse Savannah River Co., Aiken, SC, May 1994.

Table 1 - Stress Strain (True) Data for SS304L and Weld Metal

Stress-Strain Data for SS304L		Stress-Strain Data for 304L Weld Metal	
Stress (psi)	Plastic Strain	Stress (psi)	Plastic Strain
37840	0.0000	40754	0.0000
39710	0.0014	42768	0.0014
41301	0.0029	44481	0.0029
42332	0.0046	45592	0.0046
43157	0.0062	46480	0.0062
43848	0.0079	47224	0.0079
44614	0.0095	48049	0.0095
45176	0.0111	48655	0.0111
45586	0.0127	49096	0.0127
46291	0.0143	49855	0.0143
46720	0.0162	50317	0.0162
47650	0.0192	51319	0.0192
48644	0.0222	52390	0.0222
49451	0.0253	53259	0.0253
50533	0.0284	54424	0.0284
51316	0.0313	55267	0.0313
51814	0.0343	55804	0.0343
52882	0.0373	56954	0.0373
53592	0.0404	57719	0.0404
55850	0.0490	60150	0.0490
58275	0.0573	62762	0.0573
60387	0.0654	65037	0.0654
62375	0.0735	67178	0.0735
64570	0.0816	69542	0.0816
66366	0.0895	71476	0.0895
68384	0.0974	73650	0.0974
70116	0.1053	75515	0.1053
71568	0.1131	77079	0.1131
73404	0.1208	79056	0.1208
75421	0.1285	81228	0.1285
77335	0.1362	83290	0.1362
78646	0.1438	84702	0.1438
80354	0.1513	86541	0.1513
81762	0.1587	88058	0.1587
83521	0.1662	89952	0.1662
85116	0.1736	91670	0.1736
86583	0.1810	93250	0.1810
88233	0.1882	95027	0.1882
89525	0.1955	96418	0.1955
91036	0.2027	98046	0.2027
92629	0.2098	99761	0.2098
94249	0.2168	101506	0.2168

95515	0.2238	102870	0.2238
96607	0.2308	104046	0.2308
98231	0.2377	105795	0.2377
99625	0.2446	107296	0.2446
101206	0.2514	108999	0.2514
102325	0.2582	110204	0.2582
103756	0.2650	111745	0.2650
105025	0.2717	113112	0.2717
106120	0.2784	114291	0.2784
107976	0.2852	116290	0.2852
108557	0.2918	116916	0.2918
109886	0.2984	118347	0.2984
111634	0.3051	120230	0.3051
111005	0.3117	119552	0.3117
114262	0.3183	123060	0.3183
115154	0.3248	124021	0.3248
116689	0.3314	125674	0.3314
117520	0.3379	126569	0.3379
118480	0.3445	127603	0.3445
120036	0.3510	129279	0.3510
121236	0.3575	130571	0.3575
122230	0.3640	131642	0.3640
123151	0.3697	132634	0.3697
123702	0.3719	133227	0.3719
124088	0.3741	133643	0.3741
124428	0.3763	134009	0.3763
124797	0.3783	134406	0.3783
125510	0.3806	135174	0.3806
125973	0.3828	135673	0.3828
126296	0.3849	136021	0.3849
126573	0.3871	136319	0.3871
126868	0.3893	136637	0.3893
127427	0.3914	137239	0.3914
127988	0.3936	137843	0.3936
128124	0.3957	137990	0.3957
128410	0.3979	138298	0.3979
128496	0.4001	138390	0.4001
129202	0.4023	139151	0.4023
129594	0.4045	139573	0.4045
129804	0.4067	139799	0.4067
130445	0.4089	140489	0.4089
131070	0.4111	141162	0.4111
131165	0.4133	141265	0.4133
131298	0.4155	141408	0.4155
131691	0.4177	141831	0.4177
132647	0.4200	142861	0.4200

