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Light-Initiated Explosive for Impulse Experiments on Structural Members

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Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115 and Livermore, California 94550 for the United States Energy Research and Development Administration under Contract AT(29-1)-789

Printed January 1976

Sandia Laboratories

SF-2900 Q(7-73)

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LIGHT-INITIATED EXPLOSIVE FOR IMPULSE EXPERIMENTS ON STRUCTURAL MEMBERS

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ABSTRACT

An experimental technique utilizing spray-deposited light-sensitive high explosive has been developed for the purpose of delivering impulse loads to mechanical structures. An intense flash of light causes the explosive to detonate, producing a nearly simultaneous, distributed impulse load on the sprayed structure. Simple structures as well as complex systems requiring contoured and/or discontinuous loading can be tested. This paper describes the experimental technique and discusses the data obtained from a test on an elastic beam. The experimental data are compared to elastic theory predictions. The good agreement between experiment and theory verifies that this technique can be used satisfactorily for studying the response of structures to impulse loading in the laboratory.

Printed in the United States of America

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ACKNOWLEDGMENT

The author would like to thank Dave Shirey for conducting the experiments and Ben Duggins for recording the response data. Also appreciated were the comments about the experimentation from Jack Schamaun, Tom Duffey and Mat Sagartz.

CONTENTS

	Page
Introduction	7
Theory	7
Experiments	9
Results	11
References	13

FIGURES

Figure		
1	Comparison Of Impulse Distribution Loading Functions	14
2	Beam Fixture Before Spraying	15
3	Beam With Spray Mask in Place	15
4	Geometry of Spray Method	16
5	Ideal Beam Loading	16
6	Load Distribution	17
7	Response Data Comparison	17

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Introduction

In recent years there has been considerable interest in impulse test techniques for studying the structural effect on weapon systems caused by X-ray induced blowoff impulse loading.[1,2] There has also been interest in using impulse tests for obtaining dynamic material properties.[3,4] Described here is an experimental technique for producing impulse loads on structures using a spray-painted coating of silver acetylide-silver nitrate *SASN), a light-sensitive explosive. This explosive combines initiation sensitivity with the ability to detonate in thin layers. The explosive layer is initiated by an intense flash of light, thus delivering a simultaneous pressure load to the surface of the test structure. This technique is particularly useful for structures with irregular surfaces or structures requiring discontinuous loads. The general test facility and technique capabilities are discussed in a previous paper.[5] Special remote handling equipment is employed to allow safe operations with this sensitive explosive.

The experimental setup and results from an elastic (free-free) beam test using SASN are presented here. Comparisons of test data with elastic theory are shown. This information is used to demonstrate the validity of using SASN for determining structural response due to impulse loading.

Theory

The objective of this article is to show the comparison between theory and experiment for an experiment that is unencumbered with unknown or difficult to evaluate parameters. The structural member chosen was a uniform beam. The boundary conditions were free-free. The beam material was aluminum (6061-T651) because its properties are well-known. The loading was held to levels which would cause only elastic response.

The loading was chosen to excite a simple response, the fundamental mode of vibration, in the beam. The equation of motion for small free lateral vibrations of a uniform beam are governed by the fourth-order equation

$$\frac{\partial^2 u}{\partial t^2} + c^2 \frac{\partial^4 u}{\partial t^4} = 0$$

where $c^2 = \frac{EI}{\rho A}$

E = Young's modulus

I = moment of inertia of the cross-section

ρ = mass density

A = cross-sectional area

This equation can be solved by separation of variables. Using the boundary conditions for a free-free beam that the bending moments and the shear forces must be zero at both ends, the frequency equation for a beam of length L can be obtained.

$$\cos\left(k_n L\right) \cosh\left(k_n L\right) = 1$$

The roots $\left(k_n L\right)$ of the frequency equation and the characteristic modes of vibration are given by Voltera.[6] The frequencies are given by

$$w_n = k_n^2 \sqrt{\frac{EI}{\rho A}}$$

The characteristic function* is given by

$$X_n(x) = \left\{\cosh\left(k_n x\right) + \cos\left(k_n x\right) - \left(\frac{\cosh\left(k_n L\right) - \cos\left(k_n L\right)}{\sinh\left(k_n L\right) - \sin\left(k_n L\right)}\right) * \left[\sinh\left(k_n x\right) + \sin\left(k_n x\right)\right]\right\}$$

and the characteristic vibration is given by

$$U_n(x,t) = X_n(x)\left[A_n \cos\left(w_n t\right) + B_n \sin\left(w_n t\right)\right].$$

*This is the mode shape of the nth mode, i.e., lateral displacement as a function of position on the beam.

