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Experimental Studies on the Tripping Behavior of Narrow T-Stiffened Flat Plates Subjected to Hydrostatic Pressure and Underwater Shock

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An experimental investigation was conducted to determined the static and dynamic responses of a specific stiffened flat plate design. The air-backed rectangular flat plates of 6061-T6 aluminum with an externally machined longitudinal narrow-flanged T-stiffener and clamped boundary conditions were subjected to static loading by water hydropump pressure and shock loading from an eight pound TNT charge detonated underwater. The dynamic test plate was instrumented to measure transient strains and free-field pressure. The static test plate was instrumented to measure transient strains, plate deflection, and pressure. Emphases was placed upon forcing static and dynamic stiffener tripping, obtaining relevant strain and pressure data, and studying the associated plate-stiffener behavior.

INTRODUCTION

Military submarine hull design has concentrated on the basic structural element, a stiffener reinforced shell. The submarine shell/stiffener form is the ring stiffened cylinder. The cylinder construction, which is the least expensive and the simplest form of shell construction, takes advantage of the high strength levels in high-strength materials through the use of ring stiffeners allowing higher load bearing capacities without the cylinder becoming unstable. Additionally, high-strength material is used for its toughness (due to low temperature requirements) and resistance to high dynamic loads (e.g., depth charge attack) [1].

The submarine ring stiffened cylinder is designed with generous safety margins against overall collapse triggered by frame yielding or tripping [1]. Tripping, a lateral-torsional buckling of stiffeners which have low lateral-torsional rigidity, has been identified as a potential form of catastrophic collapse which may take place with but a single application of load. The stiffener tripping form of collapse is a sudden and drastic reduction in load-carrying ability, a damage mechanism which occurs through compression plastic instability affecting a large critical region of cross-section. Predictions of this prime modeof failure need to be supported by good test data that is inside the current ship design range. To date, supporting experimental data gor this panel and grillage behavior is extremely scarce. Generous safety margins have been the accepted practice to avoid premature sideways tripping rather than to predict it. However, avoidance design is really an extension of design based on acceptable risk, where additional strength is necessary to provide a certain level of safety against extreme conditions [2]. Avoidance designs may not be the answer since stiffeners (i.e. frames) may over play their part and, because of excess rigidity, actually cause premature failure of the shell by inducing in it additional components of stress. It has been observed that the cause of ultimate collapse in the plating of a "thin-walled" shell is excessive circumferential stress rather than longitudinal stress and there may be excessive yielding of the shell at the toes of frame flanges (before collapse finally occurs) due to high circumferential stress [3]. The alternative approach is then: how weak may the frame rings be and still be adequate? It has been generally recognized that a stronger, more resilient type of construction is that in which frames and shell are nearly equal in strength as opposed to a hard-framed structure.

Frame dimensions are also of concern; using high web height- to-thickness ratios could lead to designs for which local stiffener tripping becomes important since excessively slender frame proportions make the frame sensitive to any tilt. Also, internal frames are equally sensitive to the effects of any tilt in bringing about tripping of frames under load. This mode of failure is usually a result of coupled flexural and torsional modes of buckling. The result in any of these cases being the same (i.e., general instability of the frame and shell in unison causing failure of the submarine hull under external pressure).

Submarine hulls require the high structural efficiency which can be achieved by reducing the excess rigidity of frames, (i.e., minimizing stress concentration). Accordingly, if frame weight can be reduced in the process and that amount of weight used in additional thickness of the shell, the cylinder's collapse strength will effectively be increased. The careful choice of ring-stiffened geometry can have a significant influence on shell performance, but there is a general lack of agreement on what the "appropriate" general collapse loads for ring-stiffened cylinders are [4].

OBJECTIVE

Submarine hull failure is a complex process involving stages of failure including initial yielding, large displacments, local instability, and finally collapse. Analysis of grillage failure and knowledge of plating behavior throughout the load range is necessary, both statically and dynamically. It is therefore of considerable importance to be able to predict the safe buckling behavior through general and reliable methods of analysis which provide necessary correlations between sea loads and their effects on a structure. According to A. E. Mansour [5], no satisfactory analysis method exists for inelastic tripping of stiffeners welded to continuous plating or for the prediction of the inelastic collapse strength. Therefore, it is more than a matter of being able to predict stresses, but the way in which the stresses are used to anticipate failure.

This investigation and analysis will follow the guideline that in many physical problems, resort to experiment is often the shortest cut to a decision as to which analyses need be made and what effects are important in those analyses [6]. Employing this guideline, data obtained on specific model design of a longitudinally narrow-flanged T-stiffened rectangular flat plate under static and dynamic (i.e., underwater charge detonation) conditions, will be investigated and analyzed.

STRUCTURE BEHAVIOR

STATIC TRIPPING PHENOMENA

Tripping (or compound failure), as shown in Figure 1, will be discussed here qualitatively in terms of a rectangular flat plate stiffened by a T-stiffener.

Generally speaking, stiffener bending stress arises from the reaction of a plating-stiffener combination to a loading (i.e. water pressure) normal to the plating, while the plating itself acts as one flange of this system. In the case of a ship hull, the shell plating performs functions of contouring and sealing in addition to sharing the load carrying requirement with the stiffeners, (ring stiffeners in the case of submarines) [7].

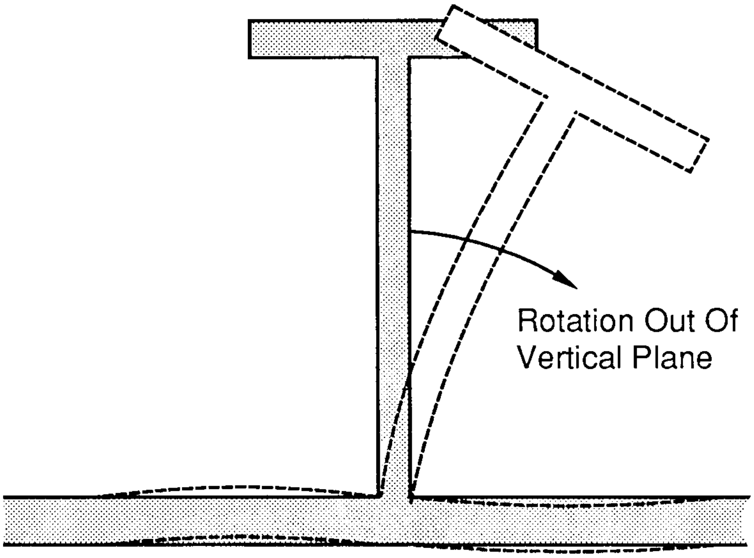


Figure 1 Stiffener Triping

The web of the T-stiffener can be considered a plate restrained against rotation (hinged) along one edge, free and elastically supported by the flange on the other one (the restraining effect of the web on the flange being small). Also, the flange can be thought of as a plate simply supported by the web along one side and free on the other [8]. In an actual structure, a stiffener welded to one side of a plate results in a considerable increase in the flexural rigidity of the stiffener since the adjacent zones of the plate take part in the bending of the deflected stiffener, that is, the stiffeners not only carry a portion of the load but subdivide the plate into smaller panels, thus increasing the critical stress at which the plate will buckle [8]. Additionally, there occurs an incompatibility of the buckling patterns (as favored by the web and the flange) which tends to make the buckling load higher than it would be for either the web or the flange of the stiffener alone [9]. Therefore, such combinations maybe able to support loads well above the load for local buckling of the plate.

Even though there is a substantial restraining effect of the plate on the stiffener and of the stiffener on the plate, there are also plate-stiffener destabilizing influences on each other. The fact that the plate prevents the stiffener from moving laterally in any other way except by rotation around the toe of the web, dictates the form of failure called tripping. This mode of failure involves the twisting of the stiffener about its line of attachment to the plating, a coupled displacement combination of sideways flexure and stiffener rotation. For example, as the load orthogonal to the plate increases, the effectiveness of the plate decreases until at some limiting stress the stiffener-plate combination fails and as the plate buckles, the rotational constraint provided by the plate at the line of attachment of the stiffener changes, thus increasing the stiffener's sensitivity to tripping. Once the stiffener starts lateral torsional buckling, any increase in deformation will cause an unloading which is triggered by yielding after considerable deformation. [2]

There is the possibility that under extreme conditions a submarine hull ring stiffener may trip. If such deformations were to become large, the support furnished by the ring to the cylinder hull would be impaired and there would be a redistribution of pressure resistance to adjacent rings resulting in a rapid deterioration in the general capacity of the shell to resist pressure.

DYNAMIC RESPONSE

Under static loading, stresses and strains are generally distributed throughout the entire body and every part of the body has an opportunity to participate. However, under impulsive loading, transient and highly localized stresses and strains exist in the rapidly changing stress system. This dynamic phenomenon involves interactions between inertial, hydrodynamic, and elastic forces which can arise as a consequence of the detonation of an explosive charge. The structural response to a plain step shock wave has attracted considerable interest since steep-fronted shock waves are characteristic of underwater explosions (UNDEX) and have similar properties [10].

The large amount of energy that is transmitted to a structure (when it is dynamically loaded) distributes itself within the metal and much of the absorbed energy is observed in the form of macroscopic and microscopic inelastic deformations. It has been noted that the critical value of the equivalent static pressure in dynamic loading is considerably higher than the static buckling pressure. The critical load is so high that buckling is plastically initiated (i.e., an unstable behavior called dynamic plastic buckling) [11]. This is a consequence to two uniquely dynamic effects. First, the shape of the structure impulsively loaded and constraints imposed upon it frequently determine both the location and the amount of plastic flow that will take place. Secondly, the intense transient stress disturbances and the extremely high pressures and rapid loading rates of impulsive loads may markedly influence the following mechanical properties of the metal being loaded: the hardness may increase, the tensile strength may go up, and yield and plastic flow characteristics are altered. Metal behavior is strongly contingent upon stress level. That is, metal possesses rigidity when elastic, but at very high stress levels it completely loses its rigidity. [12,13]

EXPERIMENT AND MODEL DESIGN

BASIC MODEL

The intention to this investigation and the several preceding it [14,15,16] has been to use one basic flat plate model and vary the stiffener types and plate thicknesses so that the UNDerwater EXplosion (UNDEX) shock response of these different geometries could be studied. But, due to several equipment failures, stiffener design geometries which showed no instability, and strain gage over-ranging, there was not a significant amount of dynamic tripping information compiled. However, each attempt was an invaluable step in the process of developing the proper model and the necessary experimental expertise.

It was clear that the model should be redesigned since no obvious tripping behavior was demonstrated in any of the previous four underwater shock tests. Also, as a preventive measure against equipment failure and strain gage over-ranging, a static test was performed (on a model of the same geometry as the redesigned test panel) to field test the same type of strain gages and same equipment used in the undex test.

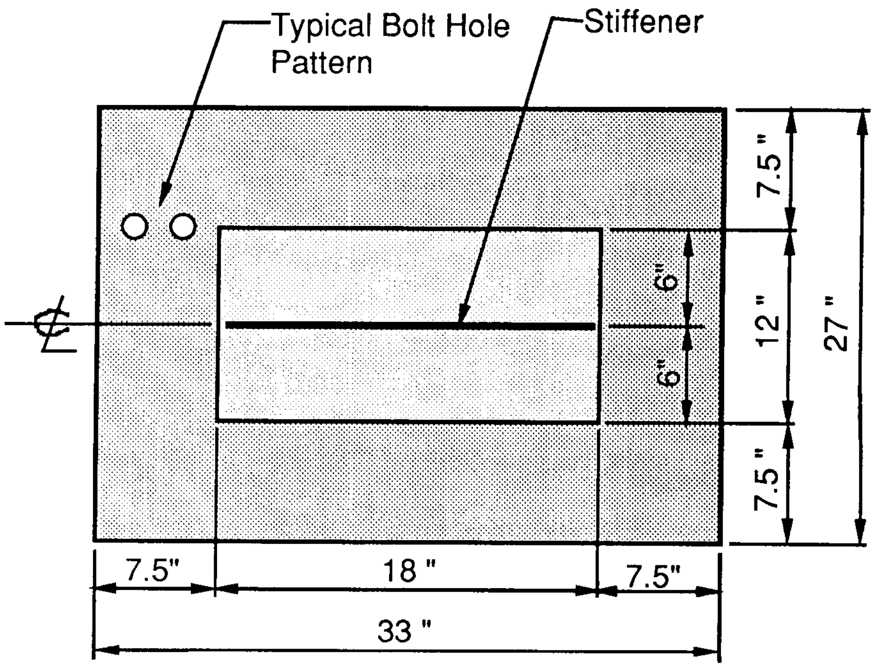
The new test panel was designed after closely examining the physical deformations of each of the previous undex test panels. The objective was to combine the greatest plate deflection with the most sensitive stiffener. The model plate thickness used in the Rentz and Shin investigation [14] exhibited the most favorable plate deformation, while the rectangular stiffener behavior in the Langan investigation [16] gave the most promise of showing instability. Based on this, the model established was a 0.1875 inch thick test panel, 18 inches in length by 12 inches in width, machined out of the center of a 6061-T6 aluminum blank measuring 27 inches by 33 inches and two inches thick. One free-standing longitudinal narrow-flanged external T-stiffener (vice a rectangular stiffener) was machined as an integral part of the plate. The T-stiffener web slenderness ratio (i.e., web height divided by its thickness) was also increased to enhance the stiffener's sensitivity to plate deflection. Additionally, to avoid the stiffener end tensile fractures observed in previous tests, the T-stiffener ends were detached from the boundaries of the cavity as shown in Figure 2.

