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SOME SPACE SHUTTLE TILE/STRAIN-ISOLATOR-PAD SINUSOIDAL VIBRATION TESTS

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INTRODUCTION

The thermal protective system for the space shuttle orbiter vehicle is complex with new and challenging engineering problems. Salient among these problems is a lack of understanding of the vibratory behavior of the Reuseable Surface Insulation tile (RSI)/Strain-Isolator-Pad (SIP) system. Studies are being conducted at the Langley Research Center to understand the dynamic characteristics of the RSI/SIP system with analytical and experimental investigations of selected single tile configurations. Two specific objectives of the tests are to assess nonlinearities, and to obtain data for the development of analytical models. Representative data from the experimental studies are presented herein.

MODELS, APPARATUS AND INSTRUMENTATION

All tiles used in the vibration tests were 152 mm x 152 mm x 95 mm (6 in. x 6 in. x 3-3/4 in.) LI900 RSI. The SIP was 4 mm x 127 x 127 (0.16 x 5 x 5 in.) thick and bonded between the tile and the tile plate. Although filler bar was bonded to the tile plate to close the gap between the tile plate and the edge of the tile, similar to an orbiter installation, it was removed for these tests to better understand the vibratory behavior of the RSI/SIP system. The tile plate was an aluminum plate 25 mm x 305 mm x 305 mm (1 in. x 12 in. x 12 in.) and was not a part of the RSI/SIP system on the orbiter.

Three types of vibration tests were performed: low-level tests in which the RSI/SIP-plate specimen was softly suspended and subjected to either inplane or normal direction low-force excitations, high-level tests in which the RSI/SIP-plate specimen was mounted on a large 133 kN (30,000 lb.) electromagnetic exciter and subjected to normal direction base excitation acceleration ranging from 0.5g to 45g, and double-shear tests in which two RSI/SIP-plate specimens were bonded together at the RSI surfaces. In this section these test configurations and associated instrumentation are described.

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Low-Level Test Apparatus

The test articles that provided low-level dynamic characteristics (figure 1) were RSI/SIP-plate specimens supported with free-free boundary conditions. As shown in figure 1, a small exciter was attached to the tile plate. The plate was supported with a soft suspension system from an overhead fixture. The mass of the plate was 6.35 kg (14 lb.) and the tile was 0.319 kg (.7 lb). The location of the exciter was changed appropriately to generate either in-plane or normal direction responses. For the purposes of this paper the normal direction was considered to be perpendicular to the largest tile surface. The responses were associated with modes in which the RSI/SIP system were essentially cantilevered from the plate. Because of the relatively large test article weight and the low force exciter, the dynamic characteristics were obtained at very low levels of SIP stress.

Accelerometers were placed on the tile plate and the tile upper surface. In addition, noncontacting deflectometers were located as shown in figure 2. Four deflectometers were used to measure normal motion while in-plane motion was detected by two deflectometers on each of two adjacent sides of the tile. All eight deflectometers were supported from a single fixture. A force gage was used to measure and control the input force.

High Level Test Apparatus

Prescribed sinusoidal acceleration of the tile plate in the normal direction was provided by a 133 kN (30,000 lb.) servo-controlled exciter. The test RSI/SIP-plate specimen was bolted to the exciter. The fixture which held the eight deflectometers used in the low-level tests was placed in position over the tile as shown in figure 3 in a manner similar to that used for the low-level test apparatus. Accelerometers were placed on the upper tile surface and on the tile plate to measure normal direction motion.

Double Shear Tests

In figures 4 and 5 the apparatus, instruments and specimen used in the double shear tests are shown. RSI surfaces of two RSI/SIP specimens were bonded together after the tile plates, shown as dotted lines in figure 5, were mounted vertically to a rigid bedplate in a manner which avoided imposition of a static preload. The result was a tile plate-SIP/RSI-RSI/SIP-tile plate combination which was symmetric about the bonding surface between the two RSI tiles. A small force plate was bonded to the side of the two tiles to distribute the point-load applied by the exciter. The magnitude of the force was determined by a force gage in line with the exciter stem. The 220 N (50 lb.) exciter was mounted rigidly to the bedplate. Three accelerometers were placed on the side next to the exciter, one at the lower middle of tiles and one each at the upper corners. Two accelerometers measured vertical acceleration at the top edges. Locations of these accelerometers are indicated in figure 5. An additional accelerometer was placed on one of the tile plates to detect normal or z-direction responses of the plate.

TEST PROCEDURE

All tests were conducted in a manner to study the dynamic response characteristics of the SIP material. The tile was assumed to act as a rigid body with the SIP providing spring and damping properties. Both normal and in-plane direction responses were studied during testing. Two significant and severe test restraints were imposed prior to the start; (1) only limited model specimens were available and (2) minimum test time must be used for any single specimen.

In all tests, response signals were amplified, recorded on analog tape and displayed appropriately using an oscillograph, meters and oscilloscopes. In addition, selected data signals were input to a spectral analyzer which separated the signal into coincident and quadrature components with respect to a reference signal, usually force or prescribed acceleration, and the components were plotted as a function of excitation frequency using an x-y_1-y_2 plotter.

In general, the same procedure was used for all tests. After the model was installed in its test apparatus and the instrumentation calibrations were verified, sinusoidal excitation forces of pre-determined levels were applied, resonant frequencies of interest were quickly located manually and instrument gains were set. The forcing frequency was lowered to the lowest frequency needed for the given test range and a frequency sweep of servo controlled constant input force or acceleration amplitude level was made with all data being recorded on an analog tape recorder. All frequency sweeps were at a rate of 0.3 Hz per second. During the sweep transducer outputs were continuously monitored with oscilloscopes, meters and with a real time co-quad plot which was generated during the data sweep. Also, a video recording of the test-specimen was obtained at the same time.

RESULTS AND DISCUSSION

Selected dynamic characteristics for RSI/SIP-plate specimens are presented first for low and high level tests in which the input excitation force is normal to the plane of the tile. The double shear test results are then presented. Finally a discussion of the mode of tile failure is presented.

Normal Tests

The transfer functions measured with the transducer mounted on top of the tile, located to determine normal direction response characteristics, indicated non-linear properties of the test specimen with significant decreases in the response frequency as the input excitation levels were increased and with discontinuities in the response signal at low input excitation levels. At the higher input levels the transfer function displayed very broad and relatively flat responses over a wide frequency range with a broad maximum response rather than the typical peak response usually associated with modal data. Normal mode data could not be determined primarily because of this broad maximum response and the indicated high damping. Consequently maximum response data are presented in figures 6 and 7 rather than natural frequencies. In figure 6 a summary of the transfer function maximum responses for a tile (number 8335) is presented as the ratio of output acceleration (accelerometer on top of tile) divided by input acceleration. The ratios shown imply a damping value of 30 to 40 percent of critical at the higher input levels. The frequency at which maximum response occurs is shown in figure 7 as a function of input acceleration for all tiles. As shown in figure 7 the frequency remains relatively constant above about 10 g for the range of input accelerations. A sinusoidal input acceleration of 10 g corresponds to a bond-line stress of 1.9 to 3.5 kPa (.3 to .5 psi) depending on whether the ratio of tile acceleration to input acceleration is 1.0 or 1.8.

Nonlinearities were apparent in the response characteristics of the tiles. At low input levels jump phenomena associated with softening nonlinearities were observed. In addition response signals were highly distorted. A typical wave form for the acceleration on top of the tile is shown in figure 8. The deviation from a sine wave is large, indicating a high degree of nonlinearity of the SIP.

Double Shear Tests

Selected response amplitudes and phase responses over a frequency of 10 to 120 Hz for the double shear tests are depicted in figure 9. These results were generated with a force amplitude input which was held nearly constant for a given range of frequency. Because of nonlinearities and out-of-plane motion of the RSI/SIP system, test results were difficult to interpret. Near resonance neither the input force signal nor the response approximated a sine wave as shown in figure 10. Nevertheless, estimates of maximun response frequencies and damping were determined from these transfer functions. Figure 11 shows damping ratio as a function of input force. These results indicate damping levels near 20 percent of critical. In figure 12 the frequency at which the maximun response occurs is plotted as a function of input force. The response frequencies decrease with input force level and remain relatively constant for force levels above about 20 N. The two curves of the figure denote in-plane responses in orthogonal directions. These responses are almost equal.

Failures

Three RSI/SIP systems were failed with sinusoidal accelerations applied at the base in the normal direction. Although the set-up tile (number 0056) did not pass the acoustic emission criterion during the proof test, vibration test results indicate this tile was at least as durable as either of the other two tiles which passed the proof test. The set-up tile (0056) and tile 8173 failed with a base input of 45g. Tile 8335 failed during a 30 g test. Approximate numbers of cycles at various levels are shown in Table I for the three tiles. A summary of SIP failures is presented in Table II. Included in the table are dynamics data measured at failure and at the most recently recorded maximum response. All failures occurred within the RSI at the bonding surfaces. These failures look similar to those obtained in static tension tests.