To excite the fundamental mode of vibration an impulse loading distributed as

$$X_1(x) = \left\{\cosh\left(k_1x\right) + \cos\left(k_1x\right) - \left(\frac{\cosh\left(k_1L\right) - \cos\left(k_1L\right)}{\sinh\left(k_1L\right) - \sin\left(k_1L\right)}\right) * \left[\sinh\left(k_1x\right) + \sin\left(k_1x\right)\right]\right\}$$

is required. If this function plus a rigid body component, which does not affect the beam response[3], is compared to the simpler function $\overline{X}(x) = C\sin\frac{nx}{L}$ it is seen in Figure 1 that there is very little difference. Experimental techniques are difficult to control to a higher accuracy than indicated, so the simpler loading function was chosen for this test series.

The characteristic vibration equation was solved with the impulse loading of $\overline{X(x)} = \frac{I}{\rho t}\sin\frac{nx}{L}$ where I is maximum impulse and t is beam thickness. The fundamental mode response predominates; however, higher modes are also excited to some small amplitude. The solution to this vibration problem was programmed to allow plotting of strain as a function of time and therefore easy comparison with experimental data.

The free-free beam problem was also solved using the computer code UNIVALUE.[7,8] This code uses a finite-differencing technique to "compute the dynamic response of beams and rings of arbitrary plane configuration whose motion is two-dimensional."

These two predictive techniques were used to calculate the vibration response of the beam.

Experiments

Test Specimen

The test specimen consisted of a 15.24 cm long 6061-T651 aluminum beam of 0.635 cm square cross section. The size was chosen to produce a frequency of particular interest to the investigator. Resistance strain gages were mounted at the

center of the beam (under maximum load) on the side opposite from the load. The gage was electrically shielded to reduce extraneous signals from the explosive initiating light source.

The strain gages were bounded with Micromeasurements AE-15 epoxy, cured for four hours at 80°C. The gages were Micromeasurements EA-13-125AC-350, with a gage factor of 2.1. The gages and lead wires were shielded so that the beam and shielding were common. The beam was held in a blast shield to reduce explosive edge relief effects on the beam's loaded surface. The blast shield was electrically common, with the beam grounded only by the instrumentation ground at the recorder.

Test Technique

A series of operations was performed to complete each test. First, the instrumented beam was mounted to the blast shield. This attachment was required to exert minimal force on the beam during and after the loading. A layer of tracing paper was stretched and glued across the opening for the beam in the blast shield. The beam was attached to the paper in the opening with spray adhesive. A gap of 0.076 cm was left between the beam and blast shield edge. Next, the beam in the fixture was placed in front of the spray gun (Figure 2). Weighing coupons were held in place by magnets every 1.27 cm along the beam length adjacent to and on either side of the beam. The beam, blast sheild, and weighing coupons were sprayed through a mask to produce a distributed explosive layer over the length of the beam surface (Figure 3). The explosive was applied directly to the tracing paper on the beam and blast shield. Figure 4 shows the geometry of the spray method. A mask with a 2.12 cm slit perpendicular to the beam axis was placed 2.54 cm from the beam surface. The spray gun nozzle traveled in a plane 15.24 cm from the beam surface and parallel to it. The spray gun, centered on the mask slit, traversed across the width of the beam. The beam and fixture were mounted on a hydraulic bench so the beam could be indexed vertically behind the mask. By moving the beam in 1.27 cm increments and making repeated spray passes, a step approximation of the desired load could be obtained along the length of the beam. Figure 5 shows the ideal and the step approximation of the load desired.[5] The sprayed explosive weight distribution was checked periodically throughout the spraying process by remotely removing and weighing the coupons. The areal density of deposited explosive is related to the impulse delivered upon detonation of the explosive. The spraying and weighing process was continued until the desired weight distribution was achieved.

The fixture, with the beam, was then placed in front of the capacitor bank discharge light source and the instrumentation lead wires connected. The explosive was surface initiated to produce the impulse loading.

The data were recorded by a magnetic tape recorder system available at the test facility. A pulsed X-ray system was used to obtain a multiple exposure of the moving beam on one piece of film during the test. This rigid body motion data provided a measurement of the total impulse applied to the beam.