STATIC TEST

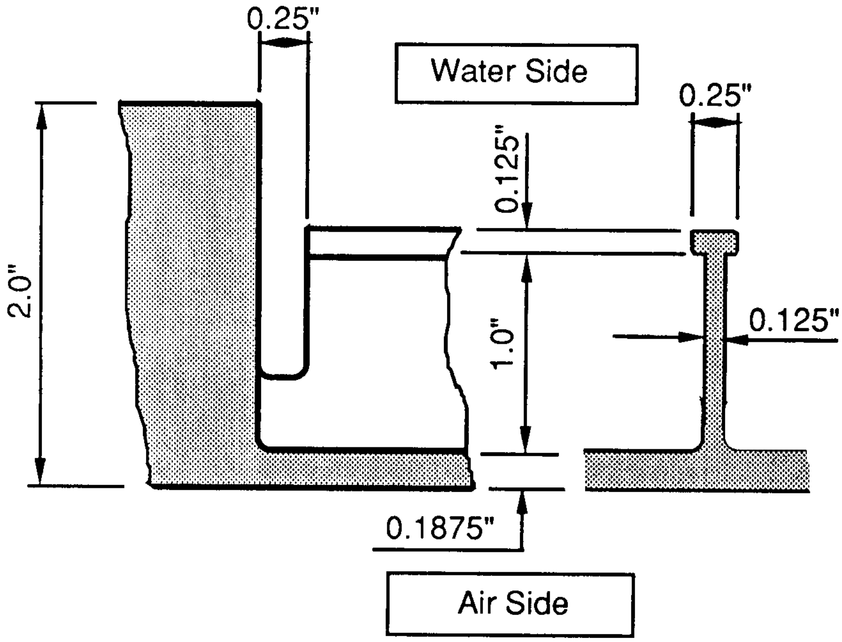
In order to verify the reliability (under more controlled conditions) of all the electronic equipment, cabling, and strain gage type (and attachment) that would be used for the underwater shock test, a static test was performed. The static test also was expected to provide valuable insight into the behavior of the redesigned test panel and the opportunity of comparing the static and the dynamic responses of a specific plate-stiffener geometry.

The experimental procedure was intentionally kept as simple as possible with the desire to collect only strain and deflection data as the stiffened plate (i.e., test panel) was deformed by increasing water pressure from zero psi to 350 psi. This pressure range was selected to cause approximately a four plate thickness deflection (deflection predictions calculated using the finite element/finite central difference computer code, EPSA, Elasto Plastic Shell Analysis) [14]. It was expected that this amount of deflection would produce tripping behavior in the stiffener. The test configuration was as shown in Figure 3.

The strongback used to enclose the test panel cavity, see Figure 4, was machined from a one inch thick high strength steel sheet and was drilled and tapped for standard three-quarter inch pipe fittings for a low point filling connection and a high point vent. Between the inlet valve and strongback there was installed a zero to 400 psig Ashcroft pressure gage and the high point vent was fitted with a standard three-quarter inch gate valve. To provide an adequate pressure seal, the strongback and test panel mating surfaces were coated with a Permatex high pressure sealant and separated by a precut one-eighth inch thick cork gasket. The test panel and strongback were then secured together by 28, one inch in diameter, A325 high strength structureal steel bolts and torqued to 500 ft-lbs. The test medium was potable water and was used to gradually fill the test panel cavity and purge it of all air. The source of applied pressure was a manually operated, single piston, reciprocating hydropump rated for 1000 psi. A check valve and gate valve arrangement was used to regulate the pressure in 25 psi increments from zero psi to 350 psi. Several minutes (2 to 3 minutes) were needed at each increment to allow deflection readings to be obtained. The strain



TOP VIEW OF TEST PANEL



SIDE-VIEW OF STIFFENER

Figure 2. Test Panel with Longitudinal Narrow-Flanged T-Stiffener

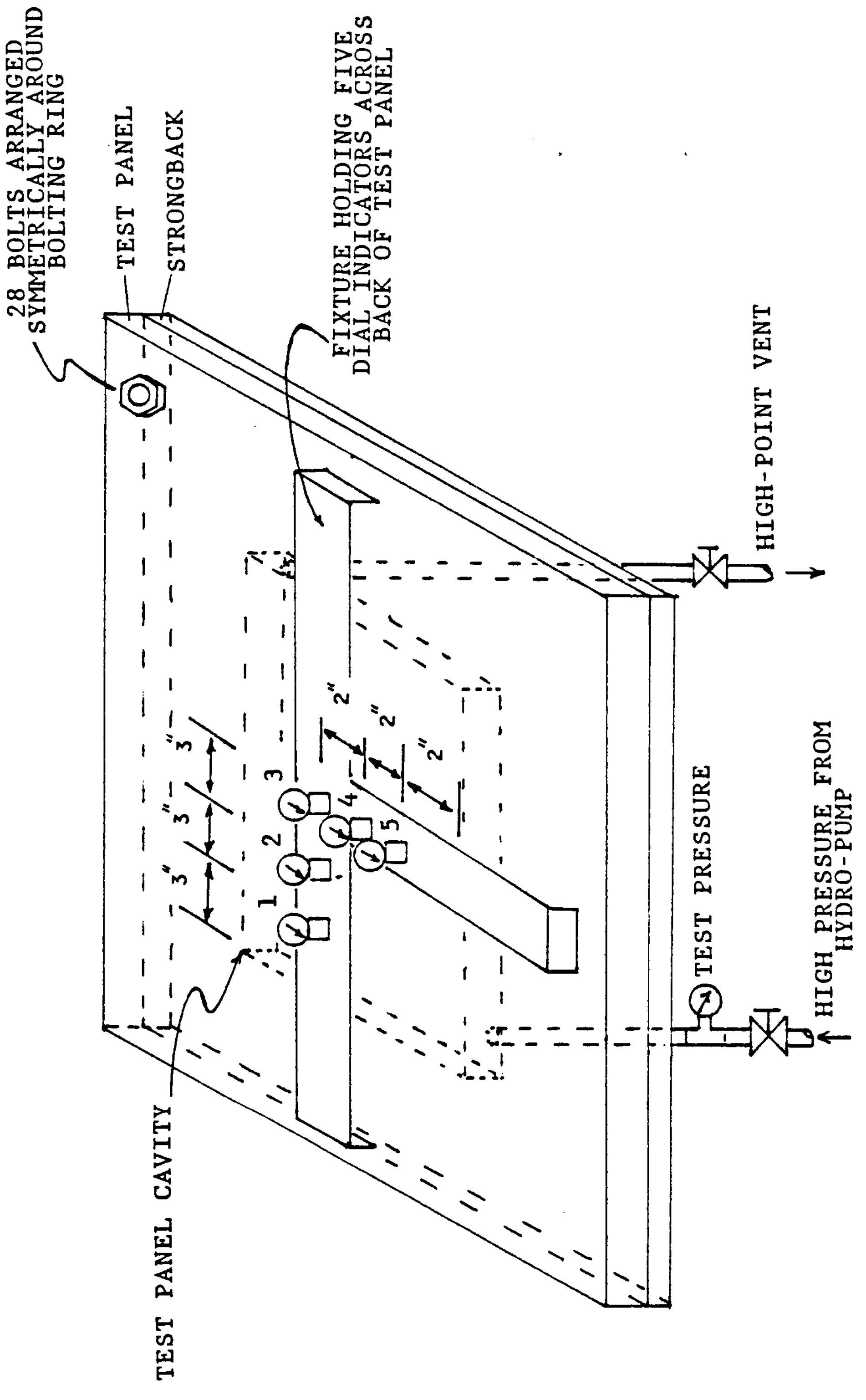


Figure 3 Static Test Configuration

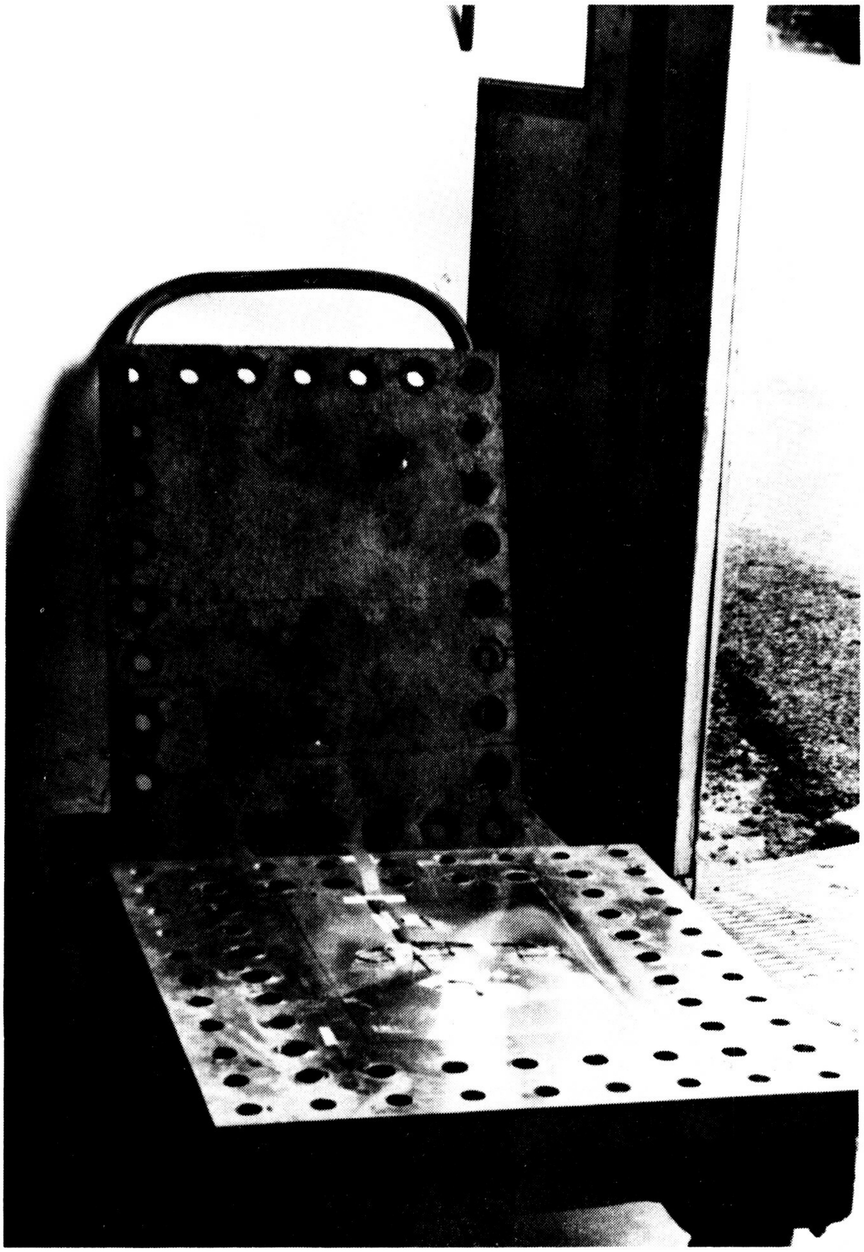


Figure 4. Static Test Strongback(Upper) and Test Panel(Lower)

measurments were recorded continuously on a magnetic tape recorder. Strain gage arrangement and details of the electronic instrumentation will be discussed in the underwater shock test section.

UNDERWATER SHOCK TEST

UNDEX EXPERIMENT DESIGN

It is well known that the shock wave loading of a body by an underwater explosion is complicated considerably by the secondary effects of the explosion phenomena. Therefore, as in previous studies [14,15,16], by using the correct test configuration and sample time window, the data sampling can essentially be limited to the response of the test panel to the incident shock wave emanating from the charge. Consequently, the secondary effects from bulk cavitation, cavitation closure, reloading from the explosive gas bubble and bubble migration, surface cutoff, and bottom reflections can be avoided or ignored [17].

The initial studies mentioned used eight pounds of TNT at a depth of four feet with a ten foot stand-off in an attempt to produce the necessary plate deflection to force stiffener tripping. Post-shot analysis of the four undex tests' pressure data [14,15,16] indicated that the TNT charges were not of a calibrated type and were reacting typically thirty percent greater in charge size (i.e., 8 lb charge was exploding with the force of a 10.4 lb TNT charge even though no booster charge was used). Under the assumption that all other eight pound TNT charges used would continue to react as larger sized charges, all test panel standoff and explosive charge depth calculations were made on the basis that the explosive charge would react approximately as a 10 pound TNT charge. Accordingly, it was determined that the charge depth be 4.5 feet with a test panel standoff of 10 feet. Using this test configuration and a four millisecond sample windown, the response expected would be that of a test panel experiencing an approximately plane shock wave.

TEST CONFIGURATION

All undex testing was performed at the West Coast Shock Facility (WCSF), Hunter's Point Naval Shipyard, San Francisco, California.

In order to simulate a hull configuration and to ensure fully clamped boundary conditions, the test panel was securely bolted to the air-back chamber shown in Figure 5, designed by Rentz and Shin [14]. Note that the stiffener is exposed so that the loading conditions at the plate center will be compressive (i.e., enhancing the possibility of tripping).

For the actual testing the test panel and chamber combination was suspended as shown in Figure 6 by steel cables attached to two pneumatic fenders. The critical dimensions of the test configuration are: charge depth set at 4.5 feet, test panel/chamber standoff of 10 feet, and two free-field pressure gages set to measure incident pressure at a ten foot standoff radius. A pressure gage was also attached to the test panel exposed surface to measure fluid pressure at the plate.

