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That Was a Blast! Air Cannons as an Introduction to Blast Loading of Structures

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Abstract

Blast loads on structures are exciting! They are big and surprising and set structures in motion. They also pique student interest in the details of transient loading, structural dynamics, and dynamic amplification of loads. Small-scale model demonstrations in structural dynamics courses are very common, with well-defined structures, subjected to free and forced vibration experiments, providing a physical representation of larger framed structures. As a course moves from well-described forcings and closed-form solutions to numerical time-stepping methods there is an opportunity with blast loads to introduce numerical methods in a highly contextualized and engaging way.

If you hand a student an air cannon and ask them to shoot you in the face, they will happily oblige. If you ask them to fire the air cannon at a small structure and characterize the blast load based on the measured response of the structure, they will ask you for a little help. They need to know the dynamic parameters of the structure, like stiffness, mass, and damping. They need to be able to measure response, and their mobile phone turns out to be a very good tool for this. Finally, they need a way to solve for the dynamic response of the structure based on an arbitrary blast loading and you happen to have introduced a spreadsheet implementation of Newmark's method. All the pieces are in place; let's see what the students do!

This paper describes the implementation and results of a blast loading experiment using air cannons and the resulting student responses. Exam performance was comparable to students in a previous offering without the laboratory. Laboratory reports provided insight consistent with prior studies of problem-based learning and that support theories that experimentation labs may be more effective than verification labs.

Introduction

Active learning approaches are regarded positively and are widely respected as an evidence-based instructional practice, particularly inquiry methods and problem-based learning [1-3]. Considerable discussion in physics teaching circles has been devoted to comparing learning in (a) more traditional "verification labs," where theories are demonstrated physically through well-controlled tests and prescribed procedures and are "in service of theory" and (b) "experimentation labs," where students are offered a theory along with tools to test that theory as they see fit [4]. Smith and Holmes summarize a body of research to conclude that "verification labs do not measurably add to students' understanding of the physical models they aim to verify" [4].

Air cannons are devices that use compressed air to generate a controlled impulse and can be used to launch projectiles or, in the case of the AirZooka and other branded toy air cannons, can produce a traveling vortex of air. These devices are often published on physics demonstration websites and countless YouTube videos are devoted to performing tricks or including smoke to make the ring visible. Air cannons of various types have been featured in other instructional innovations: projectile motion [5], hurricane debris [6], and fluid dynamics [7]. Instructors using toy air cannons to excite small-scale structural models could not be found in a literature review.

This case study examines an innovation in the blast loading module of a senior/graduate elective course in structural dynamics. The motivation for the innovation derived from multiple sources, including

- a departmental and institutional focus on hands-on learning;
- the joy of playing with an AirZooka;
- evidence-based best practices including active learning approaches, problem-based learning, and experiences favoring experimentation and inquiry over verification [1-4];
- ABET outcome 6: "an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions," specifically the ability to *develop* experimentation, which has been particularly challenging to assess and incorporate into instruction [8]; and
- considerations regarding coursework outside of the capstone that integrate multiple concepts, experimentation, and problem-solving approaches.

Methods

The blast load laboratory is one of ten labs offered in a course that is cross-listed as a senior and graduate elective at a small public polytechnic institution. Course enrollment is usually around ten students. The instructor has offered this course five times in the last ten years and this is the first year a lab devoted to blast loading was offered. Prior labs at this point in the course had been devoted to comparing theories and methods: Duhamel's integral, Newmark's Method, and other time-stepping procedures to solve for structural response to arbitrary loading, a prerequisite for further study of seismic ground motions. The time spent comparing numerical methods always seemed less valuable than giving students time to use the methods, particularly when comparing to a measured structural response. Thus, the inquiry-based approach to teaching blast loads was developed and is described here.

Assessment of the impact of this innovation was performed by scrutinizing performance on an exam question involving blast load response of a hypothetical steel frame structure during this year, when the blast loading lab was performed, and a prior year when a different lab was included. Student laboratory reports for this year, when the lab was conducted, were examined qualitatively for the intervention group, but no control group was available since a blast loading laboratory had not been included in previous course offerings.

The blast load laboratory assignment is provided in Figure 1.