Impulse Calibration

The impulse applied to the beam was evaluated locally as well as macroscopically. The local impulse was predicted using coupon areal density from measured explosive weight. The impulse value was determined from the facility empirically determined calibration data. Local impulses were predicted at eleven positions along the beam. The explosive on some of the coupons was subsequently detonated in a pendulum impulse measuring device to verify proper explosive formulation. The macroscopic impulse was measured by observing the rigid body velocity of the beam after detonation of the explosive.

Light Array

The light array used for this test is described in reference 9.

Explosive Behavior

A previous investigation showed that the explosive initiates at all points over the surface within 1 μs and that the applied pressure is about 2 to 3 μs in duration with a magnitude of about 1 kilobar per kilotap up to about 500 Pa•s (5 kilotaps). Simular results are expected for this experimental series for impulses below 500 Pa•s. The explosive initiates about 18 μs after the capacitor bank light source is triggered.

Results

Figure 6 shows the loading on the beam. The coupon data are compared to the ideal desired load of 150 Pa•s. The rigid body velocity measurement indicated a peak load of 163.5 Pa•s. The theoretical calculations are based on a 163.5 Pa•s peak load for both UNIVALUE and the simple theory.

Figure 7 shows the comparison between the theories and the experiment. The simple theory is plotted for the fundamental mode (n=1) only for a load distribution of $I(x) = 163.5 \sin(\pi x/L)$ Pa·s (w_1 = 1402 Hz). The UNIVALUE theory calculated for the same load is limited in frequency content by the particular plotting routine used (20 kHz). The experimental data are limited to about 20 kHz by the tape recorder used for data collection (amplitude attenuation is 3 db at 20 kHz). The higher frequency apparent in the experimental data is the frequency of the third modal vibration (7570 Hz). The simple theory for n=3, although not shown here, agrees well with this experimental data. Higher modal frequencies are limited by the data recording system.

The agreement between theory and experimental data verifies that the proper structural response is excited by the impulse loading of this technique. The response of structures where unknown material properties or geometric complexity prevent complete analysis can now be studied in the laboratory.

This technique has recently been used in several weapon system tests.[9,10,11] A series of tests using this particular beam loading technique has been completed for the determination of the dynamic material properties of CIP/HIP-1 beryllium.

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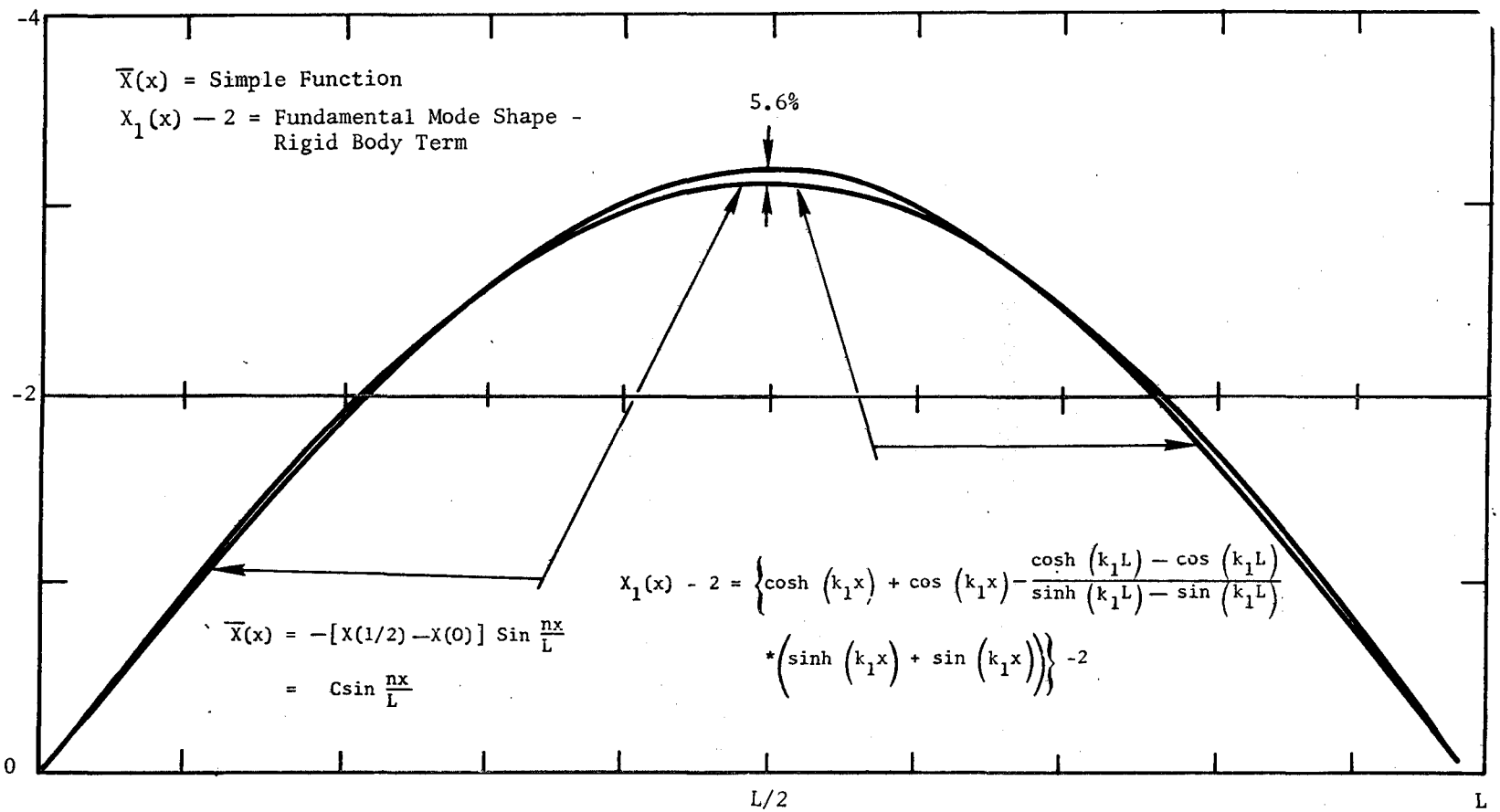