Strain measurements were taken on both the water exposed side and the air-backed side of the test panel as shown by Figure 7. The strain gage placement was determined on the basis of symmetry and the stiffener position. Consequently, the strains observed should be consistent with their position on the plate and would approximate the values and trends exhibited by symmetrically equal positions on other portions of the plate. Additionally, gages on the stiffener flange should be the first to show tripping effects, with the longitudinal array of three gages on the airside centerline soom mimicking the same trend.

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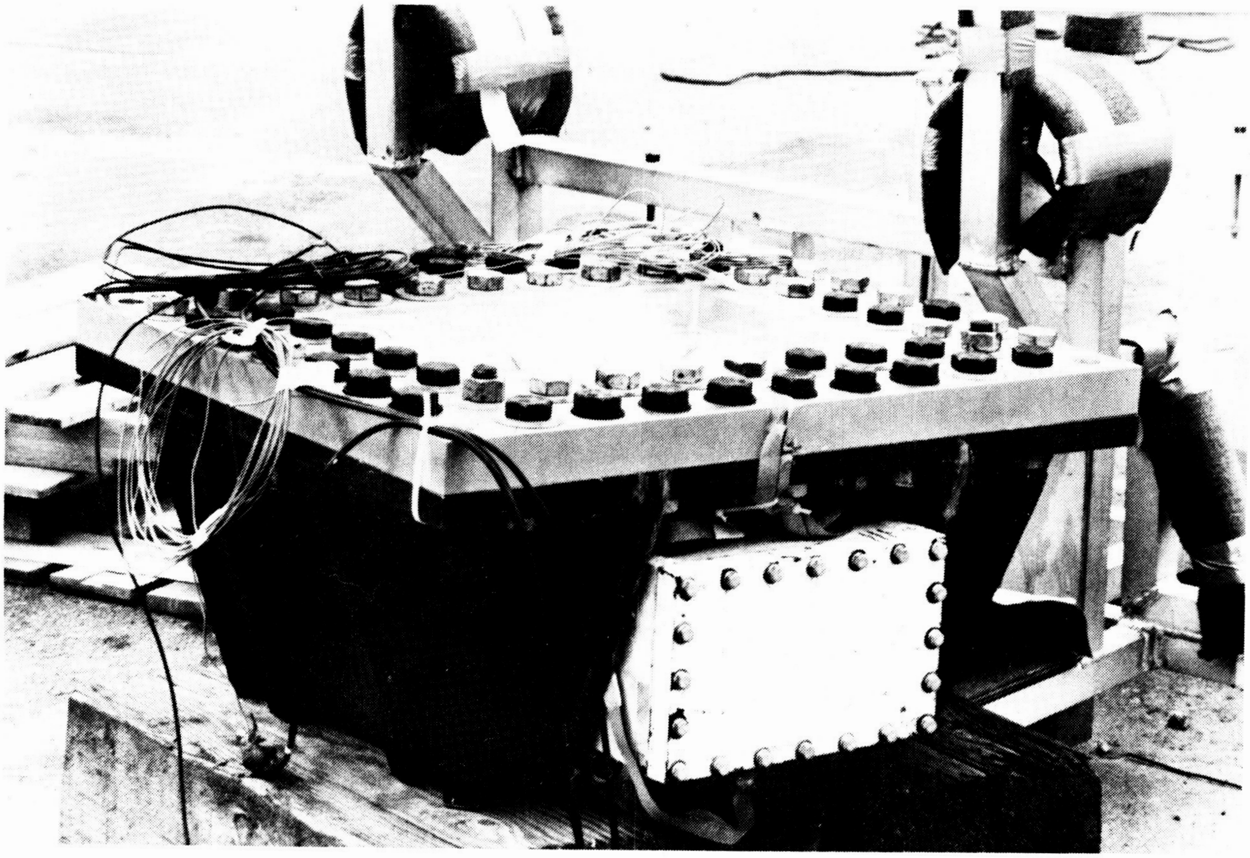

Figure 5. Test Panel Bolted to Air-Back Chamber

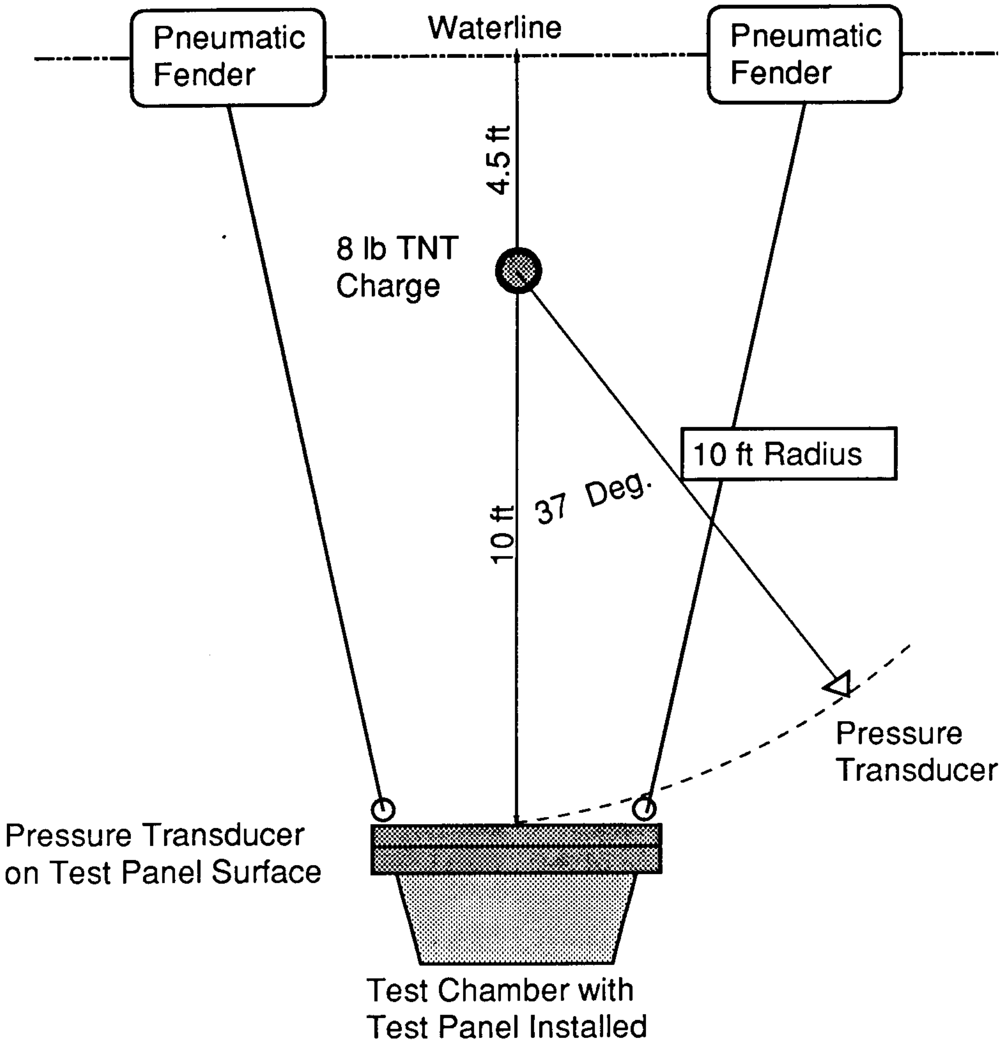

Figure 6. Schematic of UNDEX Test Geometry

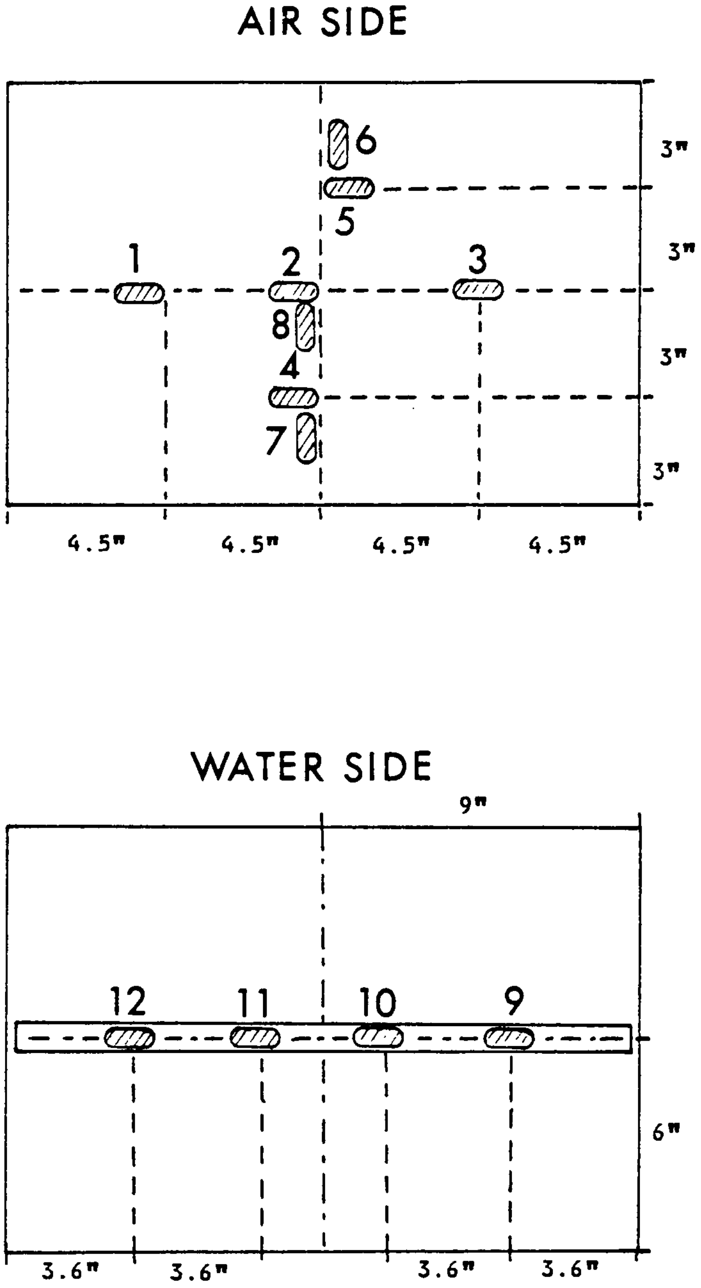

Figure 7 Diagram of Strain Gage Placement

INSTRUMENTATION

Twelve strain gages and three pressure transduces were placed as previously discussed and depicted in Figure 7. The strain gages were attached as described in [14] and coated with silicone sealant to ensure water tight integrity. The tourmaline pressure transducers were tied in their respective positions.

SPECIFICATIONS OF EQUIPMENT

EQUIPMENT	TYPE	RANGE
strain gages	CEA-350 ohms	50k microstrain
pressure transducers		.25" Tourmaline 10 ksi, 97% response ratio
amplifiers	Ektron 563F J	------------------

Two Honeywell MD-101 Wideband II (direct record) tape units were used to record all data channels at a tape speed of 120 inches-per-second. Post-shot processing of the recorded strain and pressure data was through the NPS Vibrations Laboratory's HP-5451C Fourier Analyzer. Equipment specifications are listed above.

RESULTS AND DISCUSSION OF DATA

STATIC TEST RESULTS

The static pressure deflection test of the panel machined for this purpose, proved to be a source of very good strain and deflection data showing the plate/stiffener behavior building up to elastic tripping as increasing water pressure deformed the plate. Deflections were measured by dial indicators at positions 1 through 5 as shown in Figure 3, the results of which appear in Table 1 and Figure 8. Deflections are again represented in Figure 9, but here deflection has been normalized to pressure at each 25 psi increment. Note the well defined regions for plastic, formation of fully plastic hinge, and elastic tripping behaviors.

Strain data was continuously recorded on the Honeywell MD-II at a tape speed of 1.87 inches per second, over the entire forty minute period needed to perform the test. Ten strain gages performed very satisfactorily while two (SG-5 and SG-11) failed for unknown reasons. The recorded strain history for each surviving gage was then displayed by a strip-chart recorded, thus providing the traces seen in Figures 10 through 13. Table 2 contains the strain values recorded at each pressure increment for each strain gage.