132702	0.4221	142920	0.4221
132737	0.4243	142958	0.4243
133034	0.4265	143278	0.4265
134036	0.4288	144357	0.4288
133980	0.4310	144296	0.4310
134365	0.4333	144711	0.4333
134721	0.4355	145095	0.4355
135494	0.4377	145927	0.4377
135781	0.4399	146236	0.4399
136029	0.4422	146503	0.4422
136385	0.4445	146887	0.4445
136723	0.4467	147251	0.4467
137371	0.4490	147949	0.4490
137757	0.4513	148364	0.4513
138114	0.4536	148749	0.4536
138865	0.4559	149558	0.4559
138869	0.4582	149562	0.4582
139248	0.4605	149970	0.4605
139615	0.4628	150365	0.4628
140083	0.4652	150869	0.4652
140227	0.4675	151024	0.4675
140635	0.4698	151464	0.4698
141105	0.4721	151970	0.4721
141494	0.4745	152389	0.4745
141768	0.4768	152684	0.4768
142216	0.4793	153167	0.4793

Table 2 - State of Strain for Burst Test

	Minimum Principal Logarithmic Strain (Lep1)				Intermediate Principal Logarithmic Strain (Lep2)				Maximum Principal Logarithmic Strain (Lep3)			
Element Number	Integration Pt. 1	Integration Pt. 2	Integration Pt. 3	Integration Pt. 4	Integration Pt. 1	Integration Pt. 2	Integration Pt. 3	Integration Pt. 4	Integration Pt. 1	Integration Pt. 2	Integration Pt. 3	Integration Pt. 4
110	-0.017400	-0.017400	-0.017400	-0.017400	0.003976	-0.001576	-0.003454	-0.006529	0.012420	0.017972	0.019850	0.022925
170	-0.083479	-0.149700	-0.135200	-0.178800	-0.009834	-0.009834	-0.009834	-0.009834	0.095502	0.161700	0.147200	0.190800
230	-0.194300	-0.180500	-0.131900	-0.115300	-0.003830	-0.003830	-0.003830	-0.003830	0.201600	0.187800	0.139300	0.122700
290	-0.100200	-0.093427	-0.083689	-0.076060	-0.002123	-0.002123	-0.002123	-0.002123	0.104600	0.097852	0.088113	0.080484
350	-0.065746	-0.073466	-0.056698	-0.065750	-0.001349	-0.001349	-0.001349	-0.001349	0.069177	0.076897	0.060129	0.069182
410	-0.054394	-0.056830	-0.053466	-0.055958	-0.000506	-0.000506	-0.000506	-0.000506	0.056315	0.058751	0.055386	0.057878
470	-0.041398	-0.045943	-0.046715	-0.050855	0.000763	0.000763	0.000763	0.000763	0.041827	0.046372	0.047144	0.051284
530	-0.045778	-0.047600	-0.049083	-0.050793	0.002796	0.002796	0.002796	0.002796	0.043175	0.044997	0.046479	0.048190
590	-0.063225	-0.064260	-0.073455	-0.074369	0.005421	0.005421	0.005421	0.005421	0.056767	0.057803	0.066998	0.067911
650	-0.096402	-0.096967	-0.105400	-0.105900	0.008425	0.008425	0.008425	0.008425	0.086228	0.086793	0.095230	0.095753
2201	-0.054180	-0.046014	-0.082483	-0.077418	0.000568	0.000568	0.000568	0.000568	0.054429	0.046263	0.082732	0.077667
2241	-0.157500	-0.098970	-0.156700	-0.105100	-0.001266	-0.001266	-0.001266	-0.001266	0.162200	0.103700	0.161400	0.109900
2281	-0.053553	-0.059263	-0.034724	-0.043231	-0.002633	-0.002633	-0.002633	-0.002633	0.060521	0.066231	0.041692	0.050199
2321	-0.018291	-0.020902	-0.018383	-0.020996	-0.001894	-0.001894	-0.001894	-0.001894	0.023027	0.025638	0.023119	0.025732
2361	-0.030386	-0.031106	-0.030146	-0.030872	-0.001269	-0.001269	-0.001269	-0.001269	0.033845	0.034564	0.033605	0.034331
2401	-0.024540	-0.029561	-0.030103	-0.034428	-0.000772	-0.000772	-0.000772	-0.000772	0.026994	0.032014	0.032556	0.036881
2441	-0.026610	-0.027610	-0.030506	-0.031403	0.000198	0.000198	0.000198	0.000198	0.027570	0.028570	0.031466	0.032363
2481	-0.038367	-0.037794	-0.046703	-0.046252	0.001834	0.001834	0.001834	0.001834	0.036309	0.035736	0.044645	0.044194
2521	-0.063511	-0.063657	-0.069488	-0.069620	0.004015	0.004015	0.004015	0.004015	0.058143	0.058289	0.064120	0.064252
2561	-0.092585	-0.091575	-0.104800	-0.103900	0.006426	0.006426	0.006426	0.006426	0.084419	0.083409	0.096591	0.095696