Perhaps the most unusual finding from the tests is a definition of the manner in which all three specimens failed in the high-level tests with base excitation. When excited sinusoidally in the normal direction in the range of 60 to 90 Hertz at a level above 15g, a fundamentally nonlinear dynamic instability (parametric resonance) occurred in which in-plane motions were observed to be so large that they exceeded the linear range of the deflectometer and for some cases, the tile actually contacted the deflectometer. These in-plane responses occurred at a frequency of exactly one-half the excitation frequency. Figure 13 shows two histories taken from a test in which the input acceleration in the normal direction was 45g. This sample was taken about two seconds prior to the failure of the specimen. Both, also, show the input is near 80 Hz. Clearly the in-plane displacement (channel 16, figure 2) occurs near 40 Hz, half the input frequency. The normal displacement (channel 12), while it is obviously affected by the half-frequency response, occurs at the frequency of the excitation, 80 Hz.

In figure 14 a portion of the output history of the channel 1 accelerometer and an in-plane deflectometer are shown for an input level of 30 g. The history was taken while the excitation frequency was being lowered slowly. Thus the frequencies depicted by the responses shown are decreasing slightly from left to right. The histories are from the response accelerometer on top of the tile (top of figure 14) and a lateral, or in-plane displacement. As the frequency is changed slowly the in-plane motion becomes unstable, as indicated by the rapid growth in amplitude. The amplitude increases until the linear range of the transducer is exceeded (far right). Prior to the instability only a small in-plane motion was taking place and the frequency was the same as the excitation frequency. As the instability occurs the lateral frequency changes to one-half that of the normal response.

Further tests are needed to determine if the responses shown for these sinusoidal inputs exhibit the same characteristics when the input is a random excitation typical of a flight environment. The implications of this phenomenon for shuttle tile tests and analyses cannot be assessed until these phenomenonological random tests are conducted.

Parametric Resonance Model

Insight into this phenomenon may be gained by considering the idealization of the RSI/SIP system shown in figure 15. The system is considered to be a lumped mass with moment of inertia concentrated at the center of mass of the tile. Spring forces are applied to a massless rigid rod of length h which is the distance from the bottom of the tile where the

SIP is located to the center of mass of the tile. For purposes of illustration the springs, representing the SIP stiffness, are assumed to be linear. Base excitation in the normal, or v, direction is sinusoidal with frequency Ω. Only motion in the plane is allowed.

Nonlinear equations of motion are written accounting for the possibility of all three planar motions as follows:

$$\begin{aligned} & m\ddot{u} + k_s u + k_s h \sin\theta = 0 \\ & m\ddot{v} + k_n v + k_n h(1-\cos\theta) = k_n v_0 \cos\Omega t \\ & I\ddot{\theta} + k_r\theta + k_s h u \cos\theta + k_s h^2 \cos\theta \sin\theta + k_n h v \sin\theta \\ & \quad - k_n h v_0 \cos\Omega t \sin\theta + k_n h^2 \sin\theta (1-\cos\theta) = 0 \end{aligned} \tag{1}$$

Perturbations are assumed as follows:

$$\begin{aligned} u &= 0 + u_1(t) \\ v &= v_L(t) + v_1(t) \\ \theta &= 0 + \theta_1(t) \end{aligned} \tag{2}$$

where subscript L is linear, n is normal, s is shear, r is rotational, and 1 is perturbation, and $v_L(t)$ is the solution of the basic linear equations of motion. This linear solution is simply the response in the normal direction to the base excitation and involves no transverse motion u or θ. The perturbations are considered to be arbitrarily small. Thus the perturbation equations are linear in the variables v_1, u_1, and θ_1. These equations are

$$\begin{aligned} & m\ddot{u}_1 + k_s u_1 + k_s h \theta_1 = 0 \\ & m\ddot{v}_1 + k_n v_1 = 0 \\ & I\ddot{\theta}_1 + \left[(k_r + k_s h^2) + k_n h v_0 \frac{\Omega^2 m/k_n}{1-(\Omega^2 m/k_n)} \cos\Omega t\right]\theta_1 + k_s h u_1 = 0 \end{aligned} \tag{3}$$

The expression for $v_L(t)$ has been incorporated and is reflected in the coefficient of $\cos\Omega t$. The equation for v_1 is uncoupled from the other equations. This equation may be solved separately from the transverse equations which involve only the perturbation variables u_1 and θ_1. Transverse motions now are written assuming response only in the first of the two transverse modes. The natural circular frequency, ω_1, for this mode is

$$\omega_1^2 = \frac{1}{2mI}\left\{\left[k_s I + (k_r + k_1 h^2)m\right] - \sqrt{\left[k_s I + (k_r + k_s h^2)m\right]^2 - 4mIk_s k_r}\right\} \tag{4}$$

The mode shape is

$$\left\{\theta\right\} = \left\{\begin{matrix} 1 \\ \dfrac{-k_s - \omega_1^2 m}{k_s h} \end{matrix}\right\} \tag{5}$$

The resulting modal equation is

$$\ddot{q}_1 + (\omega_1^2 + \epsilon \cos \Omega t)\, q_1 = 0 \tag{6}$$

where

$$\epsilon = \Omega^2 \frac{v_0}{h} \; \frac{1 - (\omega_1^2 m / k_s)}{\{1 + [1 - (\omega_1^2 m / k_s)](r/h)^2\}[1 - (\Omega^2 m / k_n)]} \tag{7}$$

The quantity r is the radius of gyration $\sqrt{I/m}$.

Equation 5 is the Mathieu equation which occurs in the description of parametric excitation (references 1 and 2 for example). Solutions exist, that is, transverse oscillations may occur, for arbitrarily small values of when the excitation frequency is twice the transverse natural frequency w_p. This behavior is entirely consistent with the behavior observed in the high-level tests. Further discussion of the Mathieu equation may be found in reference 1-3.

CONCLUSIONS

Normal and double-shear vibration tests have been conducted on several RSI/SIP specimens primarily to obtain vibration characteristics of the SIP. Findings from these tests are summarized in this section.

Above about 10g normal input acceleration on the tiles tested, the maxmiun response frequency was relatively constant at about 100 Hz. Damping at these frequencies determined approximately from amplitude ratios, appears to be in the range of 30 to 40 percent of critical.

Frequencies of maximun response in the double shear tests also remain relatively constant for the higher force levels. These frequencies are generally in the 40-45 Hz range. Damping in the in-plane directions is somewhat less than damping in the normal direction. The in-plane damping is about 20 percent of critical. Valid information in this test was particularly difficult to obtain due to signal distortions resulting from SIP material nonlinearities.

Nonlinearities were evident in the data from both normal and shear tests. The fact that resonant frequencies and damping both have large shifts with level of excitation is a manifestation of nonlinearities. High signal distortion also results from the material nonlinearity. Jump phenomena, characteristic of nonlinear systems, also was observed, particularly at lower input levels.

Perhaps the most unusual finding from the tests is the occurrence of a dynamic instability which appears to be a result of a large effect of a geometric nonlinearity of the test specimen and could be a major contributing factor in the failure. Responses in this instability are characterized by large in-plane motion at a frequency one-half that of the normal driving frequency. In all cases the instability was observed at a 20g input level or higher. It is emphasized that all tests were sinusoidal and further tests with random inputs typical of flight environments are needed to ascertain whether this phenomenon could occur during service conditions.

REFERENCES

1. Neyfeh, Ali H.; and Mook, Dean T.: Nonlinear Oscillations, Chapter 1 and 4, John Wiley & Sons, Inc., 1979.

2. Minorsky, Nicholas: Nonlinear Oscillations, Chapter 20, D. Van Nostrand Co., Inc. 1962.

3. Struble, Raimond A.: Nonlinear Differential Equations, pp. 220-234, McGraw-Hill Book Co., Inc. 1962.

TABLE I. - Estimation of number of cycles applied to RSI-SIP-plate systems in high-level tests

Tile Number	Estimated Number of Cycles x 10^{-6}				
	15g	15g	20g	30g	45g
0056	7.13	1.66	1.05	1.66	0.01
8335	9.90	0.15		0.01	
8173		0.005		0.26	0.02

TABLE II. - Summary of data near tile/SIP specimen failures from sinusoidal excitation in the normal direction

Tile	Maximum normal response				In-plane response at failure			
	Input g rms	Freq. Hz	Response peak g	C/C %	Input g rms	Input Freq. Hz	Response Freq. Hz	Response $\frac{\text{Normal}}{\text{In-plane}}$
0056	30	115	48.7*	31	45	78	39	1.1
8335	15	90	25.5	29	30	60	30	1.5
8173	30	90 to 120	40*	38	45	80	40	2