The effect of stiffener unloading and stress redistribution as the stiffener began to elastically trip can be clearly seen in Figures 10 and 11. The region of the plate most sensitive to symmetrical stiffener tripping would be the area near the toe of the web, accordingly strain gage SG-2 would and did first sense the stiffener unloading. Additionally the center of the plate and the stiffener continued to be areas of largest strain (SG-2 and SG-10) until elastic tripping was observed at approximately 225 psi, at which point the stiffener web was elastically buckling and unloading as was demonstrated in all other regions of the plate (Figures 12 and 13). Also note that strains monitored at the far ends of the stiffener (SG-1, 3, 9, 10 and 12) continued to increase until elastic tripping occurred, at which point the rate of strain-increase became greater at these

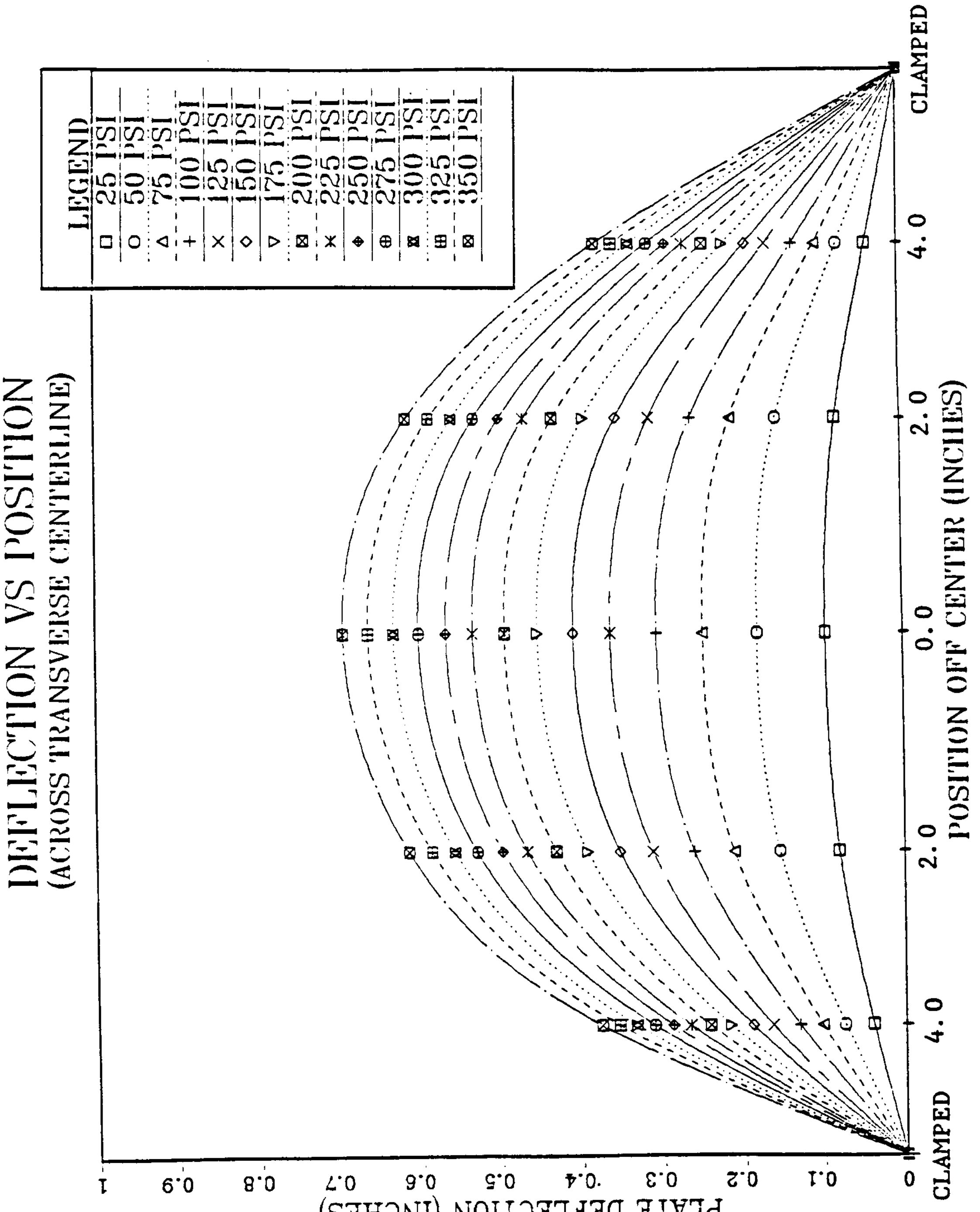

Figure 8 Plot of Static Deflection Test Results

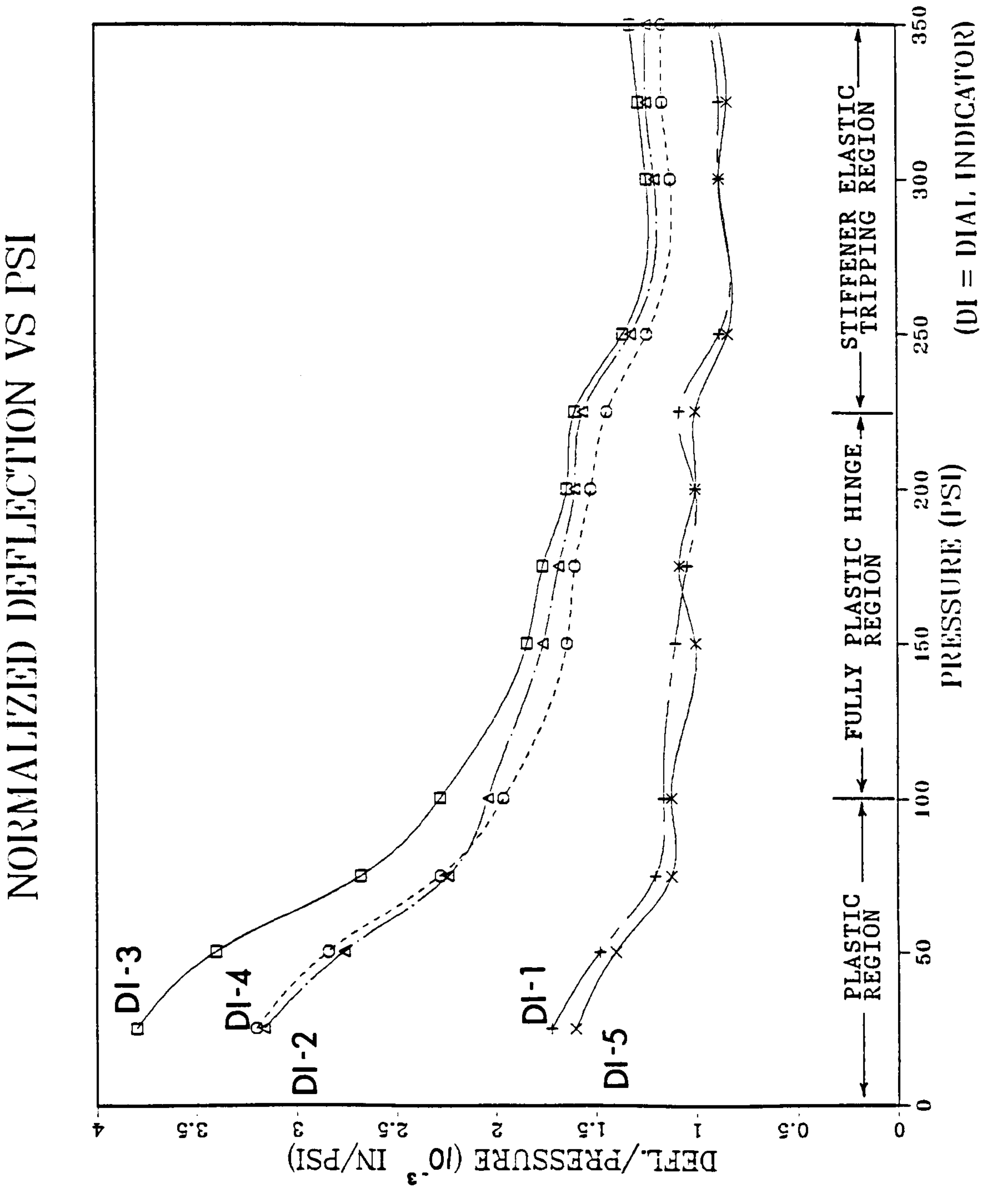

Figure 9 Plot of Static Deflection Normalized to Pressure

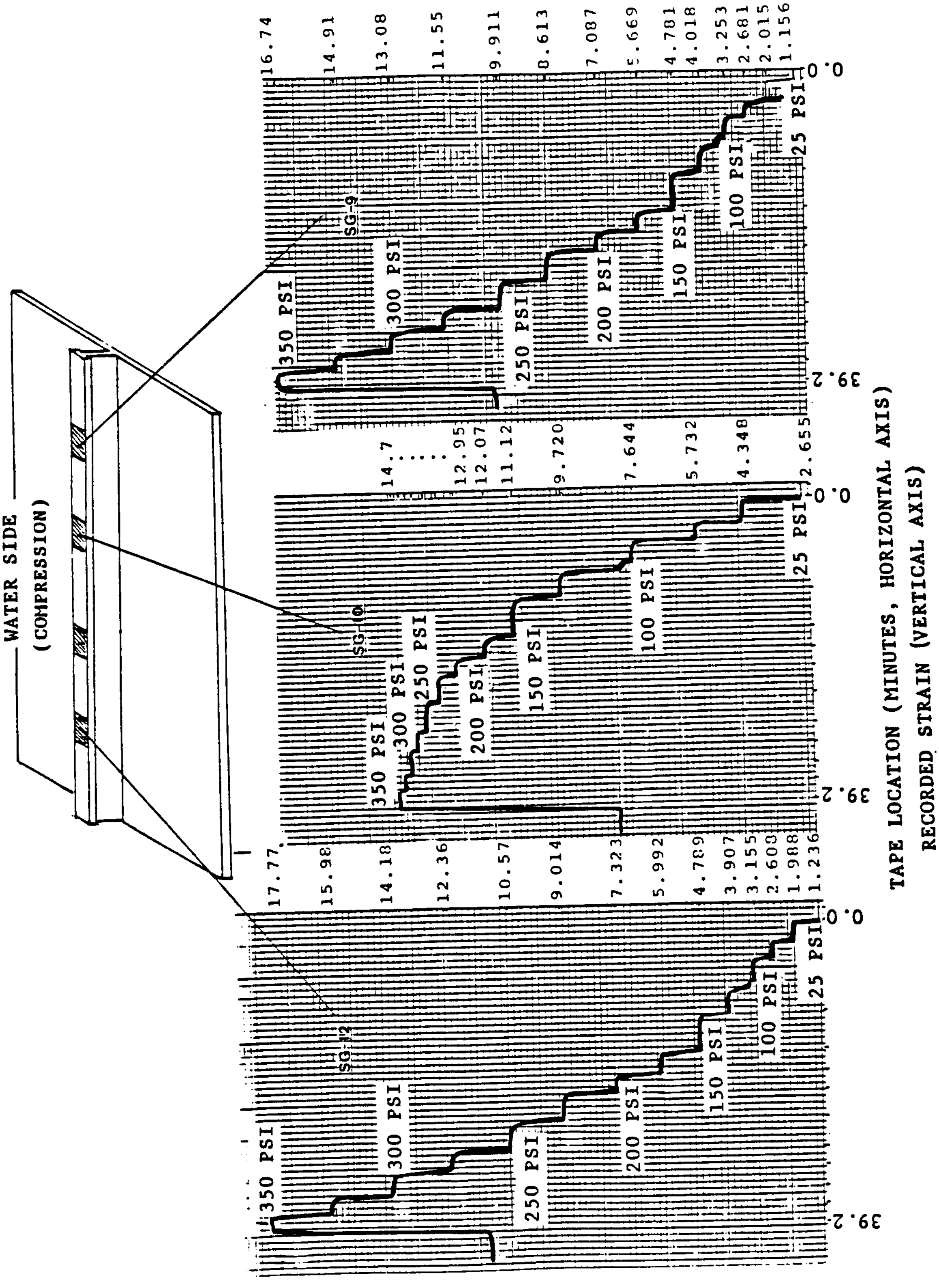

Figure 10 Static Strain History Recorded Longitudinally Across Flange of T-Stffener

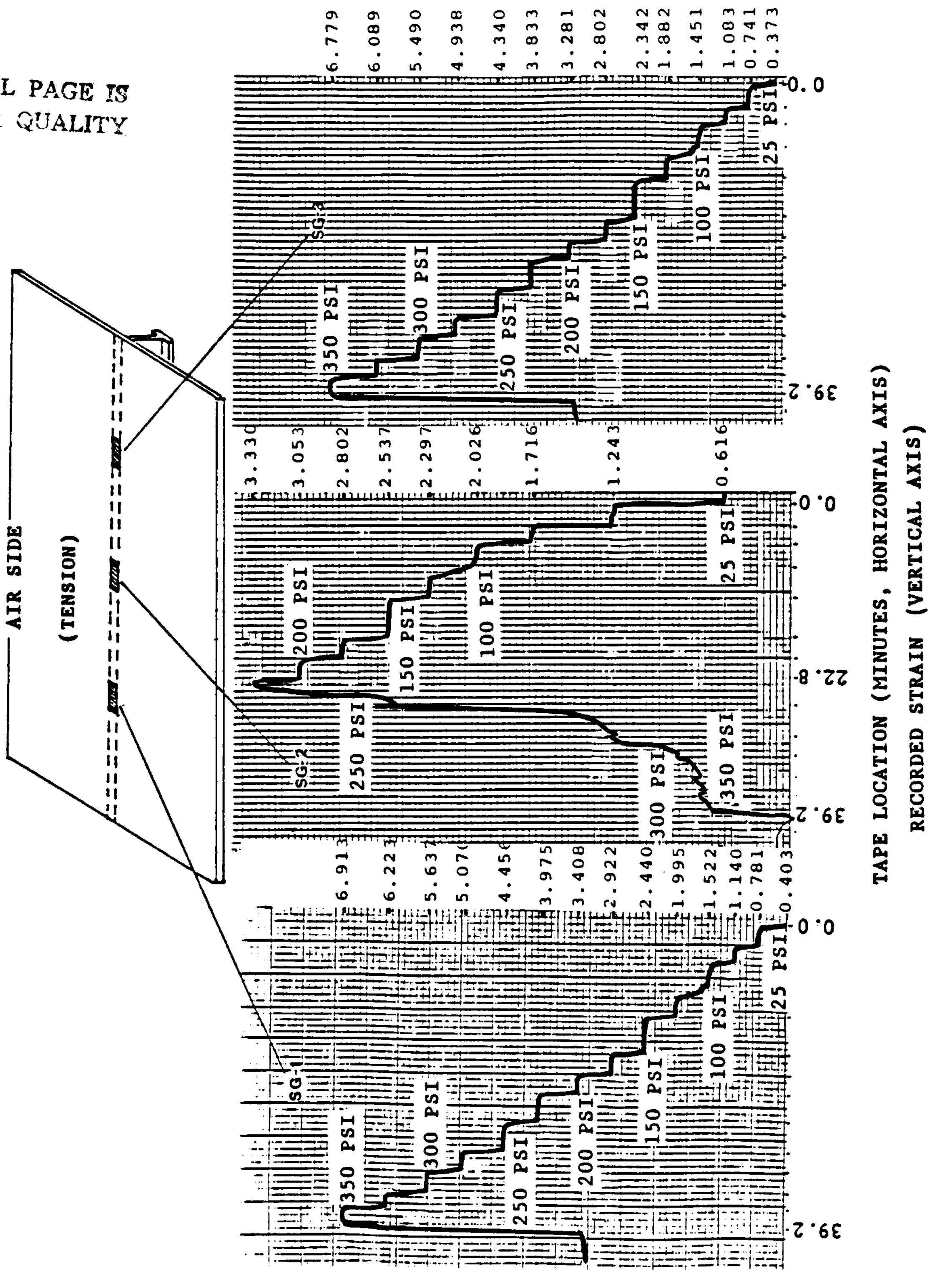

Figure 11 Static Strain History Recorded Longitudinally Across Centerline of Plate Back