Table 3 - State of Strain for Burst Test

Magnitude of total Strain				
Element Number	Integration Pt. 1	Integration Pt. 2	Integration Pt. 3	Integration Pt. 4
110	0.021745	0.025065	0.026622	0.029512
170	0.127225	0.220576	0.200109	0.261669
230	0.280017	0.260507	0.191877	0.168416
290	0.144864	0.135308	0.121541	0.110758
350	0.095445	0.106359	0.082656	0.095452
410	0.078297	0.081741	0.076984	0.080507
470	0.058855	0.065282	0.066373	0.072228
530	0.062988	0.065561	0.067655	0.070072
590	0.085143	0.086602	0.099568	0.100857
650	0.129613	0.130409	0.142299	0.143019
2201	0.076800	0.065252	0.116826	0.109663
2241	0.226090	0.143354	0.224959	0.152071
2281	0.080856	0.088913	0.054322	0.066301
2321	0.029468	0.033133	0.029597	0.033265
2361	0.045502	0.046517	0.045163	0.046188
2401	0.036489	0.043581	0.044347	0.050459
2441	0.038318	0.039732	0.043827	0.045095
2481	0.052856	0.052046	0.064635	0.063998
2521	0.086200	0.086406	0.094637	0.094823
2561	0.125459	0.124034	0.142668	0.141401

Table 3 - State of Strain for Burst Test (cont'd)

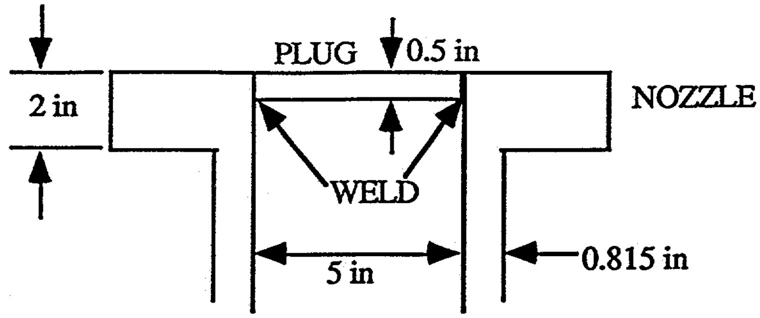
State of Strain (%)						
Element Number	Integration Pt. 1			Integration Pt. 2		
	Minimum (%)	Intermedi-ate (%)	Maximum (%)	Minimum (%)	Intermedi-ate (%)	Maximum (%)
110	-80.02	18.28	57.12	-69.42	-6.29	71.70
170	-65.62	-7.73	75.07	-67.87	-4.46	73.31
230	-69.39	-1.37	72.00	-69.29	-1.47	72.09
290	-69.17	-1.47	72.21	-69.05	-1.57	72.32
350	-68.88	-1.41	72.48	-69.07	-1.27	72.30
410	-69.47	-0.65	71.93	-69.52	-0.62	71.87
470	-70.34	1.30	71.07	-70.38	1.17	71.03
530	-72.68	4.44	68.54	-72.60	4.26	68.63
590	-74.26	6.37	66.67	-74.20	6.26	66.75
650	-74.38	6.50	66.53	-74.36	6.46	66.55
2201	-70.55	0.74	70.87	-70.52	0.87	70.90
2241	-69.66	-0.56	71.74	-69.04	-0.88	72.34
2281	-66.23	-3.26	74.85	-66.65	-2.96	74.49
2321	-62.07	-6.43	78.14	-63.09	-5.72	77.38
2361	-66.78	-2.79	74.38	-66.87	-2.73	74.30
2401	-67.25	-2.11	73.98	-67.83	-1.77	73.46
2441	-69.45	0.52	71.95	-69.49	0.50	71.91
2481	-72.59	3.47	68.69	-72.62	3.52	68.66
2521	-73.68	4.66	67.45	-73.67	4.65	67.46
2561	-73.80	5.12	67.29	-73.83	5.18	67.25

Table 3 - State of Strain for Burst Test (cont'd)