*Signal Clipped

**Two Peaks

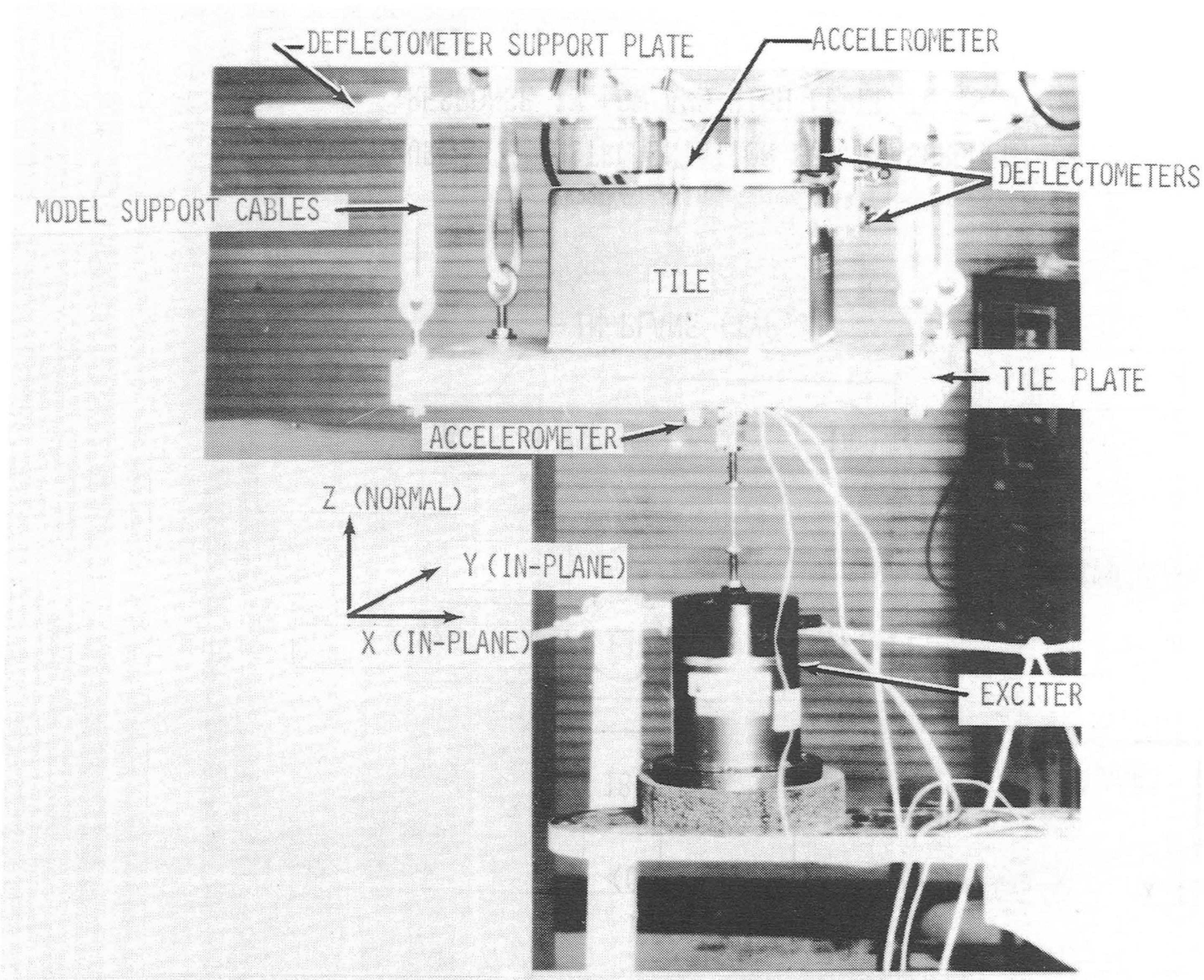

FIGURE 1 - TEST APPARATUS FOR LOW-LEVEL INPUT FORCES

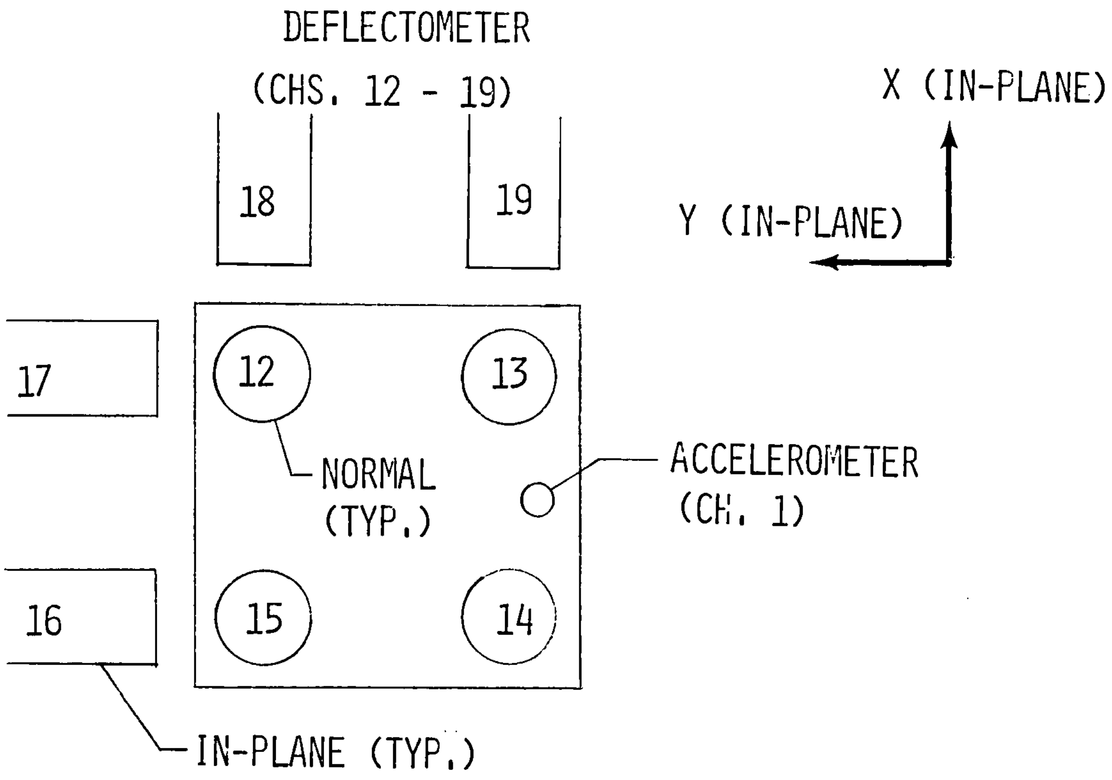

FIGURE 2 - INSTRUMENTATION FOR MEASUREMENT OF RESPONSE IN LOW AND HIGH LEVEL TESTS.