Figure 1. Comparison of Impulse Distribution Loading Functions

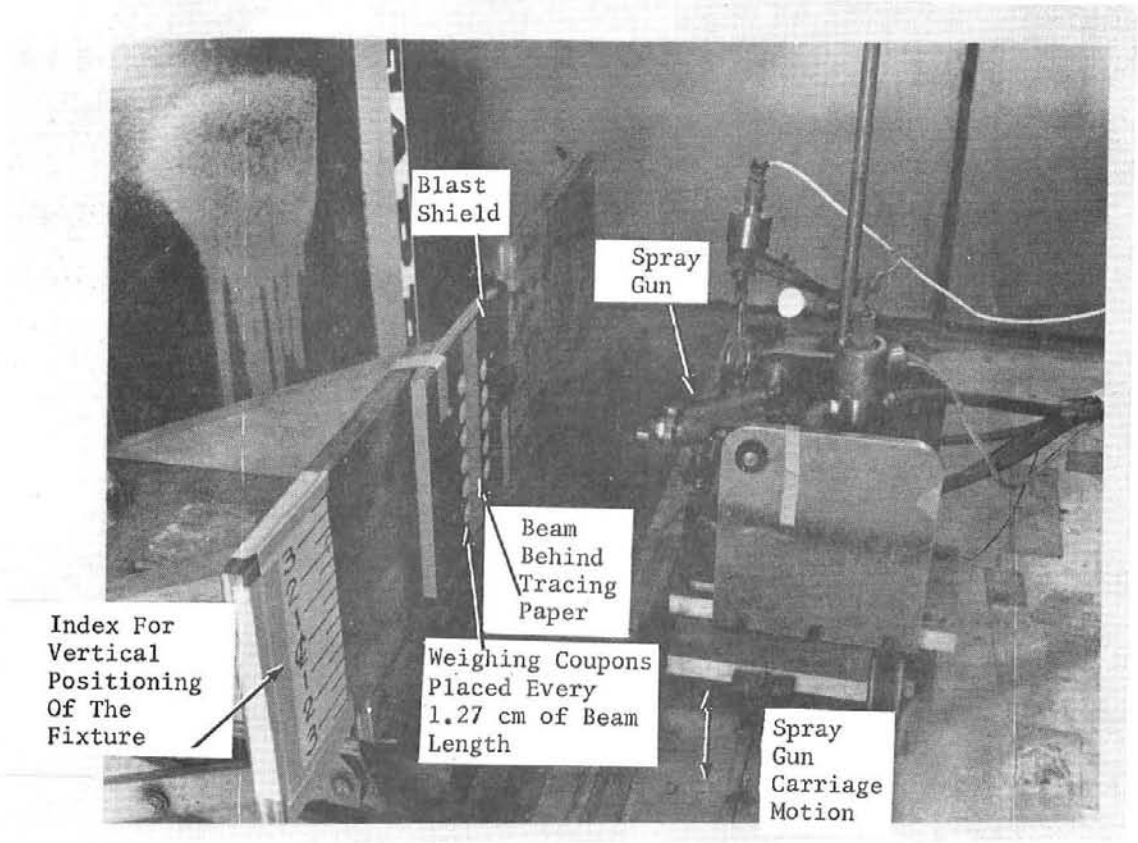

Figure 2. Beam Fixture Before Spraying