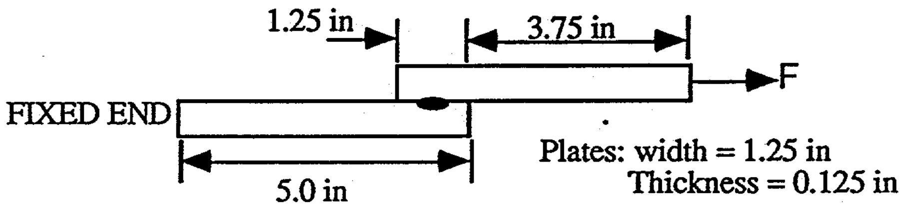
State of Strain (%)						
Element Number	Integration Pt. 3			Integration Pt. 4		
	Minimum (%)	Intermedi-ate (%)	Maximum (%)	Minimum (%)	Intermedi-ate (%)	Maximum (%)
110	-65.36	-12.97	74.56	-58.96	-22.12	77.68
170	-67.56	-4.91	73.56	-68.33	-3.76	72.92
230	-68.74	-2.00	72.60	-68.46	-2.27	72.86
290	-68.86	-1.75	72.50	-68.67	-1.92	72.67
350	-68.60	-1.63	72.75	-68.88	-1.41	72.48
410	-69.45	-0.66	71.95	-69.51	-0.63	71.89
470	-70.38	1.15	71.03	-70.41	1.06	71.00
530	-72.55	4.13	68.70	-72.49	3.99	68.77
590	-73.77	5.44	67.29	-73.74	5.37	67.33
650	-74.07	5.92	66.92	-74.05	5.89	66.95
2201	-70.60	0.49	70.82	-70.60	0.52	70.82
2241	-69.66	-0.56	71.75	-69.11	-0.83	72.27
2281	-63.92	-4.85	76.75	-65.20	-3.97	75.71
2321	-62.11	-6.40	78.11	-63.12	-5.69	77.35
2361	-66.75	-2.81	74.41	-66.84	-2.75	74.33
2401	-67.88	-1.74	73.41	-68.23	-1.53	73.09
2441	-69.61	0.45	71.80	-69.64	0.44	71.77
2481	-72.26	2.84	69.07	-72.27	2.87	69.06
2521	-73.43	4.24	67.75	-73.42	4.23	67.76
2561	-73.46	4.50	67.70	-73.48	4.54	67.68

Table 4 - State of Strain for Shear Test

Element Number	Minimum Principal Log Strain Lep1	Intermediate Principal Log Strain Lep2	Maximum Principal Log Strain Lep3	Magnitude of Total Strain	State of Strain		
					Minimum (%)	Intermediate (%)	Maximum (%)
1488	-0.0945	-0.0109	0.1070	0.1432	-66.02	-7.61	74.72
1489	-0.0938	-0.0031	0.0981	0.1358	-69.10	-2.25	72.25
1490	-0.0800	-0.0004	0.0805	0.1135	-70.50	-0.34	70.92
1491	-0.1016	-0.0003	0.1029	0.1446	-70.26	-0.24	71.16
1492	-0.1072	-0.0015	0.1080	0.1522	-70.44	-1.00	70.97
1788	-0.1013	0.0089	0.0944	0.1387	-73.01	6.41	68.03
1789	-0.0877	0.0049	0.0819	0.1201	-73.02	4.09	68.20
1790	-0.0634	0.0031	0.0598	0.0872	-72.71	3.53	68.56
1791	-0.0947	0.0058	0.0882	0.1295	-73.07	4.51	68.12
1792	-0.1094	0.0082	0.1010	0.1491	-73.36	5.49	67.73
2088	-0.0653	-0.0081	0.0749	0.0997	-65.48	-8.17	75.14
2089	-0.0576	-0.0026	0.0614	0.0843	-68.36	-3.08	72.92
2090	-0.0479	-0.0021	0.0499	0.0692	-69.21	-3.01	72.12
2091	-0.0689	-0.0036	0.0735	0.1008	-68.34	-3.58	72.91
2092	-0.0744	-0.0050	0.0785	0.1083	-68.72	-4.63	72.50
4208	-0.2989	-0.0154	0.3171	0.4360	-68.55	-3.54	72.72
4209	-0.1945	-0.0048	0.1993	0.2785	-69.83	-1.72	71.56
4210	-0.1680	-0.0004	0.1692	0.2384	-70.46	-0.16	70.96
4211	-0.1859	-0.0071	0.1933	0.2683	-69.29	-2.66	72.05
4212	-0.3020	-0.0168	0.3224	0.4421	-68.31	-3.80	72.93
4508	-0.1784	0.0148	0.1637	0.2426	-73.54	6.11	67.48
4509	-0.0577	0.0065	0.0515	0.0776	-74.33	8.32	66.37
4510	-0.0310	0.0014	0.0289	0.0424	-73.08	3.22	68.18
4511	-0.0597	0.0094	0.0507	0.0789	-75.68	11.87	64.27
4512	-0.1924	0.0195	0.1736	0.2599	-74.04	7.50	66.80
4808	-0.2064	-0.0128	0.2217	0.3032	-68.08	-4.24	73.13
4809	-0.1300	-0.0041	0.1338	0.1866	-69.67	-2.22	71.70
4810	-0.1075	-0.0009	0.1091	0.1532	-70.19	-0.56	71.23
4811	-0.1194	-0.0075	0.1269	0.1744	-68.46	-4.32	72.76
4812	-0.2030	-0.0176	0.2242	0.3030	-67.01	-5.82	74.00