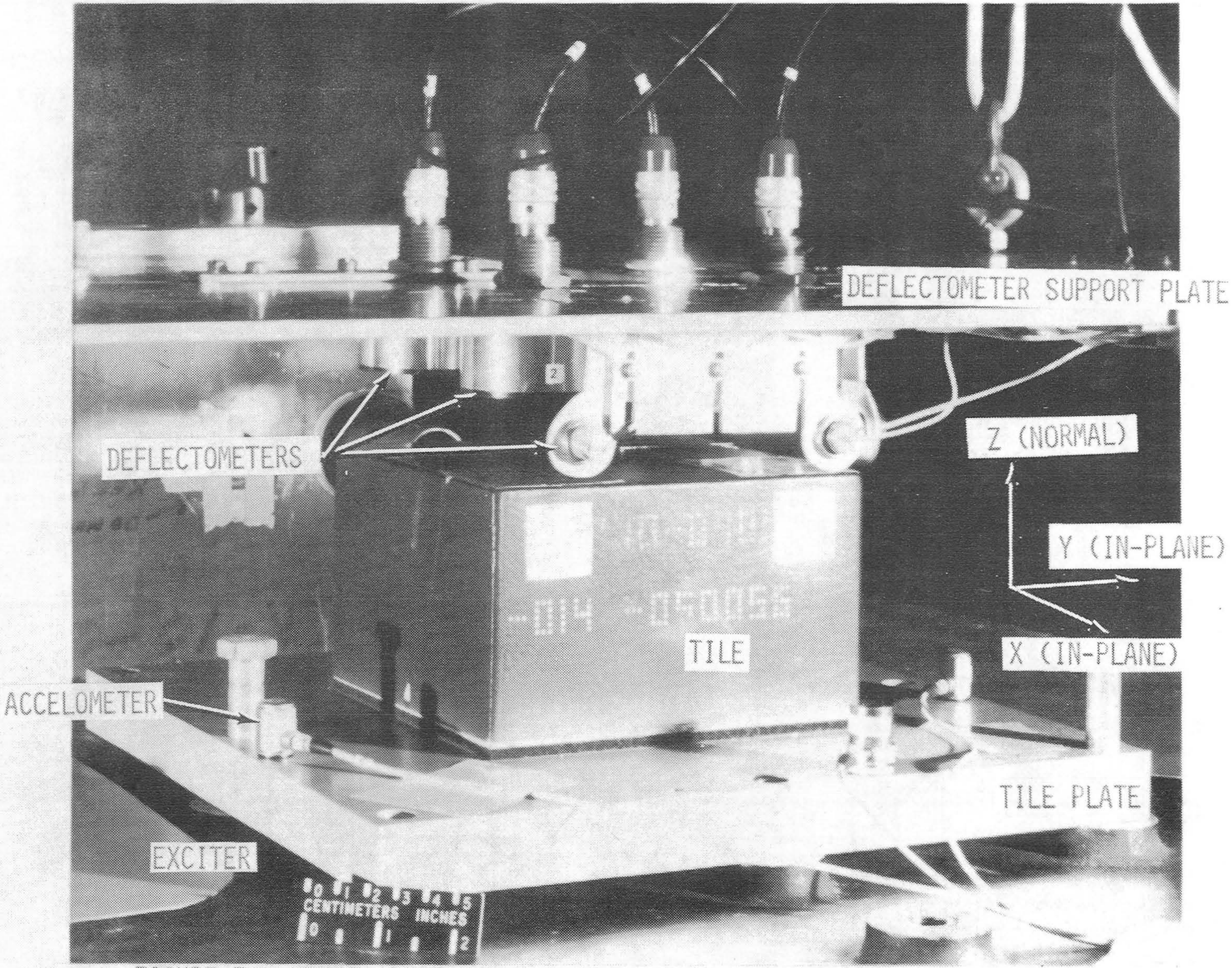

FIGURE 3 - TEST APPARATUS FOR HIGH-LEVEL INPUT ACCELERATION

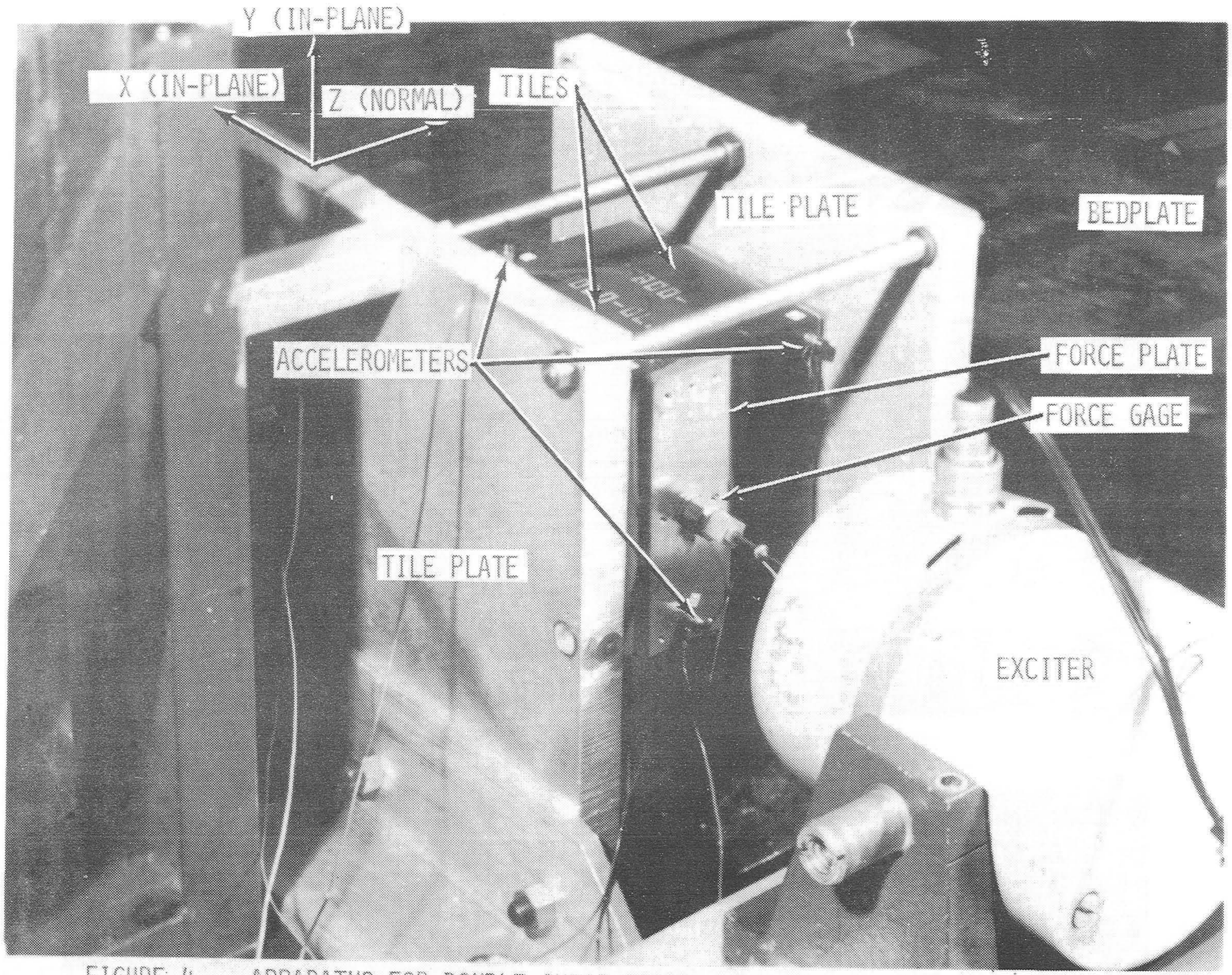

FIGURE 4 - APPARATUS FOR DOUBLE SHEAR TESTS

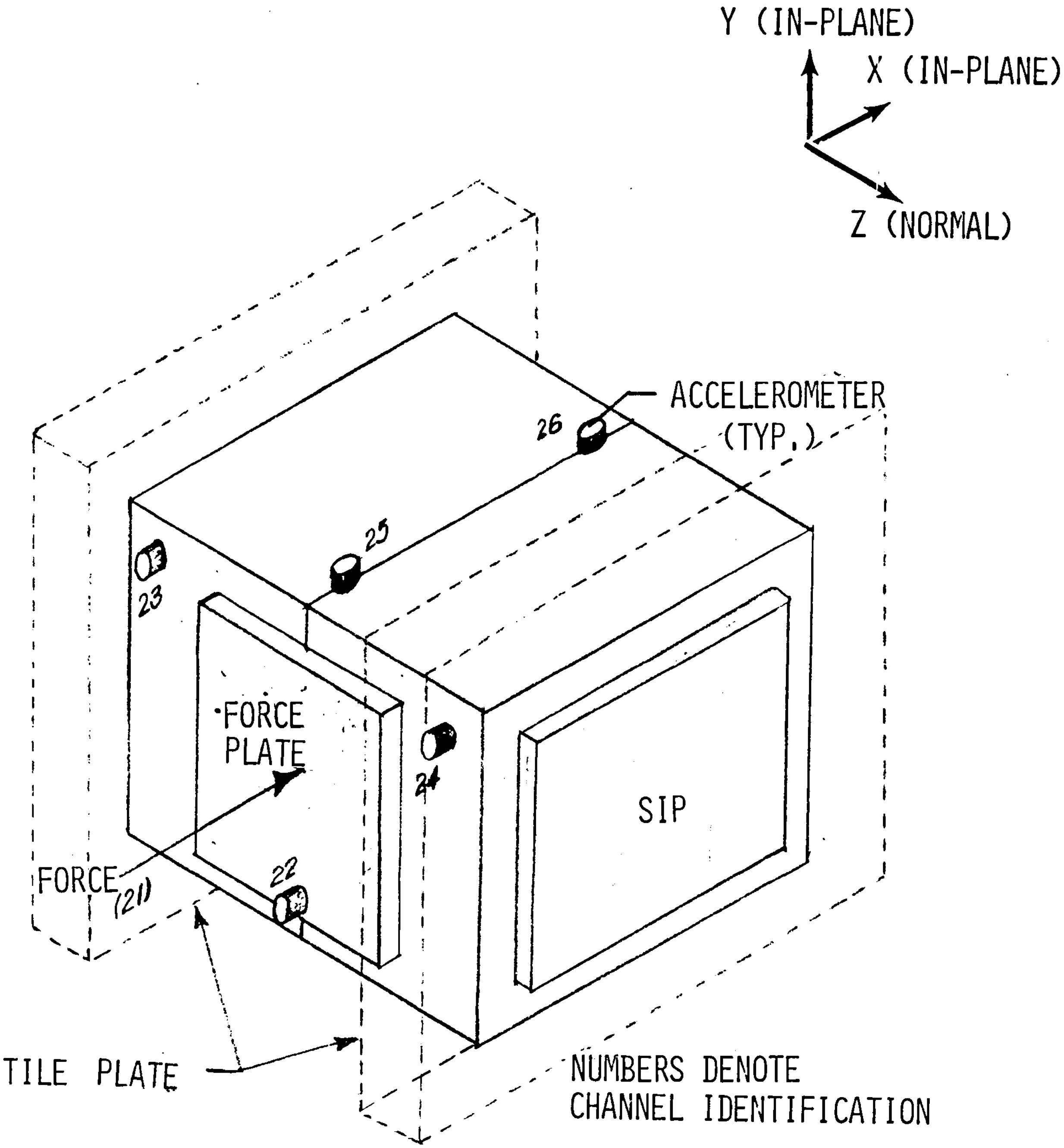

FIGURE 5 - ACCELEROMETER LOCATIONS FOR DOUBLE SHEAR TESTS.