Using the Newmark's Method spreadsheet developed and confirmed with Chopra Examples 5.3 and 5.4, we will explore blast load response of our one-story structure model from Labs 1 and 2.

1) Select an appropriate tool or tools to measure the response of the structure based on those outlined at http://bit.ly/phonevib.

2) Develop a system for applying a blast load. Consider the AirZooka, a compressed air hose in one of the high-bay labs (like Structures or Concrete), or another method like physical contact. Consider using the acoustic stopwatch, phone-based video recording, or other tools to identify the duration of the blast load.

3) Prepare and conduct a well-controlled experiment to apply a blast load and measure the response of the structure. Blast response is here .

4) Modify the Newmark's Method spreadsheet to plot a comparison of the measured response of the structure with the response calculated using Newmark's Method. Use best estimates of all structural parameters (mass, stiffness, damping, etc.) determined in prior labs. The primary unknown should be the magnitude of the blast force and profile (force vs time), assuming the duration of the blast has been measured effectively. Adjust the profile until the calculated and measured structural responses agree.

5) Discuss the results of this experiment, paying particular attention to the methods employed and the potential uncertainty in the nature of the blast load.

Both 400- and 500-level students should prepare a complete laboratory report. Please attach your spreadsheet along with the report when submitting this assignment.

Figure 1. Description of the laboratory activity provided on the course learning management system.

Students were provided with a website that describes mobile phone-based tools for measuring dynamic response of a small structure; they had previously used these tools to evaluate the model structure in prior laboratories related to natural frequency and damping ratio. In those laboratories, multiple methods of loading (static, free vibration, forced vibration), modeling assumptions (top floor as lumped mass versus including tributary length of columns), analysis (time domain, frequency domain), and measurement (accelerometer, phone-based LiDAR, stroboscope) were used to identify a best estimate of the structure's natural frequency, as well as assess the value of the various methods of measurement.

In the natural frequency lab, the students had determined that the stiffness of the structure based on free vibration testing was 2.68 lb/in and was the most accurate representation of the stiffness of the structure in a dynamic scenario. Greater stiffnesses had been obtained by testing the structure with a static load (3.05 lb/in), using an analytical model with a fixed-fixed column assumption and rigid top beam (3.39 lb/in), and using a matrix structural model that incorporated the flexibility of the top beam and incorporated static condensation (2.86 lb/in). The students had ultimately agreed that the lumped mass ought to include both the mass of the top beam as well as the top half of each column and the fasteners. These had been measured to have a weight of 1.657 lb. The structure is depicted in Figures 3 and 4.

The damping ratio was determined in a subsequent lab based on an average of each student's log decrement analysis of a free vibration decay signal measured using a phone-based accelerometer. The test structure is very lightly damped and was determined to have a damping ratio of 0.28%.

Through discussion of these prior labs, all students had agreed that these structural parameters represented the best possible estimates with the tools available. Thus, the structure could now be used as a measurement tool to identify the nature of an unknown impulse load applied to it.

In the class period prior to the blast loading lab, students had coded and validated a spreadsheet implementation of Newmark's Method (Figure 2), a numerical time-stepping method that allows for the solution of the displacement, velocity, and acceleration response of a single-degree-of-freedom system to an arbitrary loading [9,10]. Thus, the students were equipped with a numerical analysis tool to relate structural response and structural loading as well as tools to measure structural response. With these tools available, the stage was set for the blast loading lab.

Lab 4 - Blast Loads on Small-Scale Structure

Inputs

mass, m =	0.005739	$lb\text{-}sec^2/in$	
stiffness, k =	2.68	lb/in	from free vibration
damping ratio, ζ =	0.0028		from free vibration, log decrement method
natural frequency, f_n =	3.439	Hz	
natural frequency, ω_n =	21.609	rad/s	Tn = 0.290764 sec
damping coefficient, c =	0.001	$=2\zeta m\omega_n$	
initial displacement, u_0 =	0		
initial velocity, v_0 =	0		
sampling interval, Δt =	0.01	sec	
Newmark parameter, γ =	0.5	*traditionally = 1/2*	
Newmark parameter, β =	0.25	*1/4 for average acceleration method, 1/6 for linear acceleration method*	