CANISTER-PLUG WELD



ASME SECTION IX SHEAR TEST

FIGURE 1 - Canister-Plug Weld and Shear Test Geometry

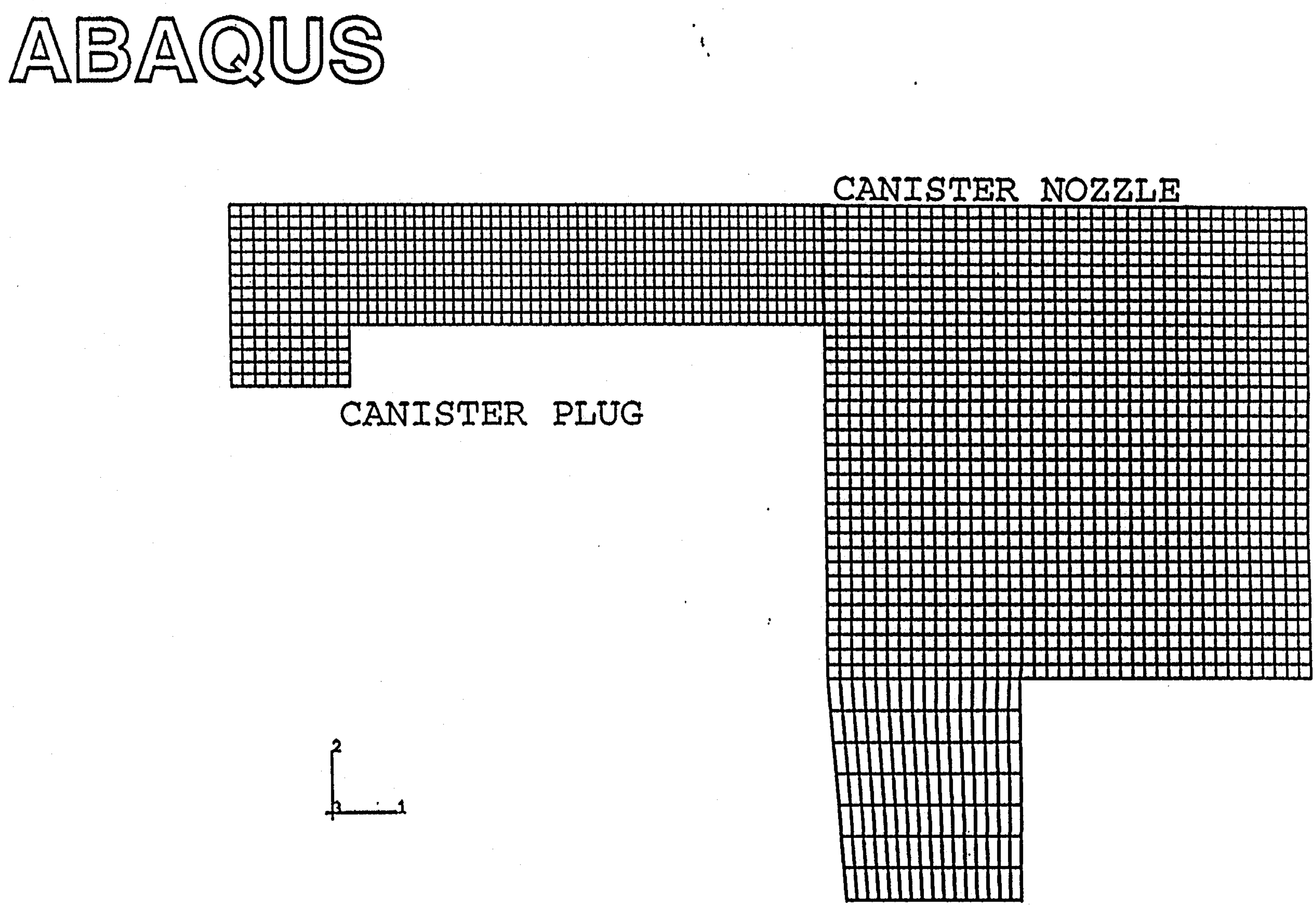