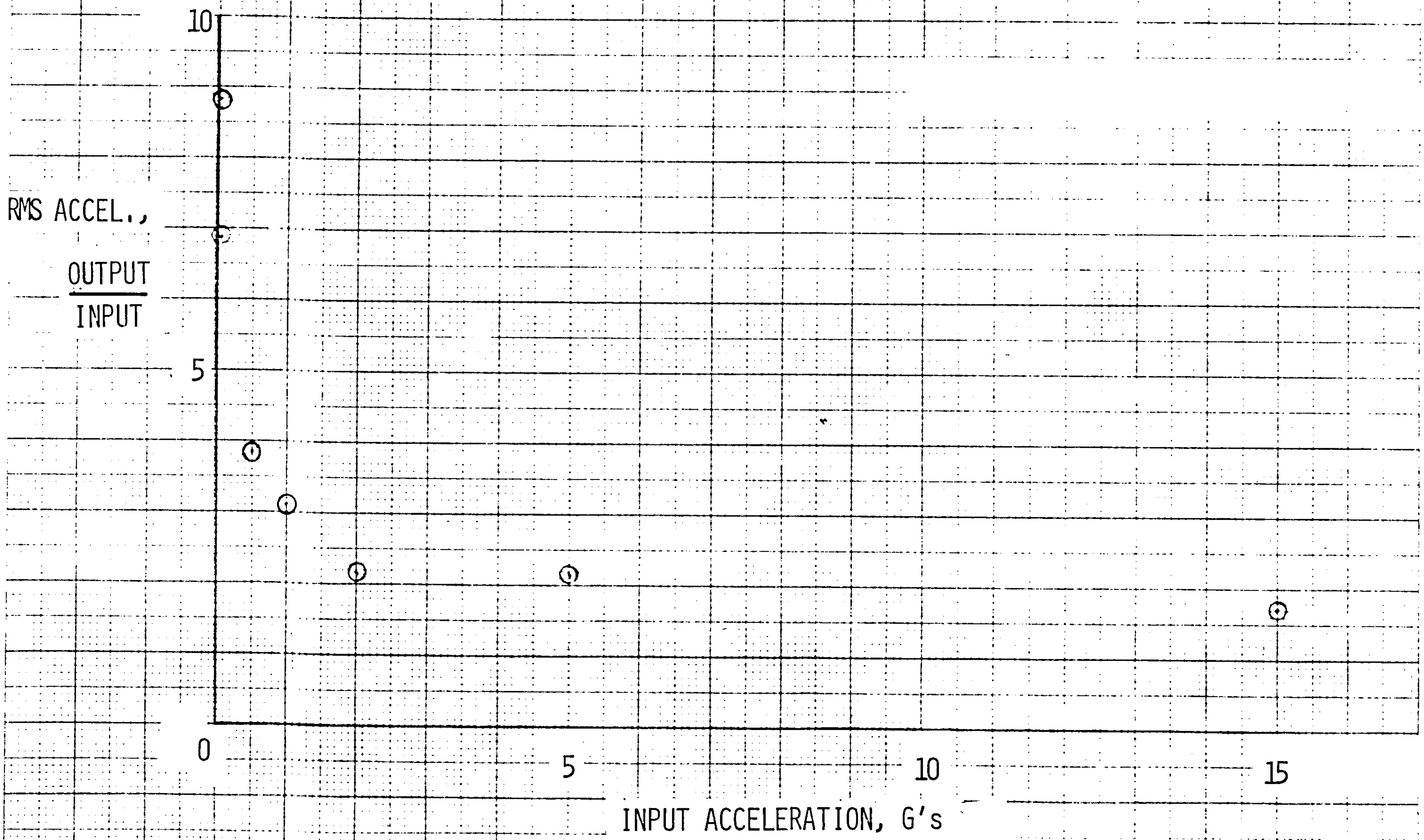

FIGURE 6 - RMS ACCELERATION AMPLITUDE RATIO AT MAXIMUN RESPONSE VS. INPUT ACCELERATION FOR TILE 8335

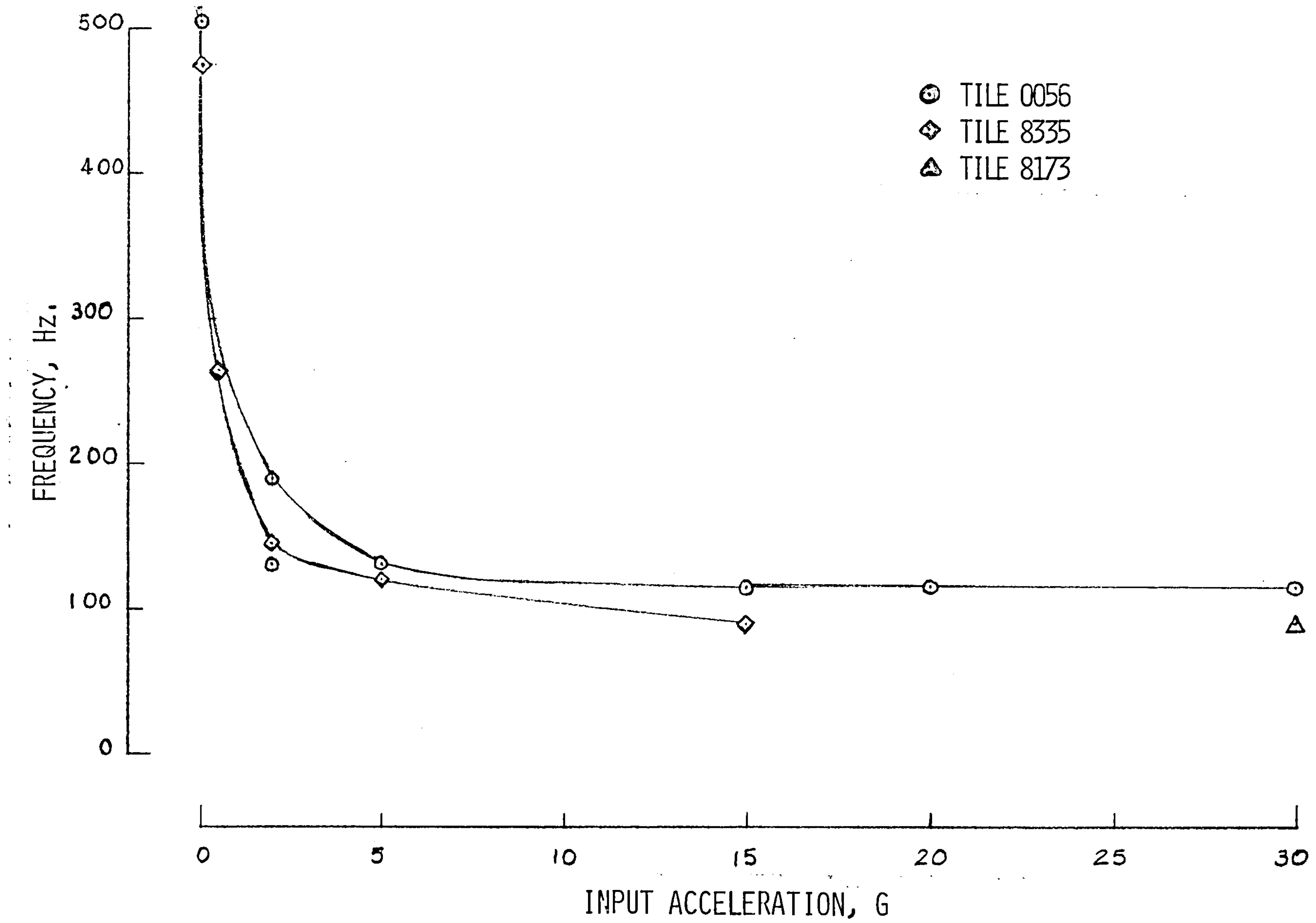

FIGURE 7 - FREQUENCIES OF MAXIMUM RESPONSE AS A FUNCTION OF INPUT ACCELERATION FOR EXCITATION IN THE NORMAL DIRECTION

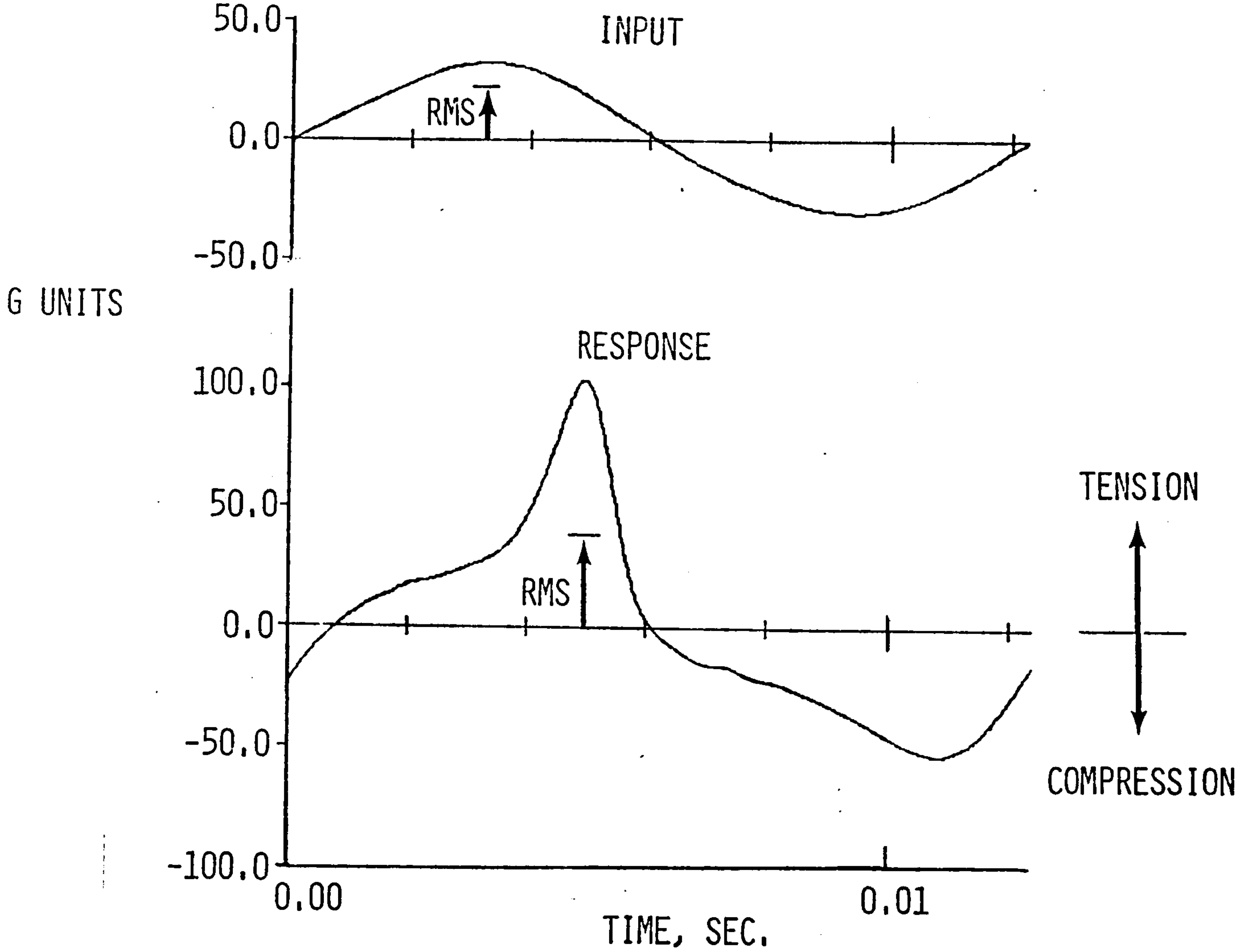

FIGURE 8 - HISTORY OF NORMAL ACCELERATION OF TILE 8173 SHOWING DISTORTION OF WAVE SHAPE

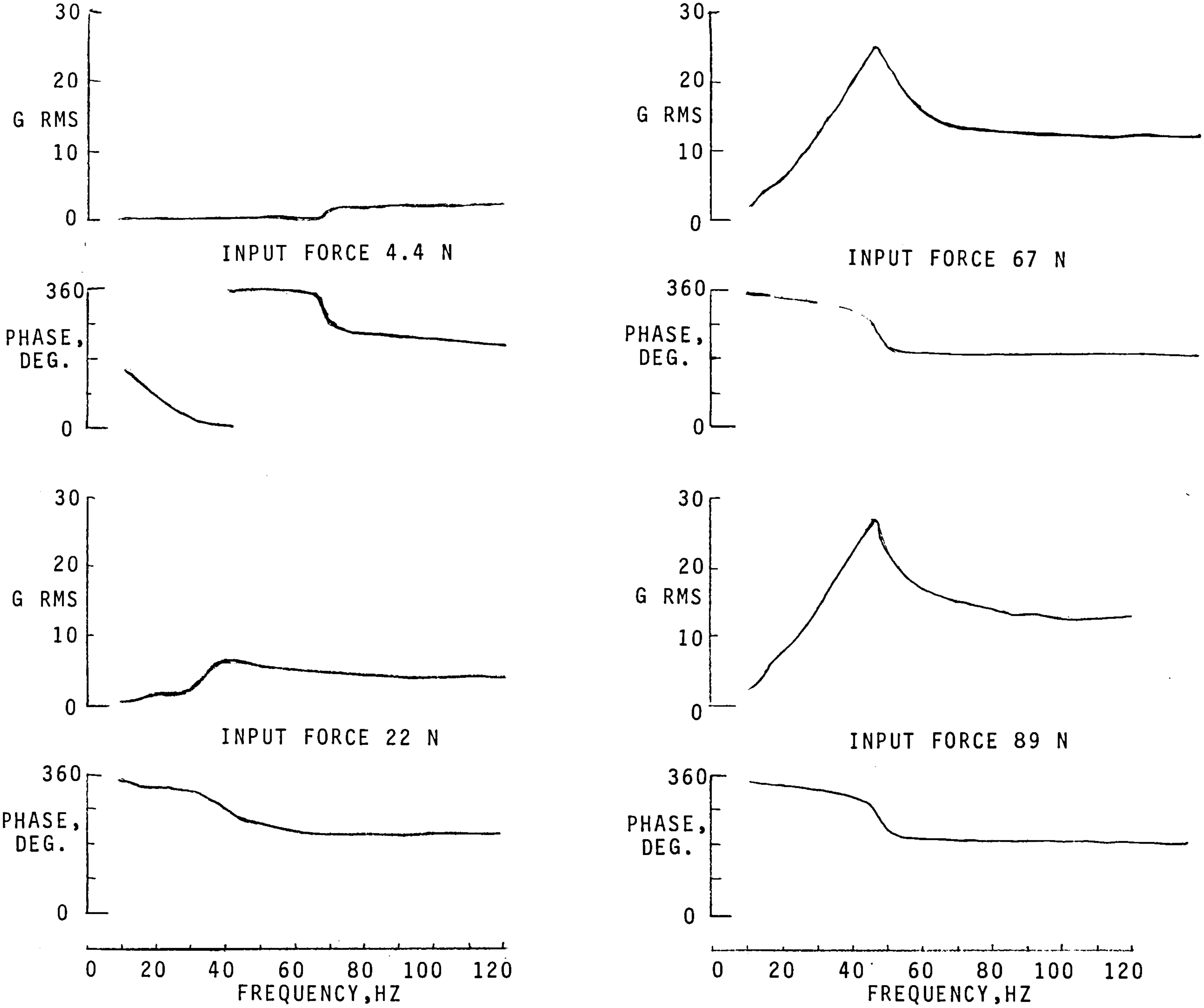

FIGURE 9 - DOUBLE SHEAR TEST FREQUENCY RESPONSE AT DIFFERENT INPUT LEVELS FOR CHANNEL TWENTY-FOUR