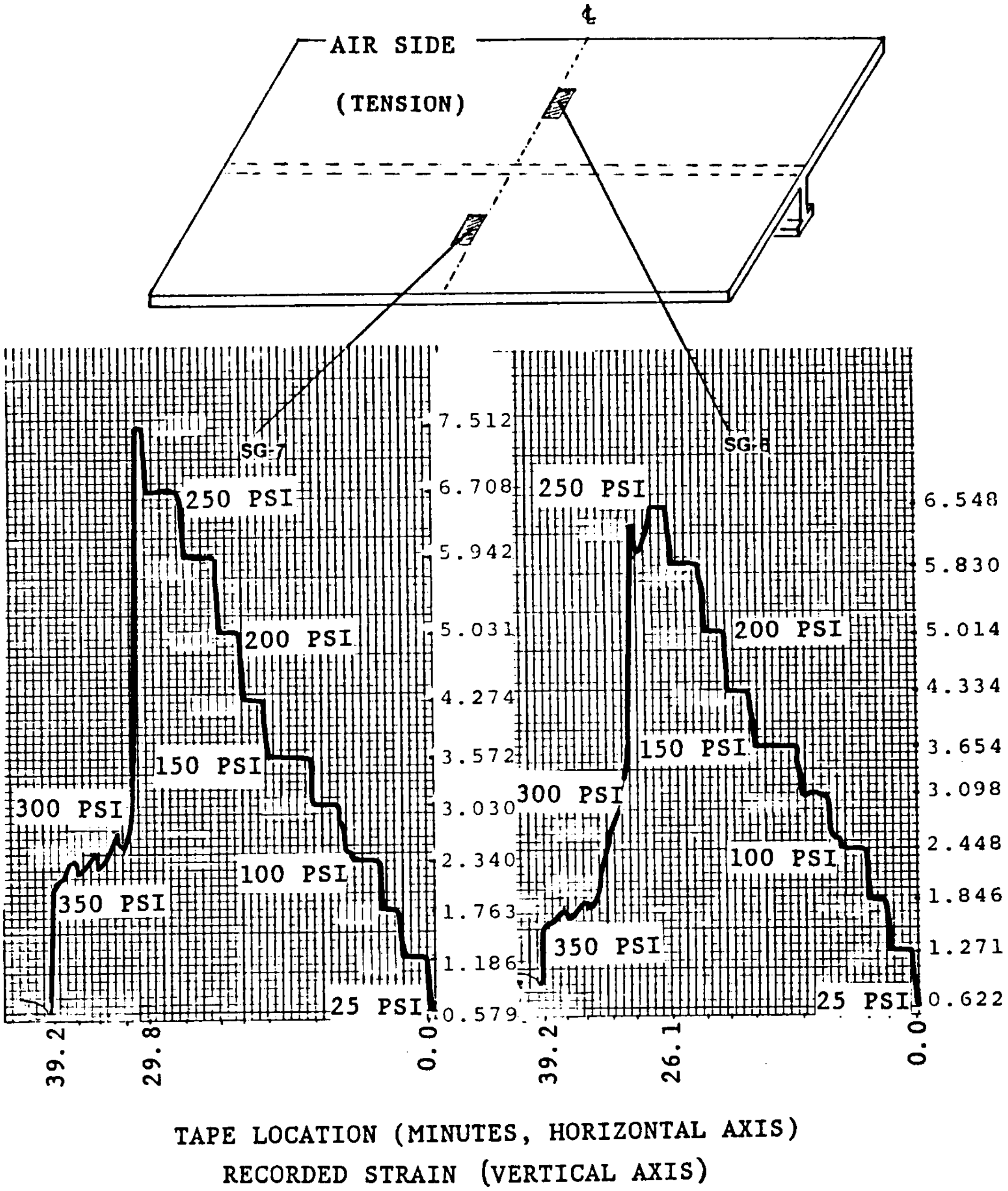

Figure 12 Static Strain History Recorded Across Transverse Centerline of Plate Back

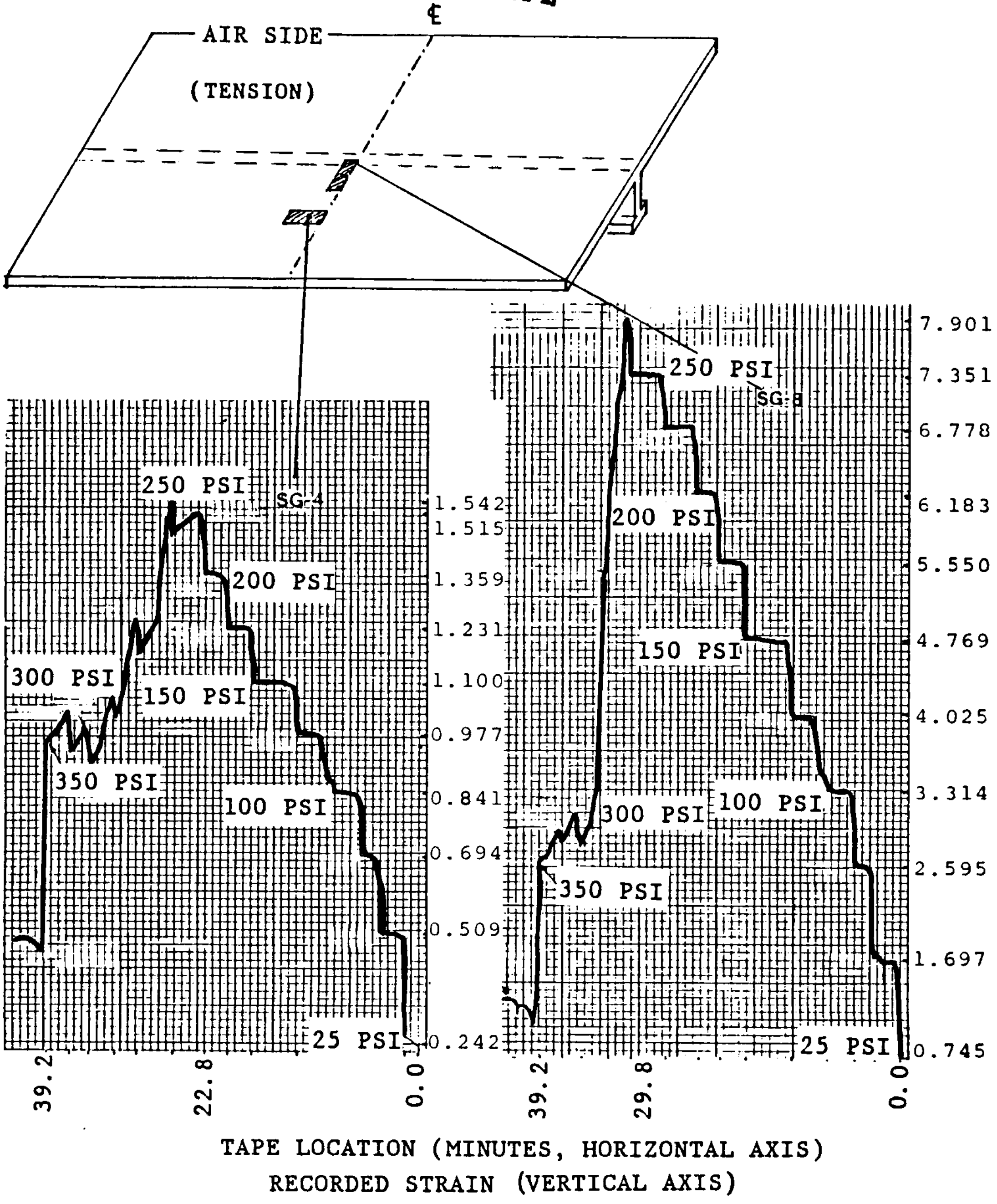

Figure 13 Static Strain History Recorded on Lower Half of Transverse Centerline of Plate Back

TABLE 1

STATIC DEFLECTION AND PRESSURE DATA

PRESSURE (PSI)	1	2	3	4	5
25	.043	.079	.095	.080	.040
50	.080	.148	.180	.154	.075
75	.110	.204	.247	.211	.103
100	.139	.255	.304	.260	.131
125	.180	.308	.361	.311	.165
150	.197	.352	.407	.352	.190
175	.223	.394	.451	.392	.217
200	.248	.434	.492	.430	.242
225	.275	.473	.532	.466	.267
250	.297	.506	.566	.497	.288
275	.321	.540	.601	.529	.311
300	.342	.570	.632	.557	.333
325	.364	.601	.664	.586	.354
350	.387	.632	.695	.615	.376

NOTE: AFTER PRESSURE WAS VENTED OFF, A PERMANENT SET OF 0.408 INCHES REMAINED AT NODE (16,13).

TABLE 2

STATIC TEST STRAIN AND PRESSURE DATA

STRAIN GAGE DATA (MICROSTRAIN)
-STRAIN GAGE POSITIONS

PRESSURE (PSI)	1	2	3	4	5	6	7	8	9	10
25	403	616	373	242	662	579	745	1156	2655	1236
50	781	1243	741	509	1271	1186	1697	2015	4348	1988
75	1140	1716	1083	694	1846	4763	2595	2681	5132	2608
100	1522	2026	1451	841	2448	2340	3314	3235	7644	3155
125	1995	2297	1882	977	3098	3030	4025	4018	9720	3907
150	2440	2537	2342	1100	3654	3572	4769	4781	11122	4789
175	2922	2802	2802	1231	4334	4274	5550	5669	12074	5992
200	3408	3053	3281	1359	5014	5031	6183	7081	12948	7323
225	3975	3330	3833	1515	5830	5942	6778	8613	13458	9014
250	4456	2633	4340	1542	6548	6708	7351	9911	13877	10574
275	5070	1261	4938	1258	6288	7512	7901	11552	14132	12359
300	5637	871	5490	1073	2754	2686	5401	13078	14314	14181
325	6223	760	6089	1030	1873	2462	3091	14910	14496	15985
350	6913	734	6779	996	1743	2377	2964	19742	14678	17770
VENT	3266	284	3189	485	10748	691	1236	10102	8190	11137

NOTE: STRAIN GAGES SG-5 AND SG-11 FAILED PRIOR TO TEST, ALSO STRAIN VALUES IN THE VENT ROW INDICATE STRAIN REMAINING AFTER PRESSURE WAS VENTED OFF (I.E. AT ATMOSPHERIC PRESSURE).

positions. This was not typical in the case of SG-10 (located 1.8 inches off the center of the point of maximum vertical deflection of the flange) where strain continued to increase but at a decreasing rate, demonstrating that the stiffener load was being redistributed to the regions of the stiffener where the web had not yet begun to rotate out of the vertical plane. The redistribution of the stresses throughout the stiffener is best illustrated in Figure 14 which is strain normalized at each 25 psi increment for strain gages SG-1, 3, 9, 10 and 12. None of these plate and stiffener gage locations showed the same elastic tripping "unloading" as did SG-2, 4, 5, 7, and 8. Accordingly SG-1, 3, 9, 10, and 12 best represented the response of the stiffener flange (SG-9, 10, and 12) and web toe (SG-1 and 3) to elastic tripping. In Figure 14 it again can be seen how the center of the stiffener flange (SG-10) begins to unload as the web rotates elastically out of the vertical plane (symmetrical tripping) and the remaining portion of the stiffener assumes the load. The strain histories also indicate that the stiffener was rotating out of the vertical plane towards strain gage SG-6, since SG-7 values were not sensitive to the initial tripping action until 275 psi, versus 250 psi for SG-6 (Figure 12). It should also be noted that the transverse centerline strain gages placed longitudinally (SG-2 and SG-4) were more sensitive to initial tripping action than those placed transversely in the same regions (SG-7 and SG-8).

As a consequence of this test it was determined that more than four plate thicknesses deflection would be required to initiate inelastic tripping. Lateral measurements of the stiffener (after the 0.695 inch centerline vertical deflection of the test planel, i.e., approximately four plate thicknesses) indicated no permanent deformation of the flange or web out of the vertical plane. Additionally, the progressive behavior of this specific plate- stiffener combination when loaded was found to be well difined, qualif\tatively predictable, and sensitive to tripping. The static field test had shown also that the equipment to be used in the underwater explosion data collection was reliable and performed well.

UNDERWATER SHOCK TEST RESULTS

The shot went off as planned and, as predicted, the 8 lb charge reacted as a 10 lb charge (determined by post-shot calculations). The dome and plume from the explosion were symmetrical, as was expected for the cylindrical charge used. Also, as had happened during the Langan test [16], the pneumatic fenders were ruptured from the force of the explosion.