FIGURE 2 - Finite Element Mesh of the Canister-Plug Weld

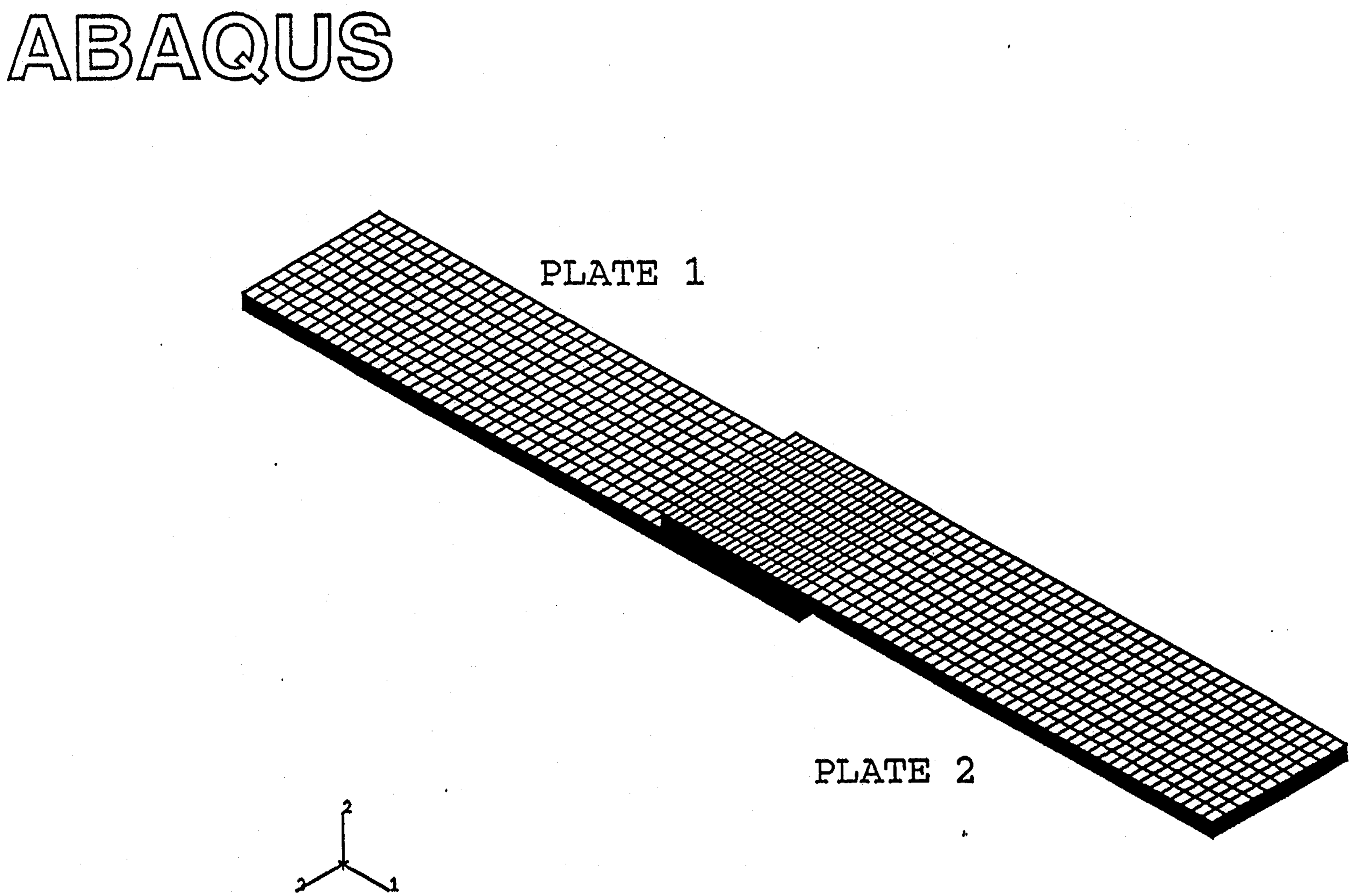


FIGURE 3 - Finite Element Mesh of