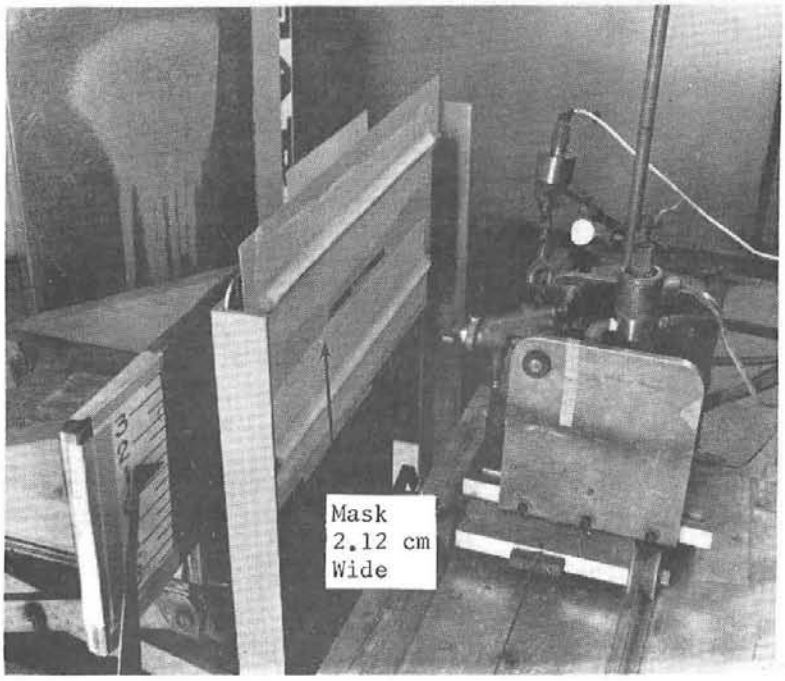

Figure 3. Beam With Spray Mask in Place

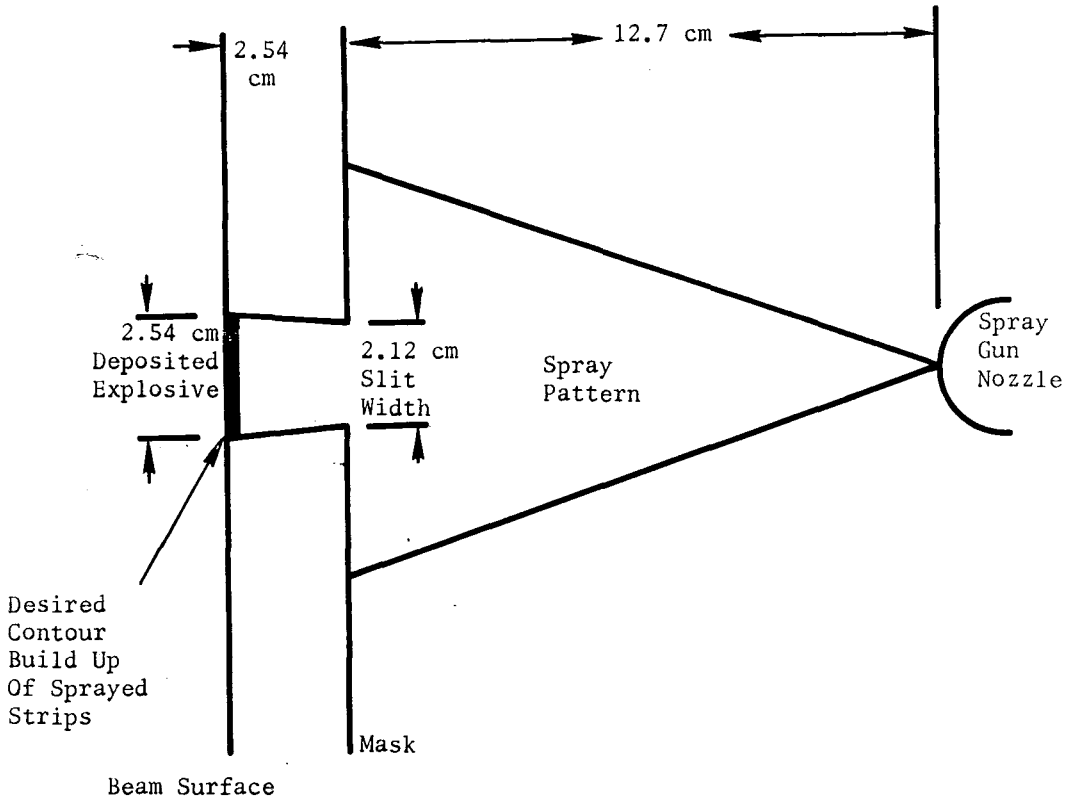

Figure 4. Geometry of Spray Method