As the chamber was pulled from the water immediately after the shot it was readily obvious that over three-quarters of the test plate surface area was blown free from the rest of the test panel. Upon closer inspection it was discovered that the missing section had been cleanly torn along the boundaries of the test panel and was lying in the bottom of the air-back chamber. As can be seen in Figure 15, the stiffener exhibited an anti-symmectric displacement configuration (i.e., the stiffener remains vertical) as described in [8]. This type of deformation is the initial stage of inelastic tripping before collapse of the stiffener. The web had begun to buckle at the point of attachment to the flange in three separate areas spaced symmetrically along the length of the stiffener: the center and four inches on either side as shown in Figure 15. The stiffener, though it had not rotated out of the vertical plane, was showing indications of doing so and collapsing to the left side of the plate. The center-most position of the plate retained a permanent vertical deflection of approximately 1.30 inches, a deflection of sever plate thicknesses. Even at this extreme amount of deformation there was not a total collapse of the stiffener. The strain histories

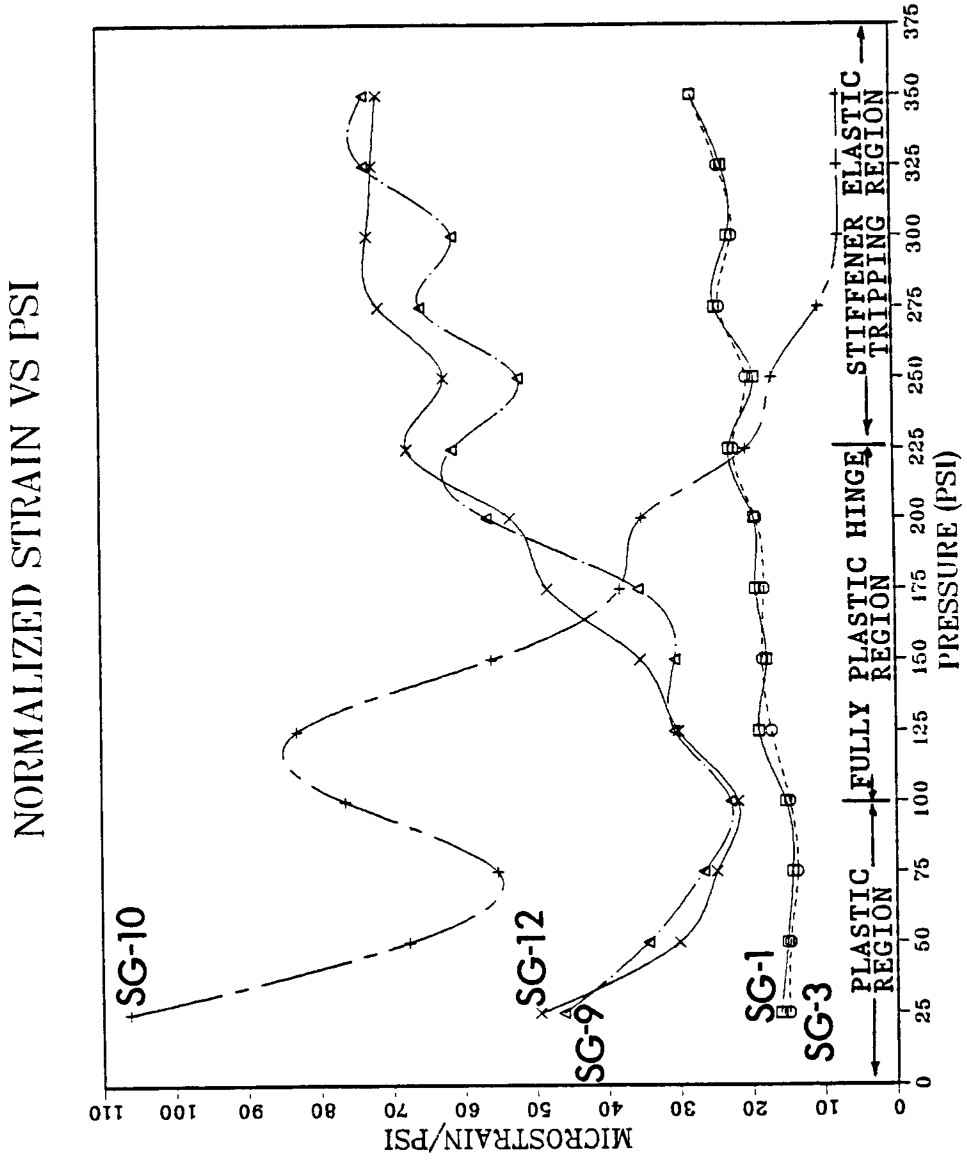

Figure 14 Plot of Static Strain Normalized to Pressure

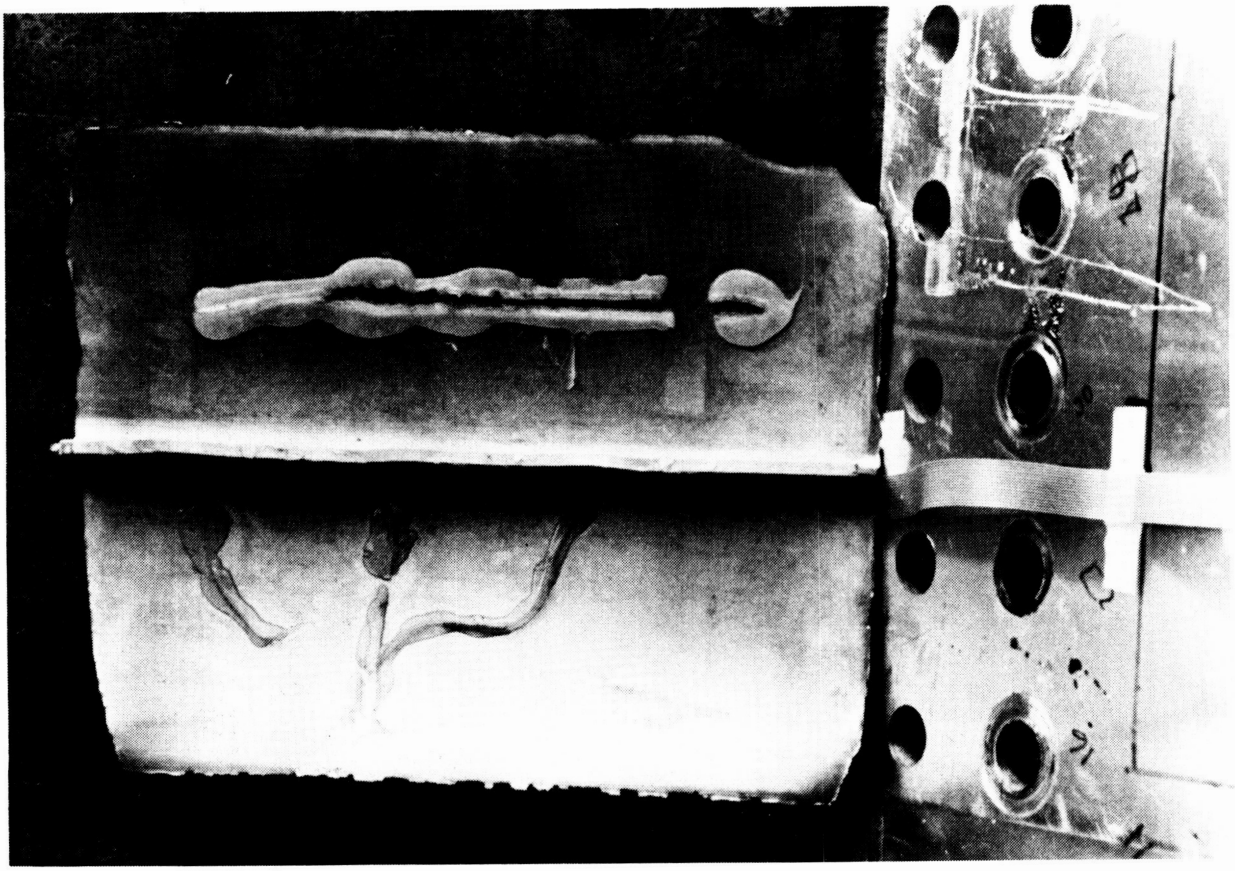

Figure 15. View of Plate Section Showing Anti-Symmetrical Section

were expected to follow the same symmetry and trends experienced in the static test, even though now the free field pressure was 3780 psi (Figure 16) and was generated by a shock wave which peaked 17.3 microseconds after arrival at the ten foot standoff radius.

The recorded peak strain values and arrival times are listed in Table 3 and associated strain histories are shown in Figures 17 through 20. Each strain gage history had been transferred from the high speed tape to disk storage on the HP-5451C Fourier Analyzer, where individual records were reviewed and outputted graphically. Typically, one strain gage history would cover fourteen records (approximately 4.48 milliseconds). Note that the voltage values on the vertical axis were multiplied by each strain gage's calibration factor to obtain the peak strain values which are annotated in each strain gage history. The strain gage histories are also marked at the time of arrival of the wave front.

A characteristic of every strain history was an eventual peak strain drop-off to a negative value. This represented the plate detaching from the water (due to cavitation at the plate surface) allowing the plate to come to rest until it was reloaded microseconds later by an onrush of water from the explosion [13]. A summary of strain gage shockwave arrival times, peak times before reloading (multiple peaks in many cases), times to cavitation (i.e., last peak time less arrival time), and reload times is provided in Table 4. Note that reload times for all strain histories in the center of the plate and across the stiffener (SG-1, 2, 3, 8, 9, and 12) were consistent at approximately 3.12 to 3.17 milliseconds. Additionally, the time period prior ro the onset of surface cavitation was also uniform in the plate center (SG-1, 2, 3, and 8) at 540 to 590 microseconds.

TABLE 3

SENSOR	ARRIVAL TIME (MILLISECONDS)	RECORDED PEAK (MICROSTRAIN)
SG-1	2.53	20.2 k
SG-2	2.50	30.0 k
SG-3	2.56	44.0 k
SG-4	2.18	17.0 k
SG-5	2.44	23.0 k
SG-6	2.50	25.2 k
SG-7	2.18	40.0 k
SG-8	2.56	35.o k
SG-9	2.24	36.0 k
SG-10	2.24	16.0 k
SG-11	FAILED	
SG-12	2.24	36.0 k
P-XDCR-1	2.10	3780 psi
P-XDCR-2	2.08	3500 psi
P-XDCR-3	FAILED	

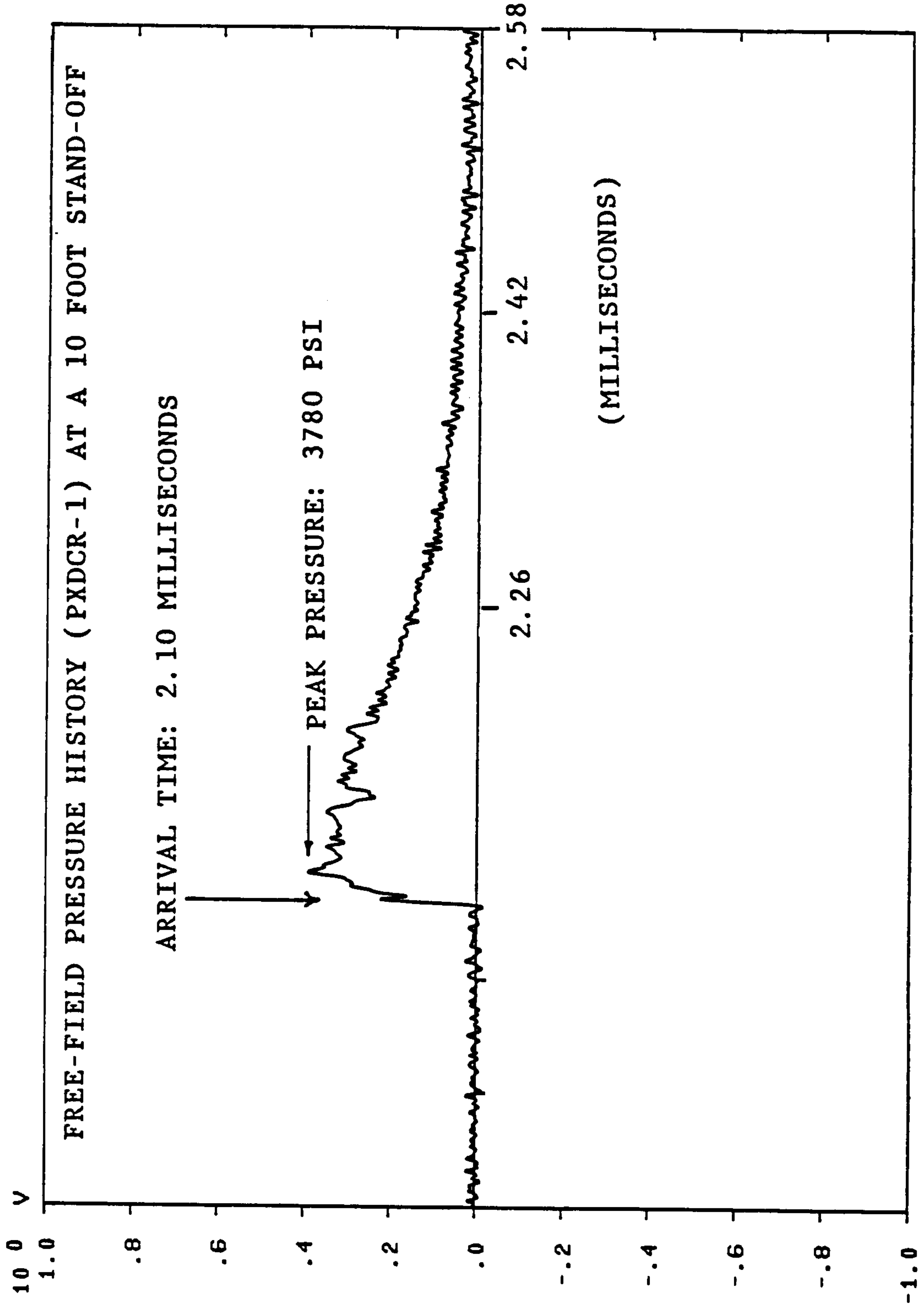

Figure 16 Free-Field Pressure and Arrival Time

comparison of observed symmetry and trends was made in Figures 17 through 20. Initially after making a general overview of all the strain histories, it became evident that the upper left end of the plate (Figure 15) was exposed to the shock wave earliest and experienced the highest strain values. The shock wave arrival time for the left side gages SG-4 and SG-7 was 2.18 msec., while the arrival time for the stiffener gages SG-9, 10, and 12 was 2.24 msec and for the gages on the opposite side of the plate it was even later (i.e., 2.44 msec and 2.50 msec). The information suggests that the test panel and air-back chamber were not parallel relative to the shock front but slightly canted to one side. The left side of the plate was apparently higher than the right, which is why all other plate strain gage arrival times were approximately 0.3 milliseconds later. This confirmed the belief that the cabling and junction box mounted to the side of the air-back chamber could possibly tilt the chamber once it was lowered into the water and only supported by the pneumatic fenders.