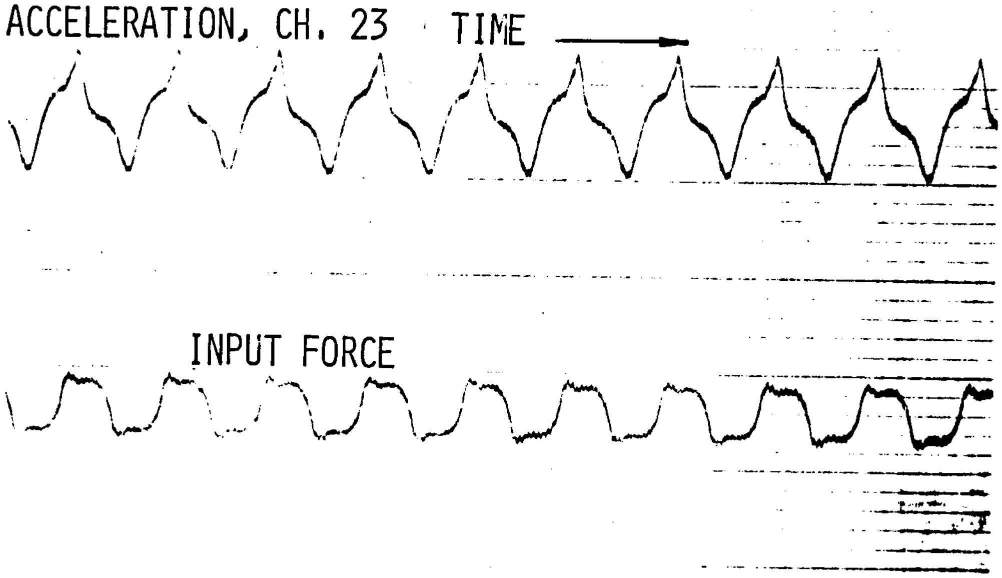

FIGURE 10 - SAMPLE HISTORY OF ACCELERATION AND FORCE FOR DOUBLE SHEAR TEST SHOWING SIGNAL DISTORTIONS

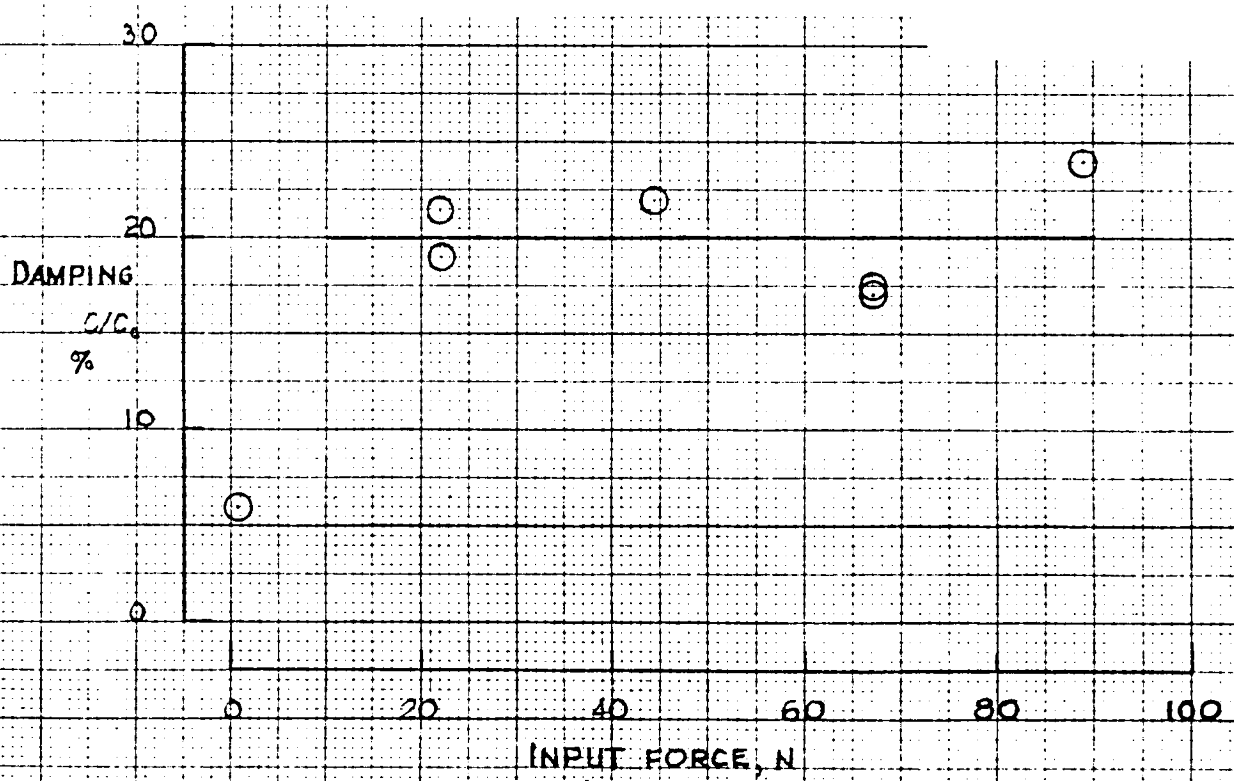

FIGURE 11 - DAMPING AS A FUNCTION OF FORCE FOR DOUBLE SHEAR TEST

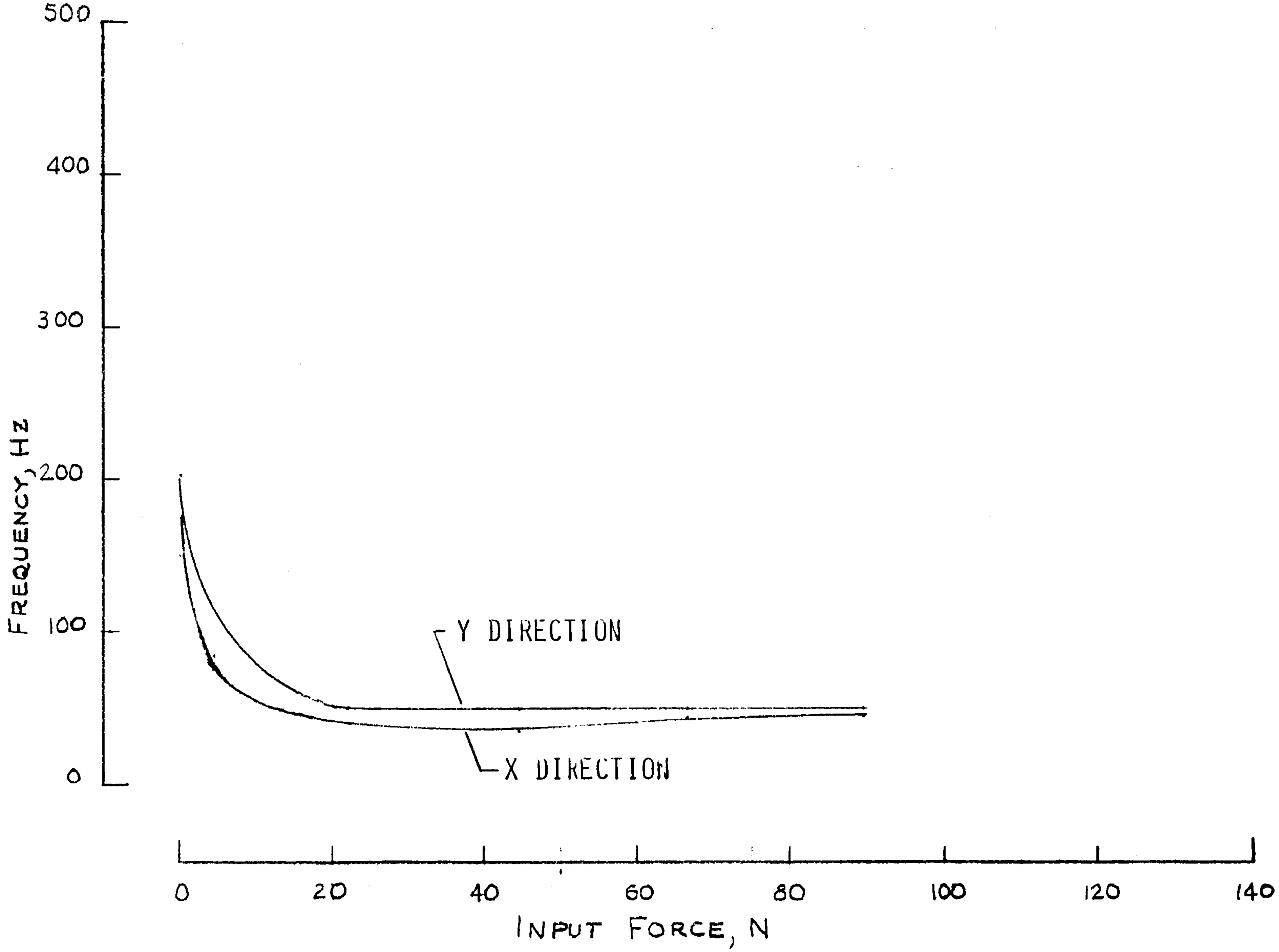

FIGURE 12 - FREQUENCIES OF MAXIMUN RESPONSE AS A FUNCTION OF INPUT FORCE FOR DOUBLE SHEAR TEST

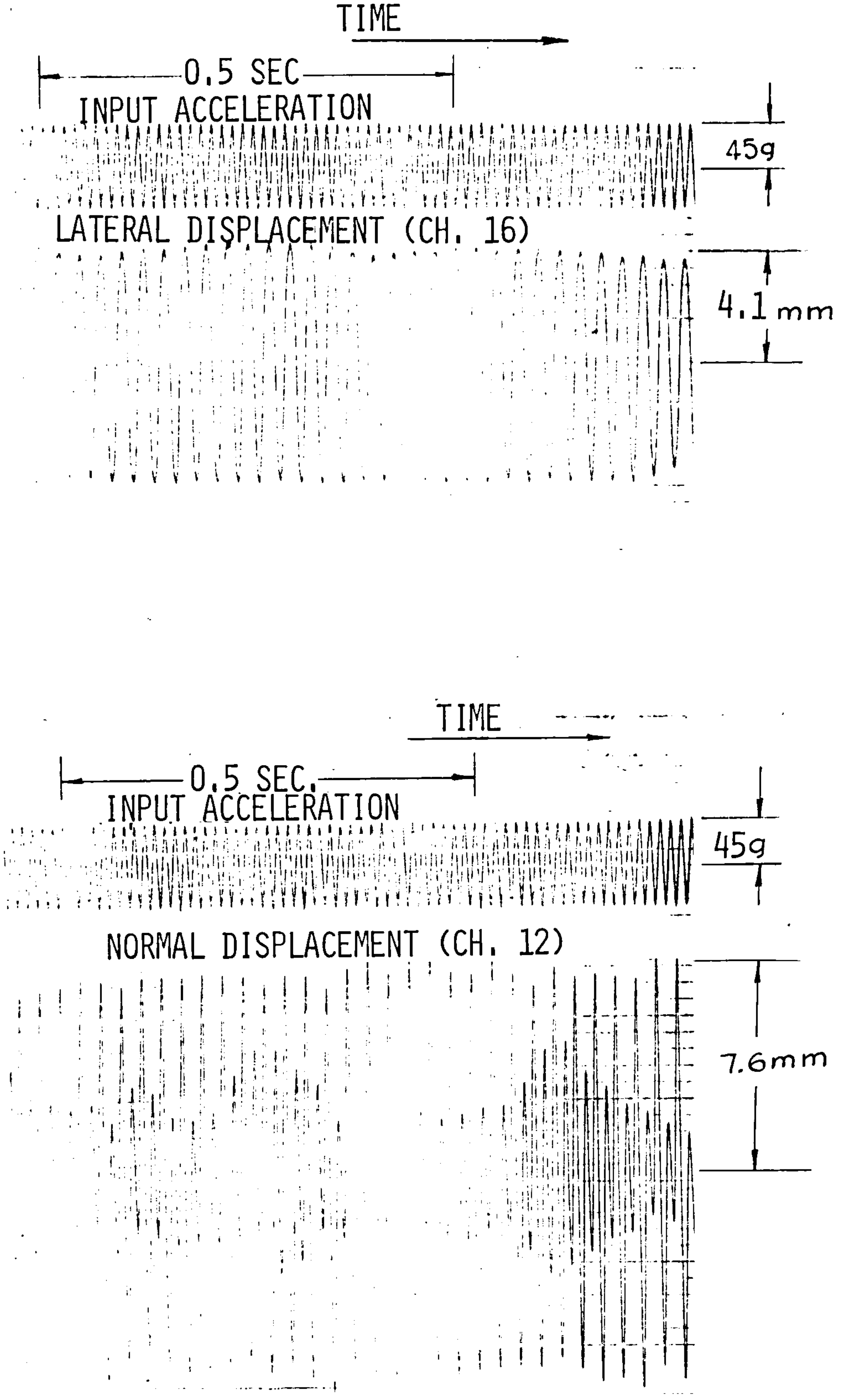

FIGURE 13 - HISTORIES FOR TILE 8173 SHOWING HALF-FREQUENCY IN-PLANE RESPONSE WITH INPUT ACCELERATION AT 45 G RMS