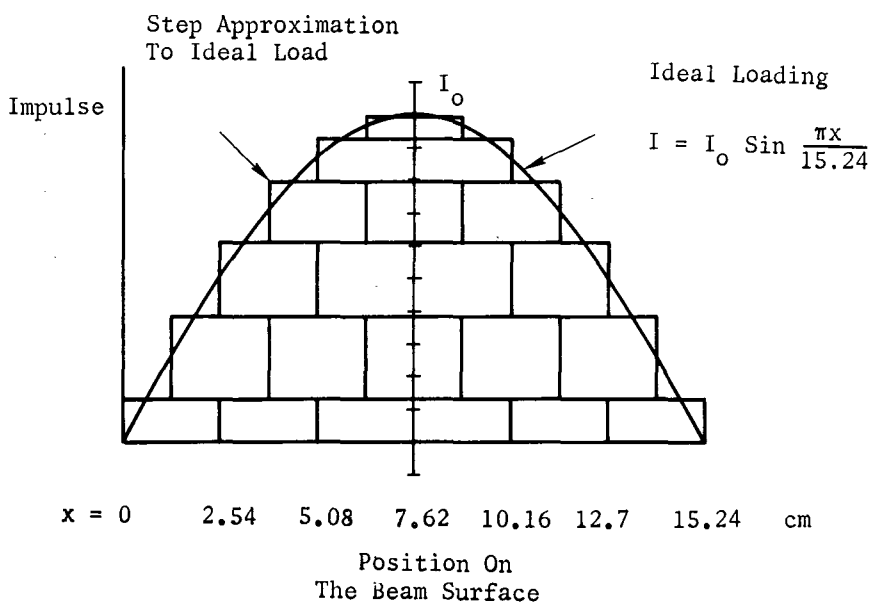

Figure 5. Ideal Beam Loading

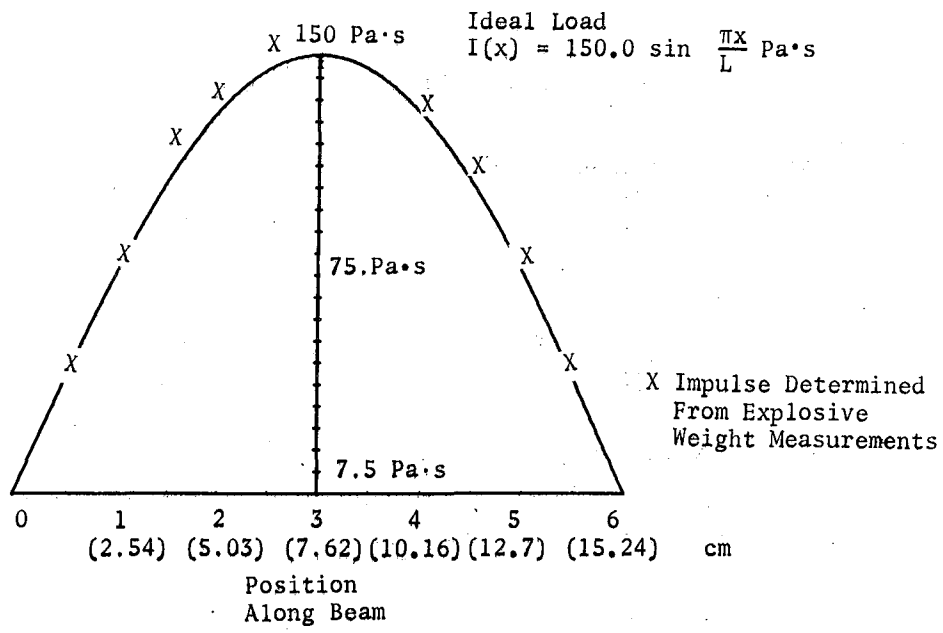

Figure 6. Load Distribution