TABLE 4

SUMMARY OF SHOCK WAVE ARRIVAL TIMES, PEAK TIMES, TIME TO CAVITATION, AND RELOAD TIMES

SENSOR	ARRIVAL TIME (MILLISEC)	*PEAK TIMES (MILLISEC)	ELAPSED TIME PRIOR TO CAVITATION (MICROSEC)	RELOAD TIME (MILLISEC)
SG-1	2.52	3.03/3.07/3.09	560	3.13
SG-2	2.50	2.98/2.99/3.07 3.09	590	3.12
SG-3	2.56	3.07/3.10	540	3.12
SG-4	2.18	2.32/2.42	240	2.43
SG-5	2.44	2.76	320	2.77
SG-6	2.50	2.77/2.81	310	2.84
SG-7	2.18	2.35	120	2.38
SG-8	2.56	3.00/3.08/3.12 3.14	580	3.17
SG-9	2.24	2.33/2.53/2.65 2.73/2.95	710	3.17
SG-10	2.24	2.45/2.60/2.70	550	2.86
SG-11		FAILED		
SG-12	2.24	2.36/2.43/2.59 2.71/3.07	830	3.17

UNDERLINED PEAK TIME INDICATES TIME OF MAXIMUM STRAIN VALUE.

The plate rectangular geometry additionally dictated that all longitudinally measured strains would be less than those measured transversely across the width of the plate in the same positions. This proved to be the case in the undex test (as well as the satic test) where the peak values of strains for SG-6, 7, and 8 (measured 90 degrees from the longitudinal gages SG-2, 4, and 5) were higher. As expected, except for the region of the plate affected by the chamber tilt, all arrival times measured on the plate were later than those for the stiffener. Additionally, it can be seen that the general shapes of the recorded strain histories in regions which are symmetrically equal are very similar (specifically Figure 18 (SG-1 and SG-3), Figure 19 (SG-6 and SG-8), and Figure 20 (SG-9 and SG-12)). As far as determining the correlation between strain histories and the physical deformation of the stiffener, it can only be speculative. For illustrative purposes Figure 20 containing SG-9, SG-10, and SG-12 strain histories will be used. Again in comparison to static test trends, it would be expected that the strain values experienced at SG-10 would never get quite as large as elsewhere on the stiffener, but build up, unload, and build up again as the stiffener experiences its progressibe deformations. Undoubtedly, the three areas of stiffener deformation shown in Figure 15 occured progressively starting with the region initially of highest compressive stress (the center of the plate) and then progressed to the next highest, probably the SG-9 portion of the stiffener, and lastly SG-12. This sequence seems to follow escpecially well the strain history undulations depicted in the curves for SG-9 and SG-12, and somewhat for all the other strain histories.

GEOMETRY AND MATERIAL CONSIDERATIONS

The results of the underwater shock test are unique for the specific test panel geometry and material used. To put this "uniqueness" in the correct perspective, a discussion of the impulsive load effects on geometry and materials follows.

The deformation of the test panel is more than just a property of the material, it also depends on the geometry of the test panel and the process used to deform it. It has been found [13] that dynamic yielding occurs only at pressures 3 to 10 times the static yield values. This is due to the fact that materials which undergo a transition from ductile to brittle behavior at lowered temperatures will generally undergo a similar transition when the loading has changed from static to dynamic.

Additionally, materials which are ductile at low temperatures tend to remain ductile under dynamic loading [12]. The flow characteristics of most metals will be influenced by the high strain-rates involved, especially in iron which has a very noticeable loss of ductility at high strain-rates. This strain-rate sensitivity determines the magnitude of the permanent deflections. It was because of materials' typical strain-rate sensitivity that a relatively strain-rate independent metal was selected for the test panel material, since the less strain-rate sensitive the material is, the less explosive charge required to cause the necessary deformations. Aluminum 6061-T6 was believed to be almost strain-rate insensitive compared to steel plate at the same strain-rates and was a readily available material. Accordingly, 6061-T6 aluminum was used for all the test panels.

The anatomy of a shock front interaction with a plate is shown in Figure 21. The reflected incident wave is compressive and is the reactive force which causes the plate to deform. additionally, the amplitude and shape of the incident wave changes rapidly as it passes through the plate. The stready decrease in the amount of permanent deformation is due primarily to the decay of the wave. The transmitted incident wave, which is microseconds later, reaches the backside reff surface of the plate and is reflected as a tensile rarefaction wave. The free surface reflected wave in many cases can lead to the development of tension

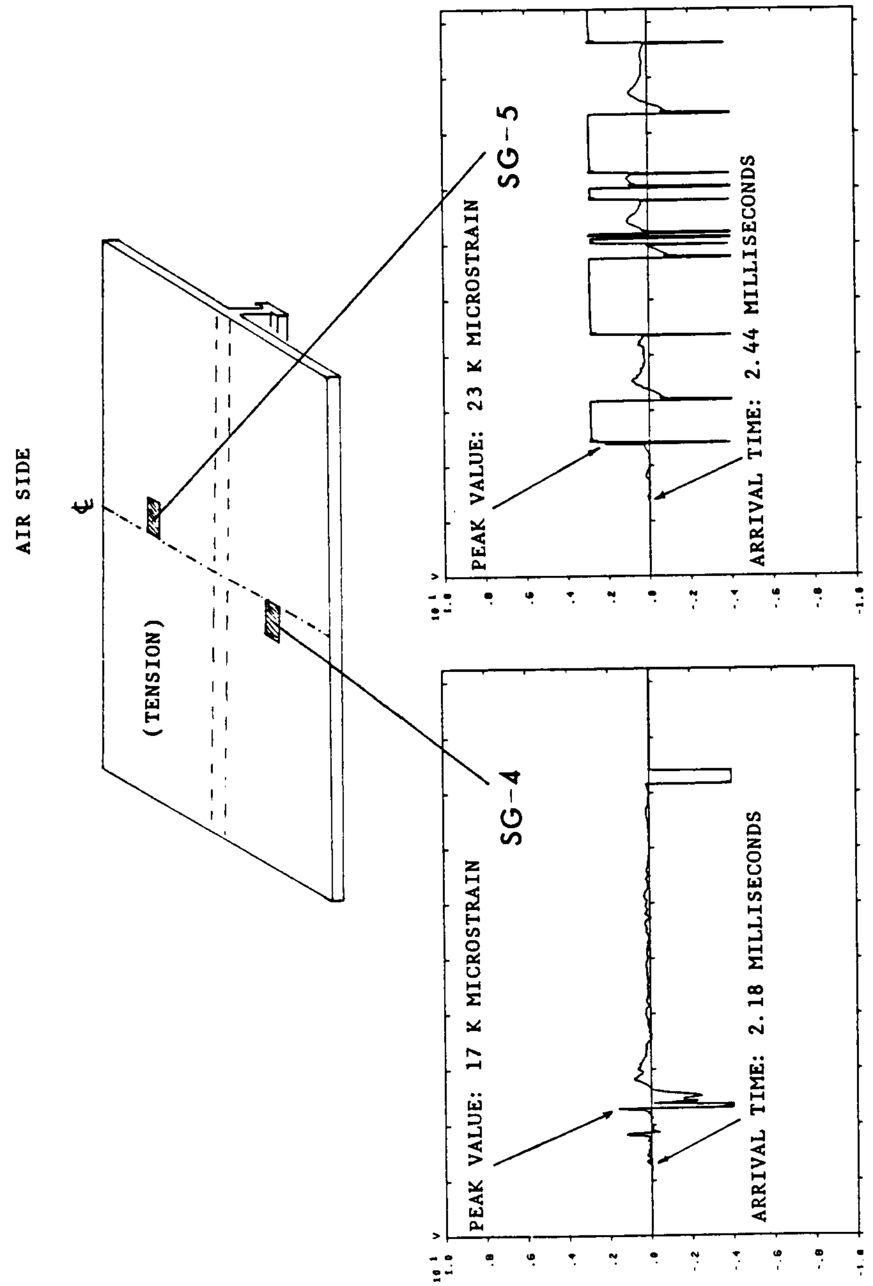

Figure 17 Dynamic Strain History Recorded Across Transverse Centerline of Plate Back

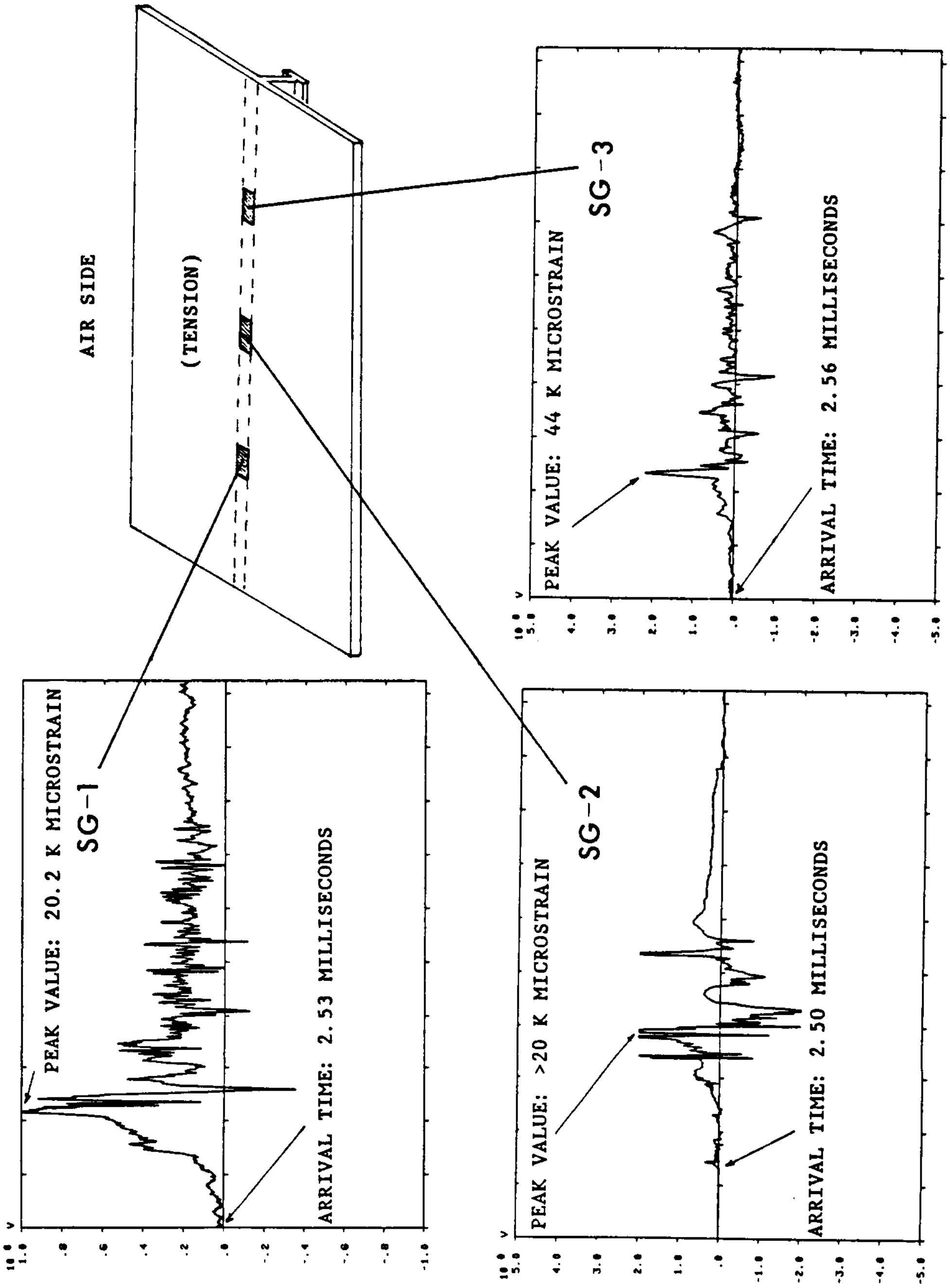

Figure 18 Dynamic Strain History Recorded Across Centerline of Plate Back (Longitudinally)