the Shear Test Weld

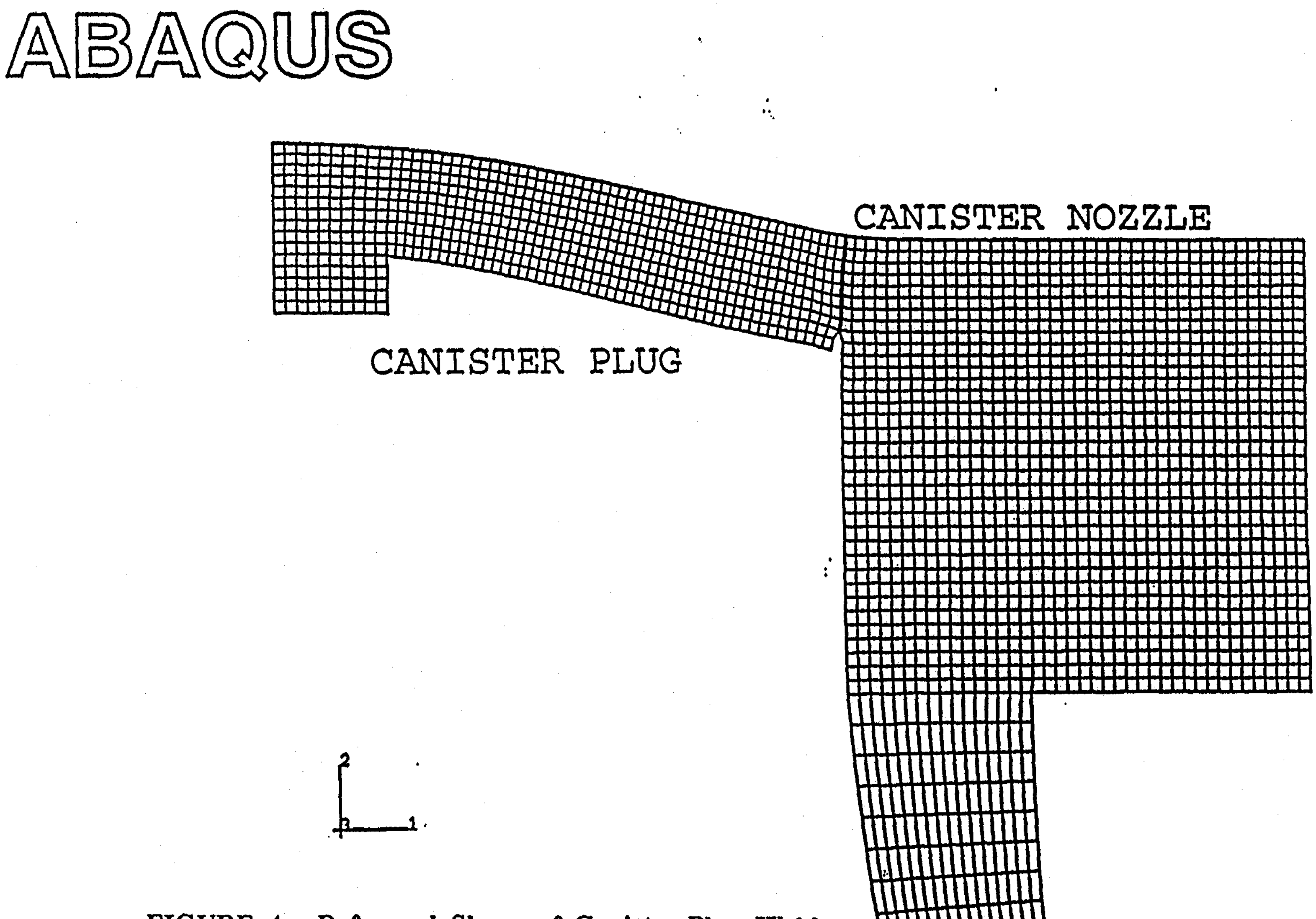


FIGURE 4 - Deformed Shape of Canister-Plug Weld
(Magnification Factor = 1)