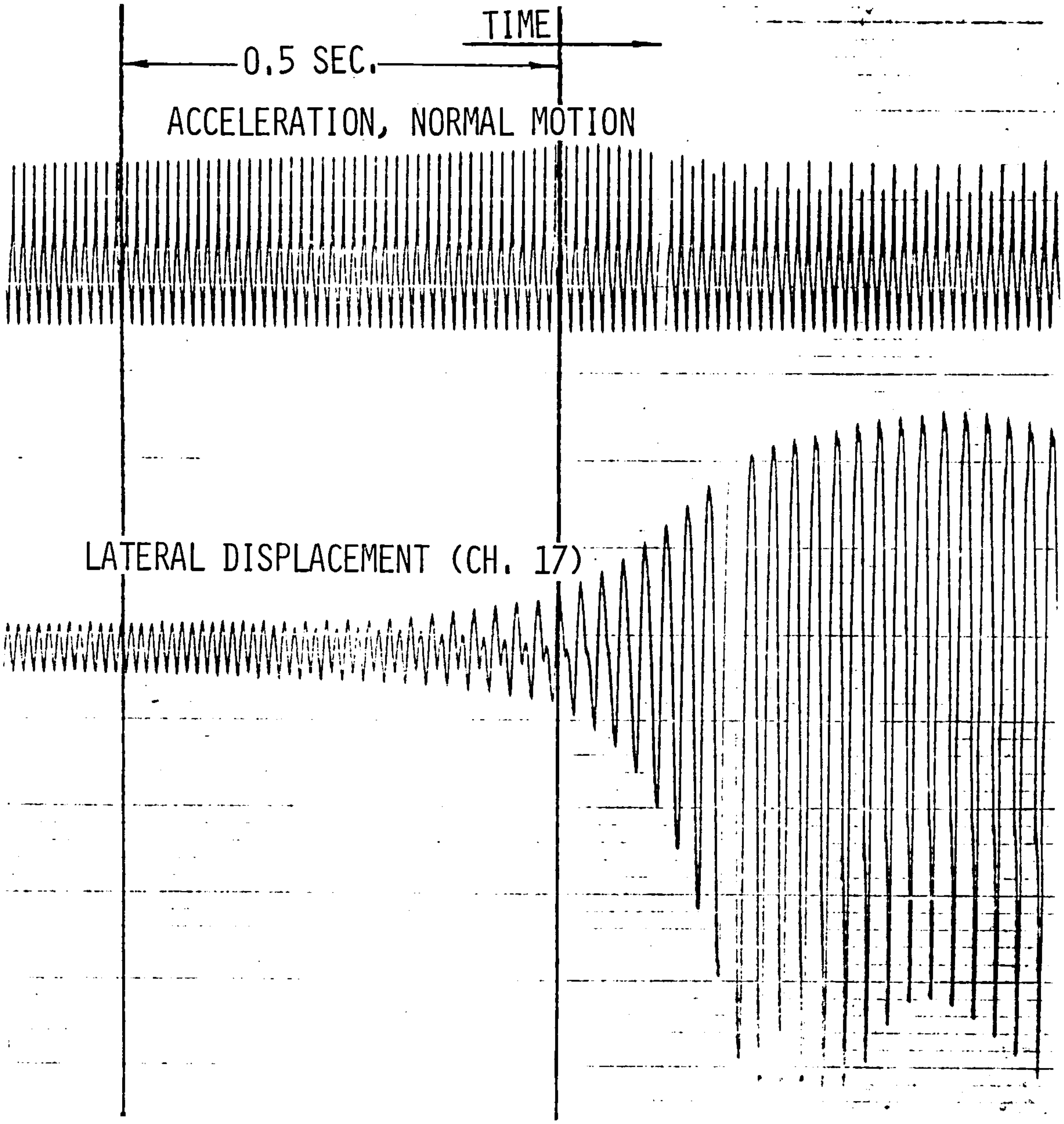

FIGURE 14 - HISTORY OF NORMAL ACCELERATION AND IN-PLANE DISPLACEMENT SHOWING INITIATION OF HALF-FREQUENCY RESPONSE WITH INPUT ACCELERATION AT 30 G RMS FOR TILE 8173

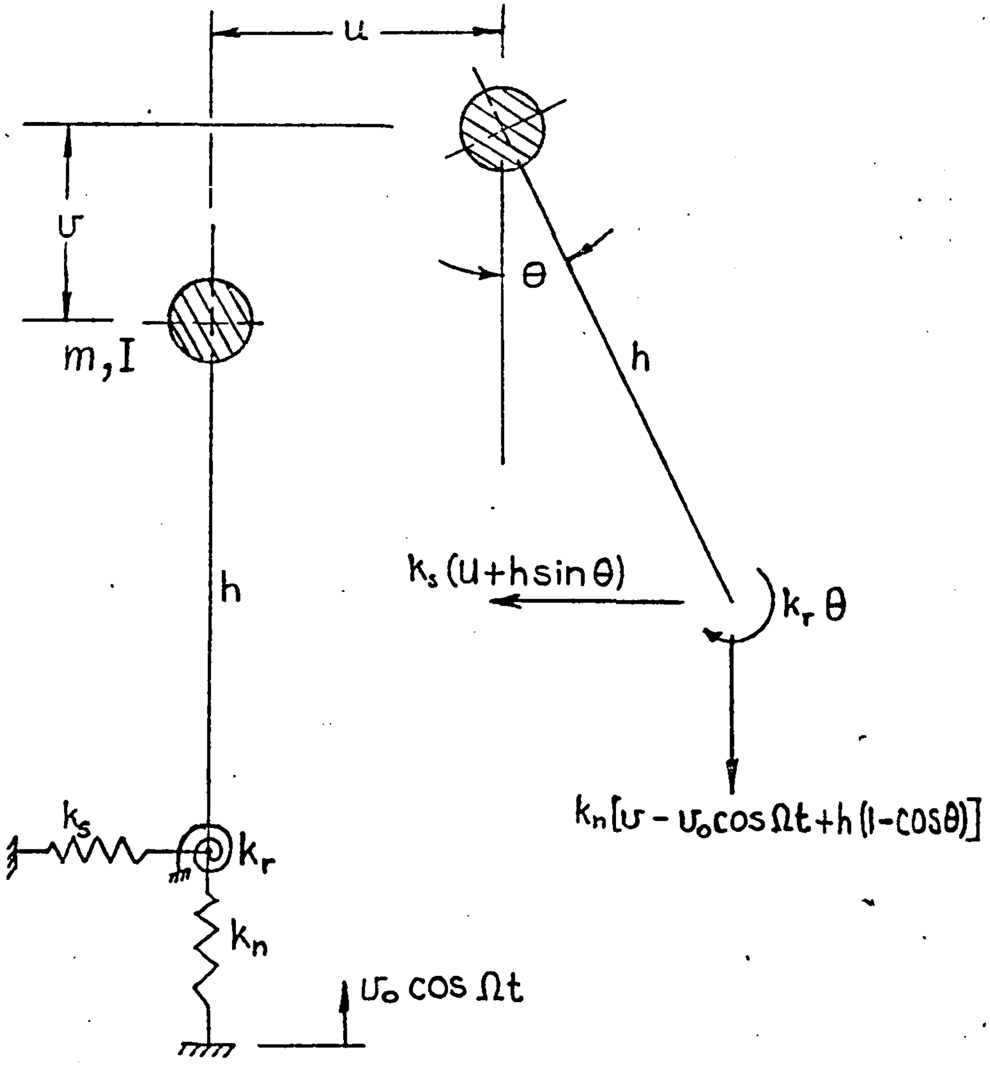

FIGURE 15 - MATHEMATICAL MODEL FOR ILLUSTRATION OF PARAMETRIC RESPONSE

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16. Abstract

Vibration tests were performed as a part of a study of the tile/strain-isolator-pad system used as thermal protection for the Space Shuttle Orbiter. Experimental data on normal and in-plane vibration response and damping properties are presented. Three test specimens exhibited shear type motion during failures that occurred in the tile near the tile/strain-isolator-pad bond-line. A dynamic instability is described which has large in-plane motion at a frequency one-half that of the nominal driving frequency. Analysis shows that this phenomenon is a parametric response.

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