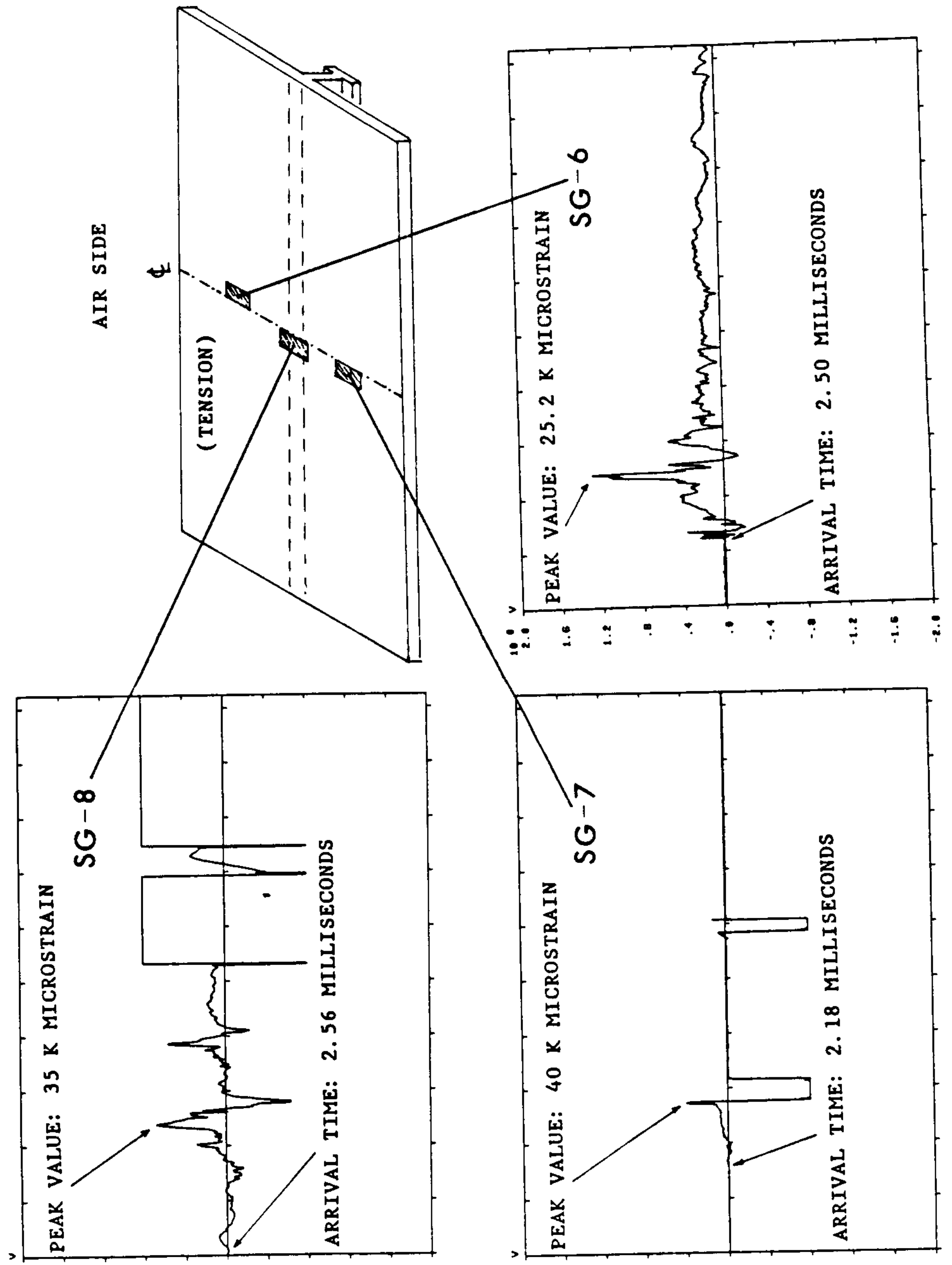

Figure 19 Dynamic Strain History Recorded Across Transverse Centerline of Plate Back (Transversely)

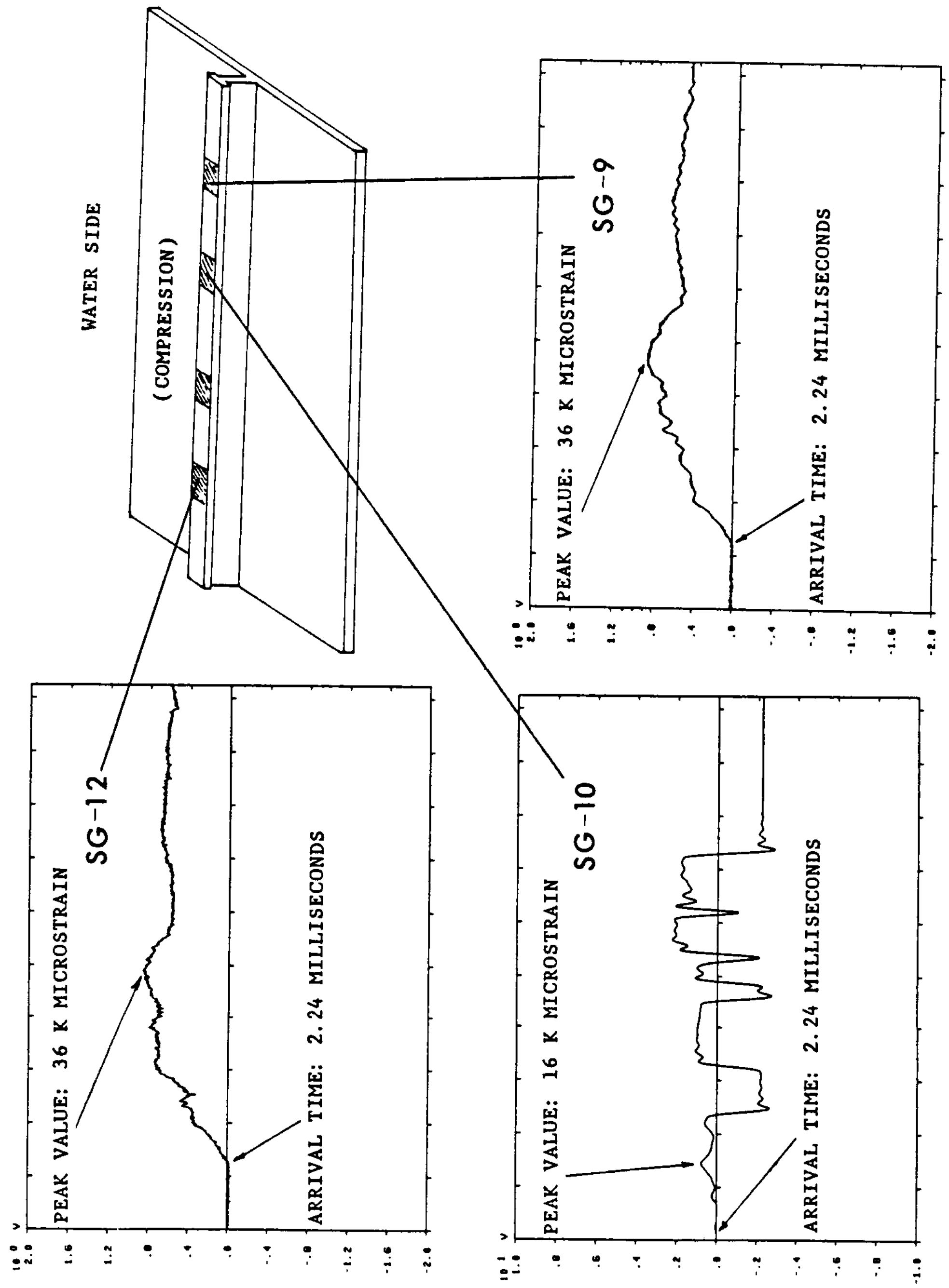

Figure 20 Dynamic Strain History Recorded Longitudinally Across Flange of T-Stiffener

fractures. Finally, the reflected tension wave is partly transmitted back into the water. [13,21]

The shock front interaction with the plate can be complicated extensively by the shape of the test panel since the geometry of a body and its constraints determine both the location and the amount of plastic flow that will take place. In most cases, interpreting the deformation and fractures that occur can be facilitated by considering the effects that the geometrical shape has on the stress waves. For example, fracturing may occur at a corner dur to the reinforcement between two (or more) tension waves that eat in simultaneously from the edge of the corner. Additionally, entrapment of the incident shock wave by the corner causes multiple reflections from the walls of the corner (pressire increasing stepwise with each further reflection), leading to a significant increase in the pressure at the corner. This combination of reinforced tension waves and pressure amplification is undoubtedly the source of the initiation of the fracturing observed in the test panel and eventual 360 degree tearing of the plate from the test panel, Figures 15 and 22.

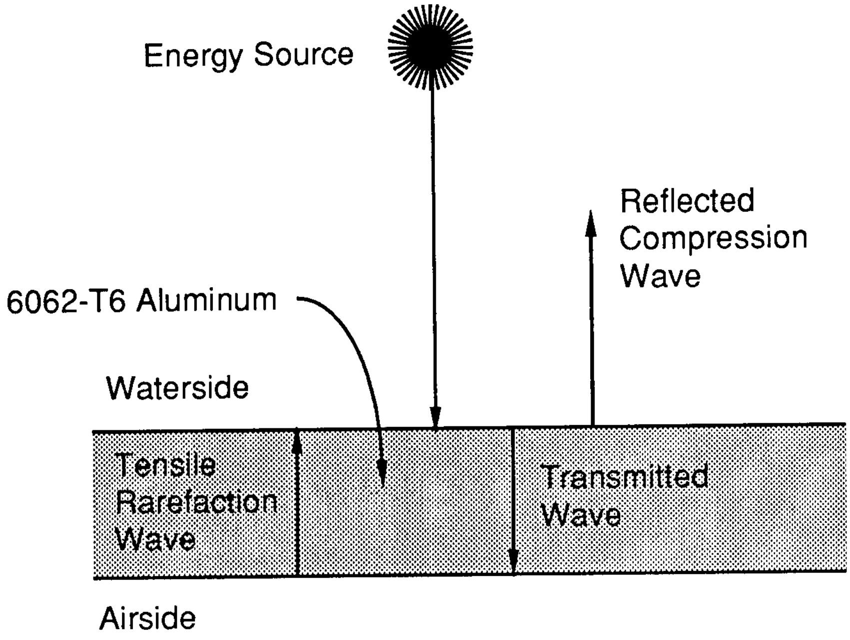

Figure 21. Shock Front Interaction with a Plate

As a closing remark to this section, it should be mentioned that the test panel incurred two surface gouges (less than three thirty-secondths of an inch deep) near the plate edge while being machined. One was weld repaired and one was left as is, and after exposure to the underwater explosion neither defect showed any involvement in the plate fracturing or deformation and apparently were not stress concentrators in this situation. This was also observed in [12],". . . the presence of notches may have little effect in impulsive load situations." However, spalling (or scabbing) was observed in the weld repaired defect.

Spalling, an unusual type of fracturing, occurs near a free-surface relatively far removed from the area of application of a pressure impulse [12]. The spalling observed was a consequence of the applied load generating both longitudinal and transverse waves which progressively struck the weld fusion boundary creating additional waves giving rise to highly localized stresses which were sufficient to cause localized fracturing in the center of the weld repair.

CONCLUSIONS

The static pressure deflection test of the panel machined for this purpose proved to be a source of very good strain and deflection data quantitatively representing the plate and stiffener behavior up to and into the elastic tripping region. Additionally, the progressive behavior of this plate-stiffener combination when loaded hydroststically was found to be well defined, quantitatively predictable, and sensitive to tripping. As a consequence of this test, it was also determined that more than four plate thicknesses deflection would be required to initiate static inelastic tripping.

The dynamic response test, though complicated by the rapidly changing nature of the variables and the complex relationship between stress, strain, and strain-rate, provided strain histories clearly depicting: the initial interaction between the shock front and the test panel, the cavitation times, and the reload times. Additionally, the shock front arrival times measured at eleven different plate locations were precise enough to indicate (through calculation) that the test chamber was not parallel to the shock front emenating from the eight pound TNT charge, but was inclined to the cable junction box side. It was also determined from post UNDEX measurements of plate deflection that even at an extreme deformation of seven plate thicknesses there was not a total collapse of the narrow-flanged T-stiffener. Additionally it has become obvious that the geometry of the test panel machined "cavity" and its constraints determined both the location and the amount of plate racturing which took place.

In summary, narrow-flanged T-stiffener tripping has been observed demonstrating both the static elastic and dynamic inelastic behaviors. Also the underlying cause of the fracturing observed in the UNDEX test plate has been attributed to the design geometry of the test panel.

It is not apparent how much effect the amplified corner pressures had on the plate deformation and strain histories, but to ensure strain histories representative of only the shock front and plate interaction, the test panel warrants redesign so as to eliminate the cavity walls surrounding the stiffened plate, thus removing boundaries which may cause shock wave pressure amplification.

As a by-product of this investigation (shock wave efects on welds), spalling of a weld repair should be of interest for any future studies evaluating the physical and metallurgical effects of an underwater explosion shock wave front on a metal panel containing multiple welds or weld repairs (e.g., spalling noted in the dynamic test plate). The importance of this is self-evident since the hull integrity of every Naval vessel is dependent upon the reliability of the welds bonding the plating together.

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