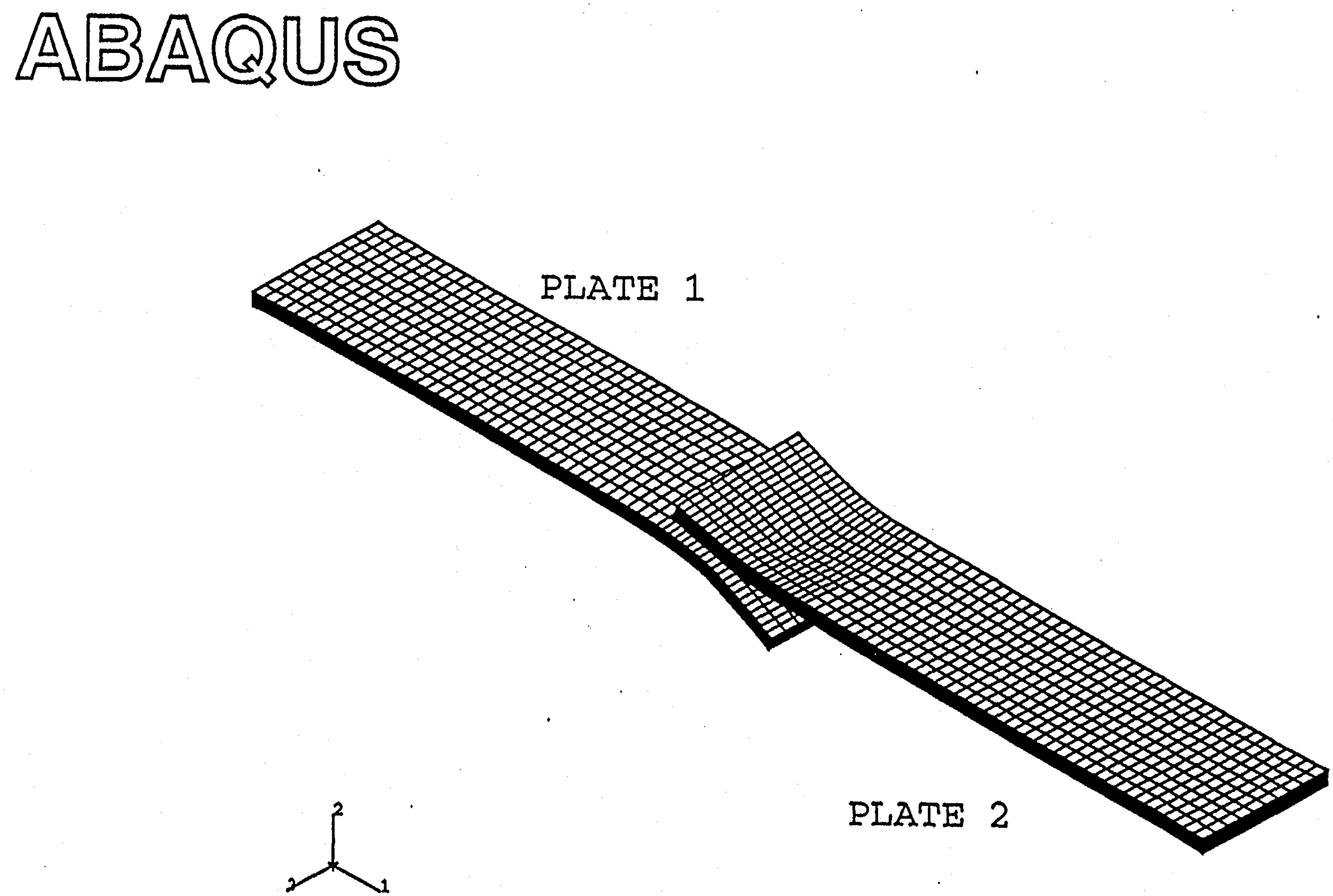


FIGURE 5 - Deformed Shape of the Shear Test Weld
(Magnification Factor = 1)