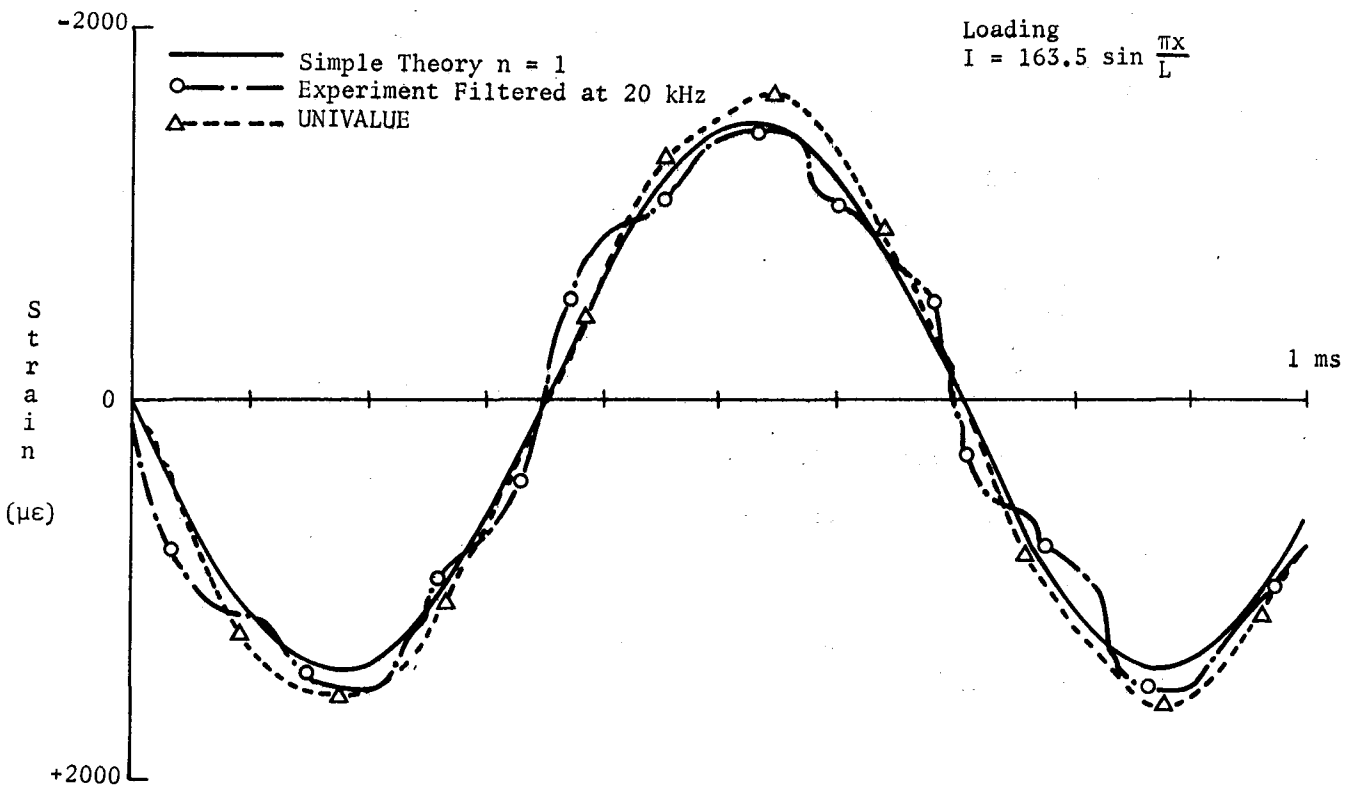

Figure 7. Response Data Comparison

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