Initial Calculations

initial acceleration, a_0 =	0	in/sec^2
khat =	232.3899	
response coefficient, a_1 =	229.7099	
response coefficient, a_2 =	2.296405	
response coefficient, a_3 =	0.005739	

Response Calculations

Time (sec)	p(t) (lb)	p_{hat} (lb)	u (in)	v (in/sec)	a (in/sec^2)
0	0	0	0	0	0
0.01	0	0	0	0	0
0.02	0	0	0	0	0
0.03	-0.9	-0.9	-0.00387	-0.77456	-154.912
0.04	-0.7	-4.25741	-0.01832	-2.1149	-113.156
0.05	0	-9.71441	-0.0418	-2.58152	19.83226
0.06	0	-15.4168	-0.06634	-2.32606	31.25951
0.07	0	-20.4011	-0.08779	-1.96361	41.23112

Figure 2. Implementation of Newmark's Method in Microsoft Excel for calculation of dynamic structural response to arbitrary loading.

Blast loading was introduced with a scene from Indiana Jones and the Kingdom of the Crystal Skull, in which Indy hides in a lead-lined refrigerator to survive a nuclear blast. The positive and negative pressure profile of a typical blast load was discussed as well as the influence of the ratio of the duration of the blast load, t_d, to the natural period of the structure, T_n. The displacement response factor (the ratio of dynamic response to static response) had been introduced previously:

$$R_d = \frac{u_o}{(u_{st})_o}$$

where u_o is the maximum amplitude of the dynamic displacement response and $(u_{st})_o$ is the amplitude of the static response to a static force equal to the maximum amplitude of the dynamic loading. The textbook content and discussion in lecture demonstrated that a maximum value of the displacement response factor is 2.0 for impulse or impact loading [9].

Finally, the toy air cannon was unveiled as the tool to supply the blast load to the model structure. Students were invited to shoot the instructor in the face or take a shot to the face and estimate force and duration of the impulse. Various estimates were offered, ranging from fractions of a pound to 20 pounds. Various attempts were made to improve these estimates, including shooting a small postage scale to see if it registered force (it did, at roughly 0.5 lb). The acoustic stopwatch on the PhyPhox app [11] was used to measure the duration between the release and end of the air cannon, but the results were unreliable, except that it was confirmed that the blast was likely a fraction of a second in duration. The students did not suggest using video for this purpose, although this potential was explored in previous labs.

(a) (b)

Figure 3. Students attempting to measure displacement response of the test structure using (a) the LiDAR sensor on an Apple iPhone running the PhyPhox app [11] and (b) the phone-based accelerometer.

The first task for the students, based on the lab description (Figure 1), was to select an appropriate tool or tools to measure the structure response. The students first selected the non-contact LiDAR sensor via the PhyPhox app [11] on the Apple iPhone 13 Pro, which was a favorite tool in previous labs. It was set up as shown in Figure 3a.

Upon studying the response measurement from the LiDAR sensor, the students quickly realized that the blast from the air cannon was reaching the phone as well, so the structural response measurement was unreliable. After significant discussion, it was decided collectively that the accelerometer would be the better tool, so long as the mass of the phone (0.56 lb) was added to the mass parameter describing the structure (Figure 3b). A surprising amount of time was spent attempting to fix the air cannon in place to improve the repeatability of the shot (Figure 4). Lively discussions were had by the students about whether this was important while the instructor attempted to remain agnostic until a decision was made to simply have one student apply the blast load as shown in Figure 3b.

Figure 4. Students attempting to improve the repeatability of the air cannon shot.

The time history of the structure response was measured using an iPhone 13 Pro running the PhyPhox app and sampling at 100 Hz. The time history was uploaded to the course LMS for distribution to the students and each of them plotted it in Microsoft Excel, in the same sheet as their Newmark Method implementation. The students were then tasked with plotting both the measured response in the same plot as the acceleration response from the Newmark Method (Figure 5) and adjusting the impulse loading until good agreement was reached. The class slowly coalesced around a short duration of 0.02 seconds with force values around 0.8 lb. Adjusting the values to 0.9 and 0.7 lb further improved the agreement (Figure 6). Finally, the displacement response was plotted to compare with the physical response observed during the testing (Figure 7).

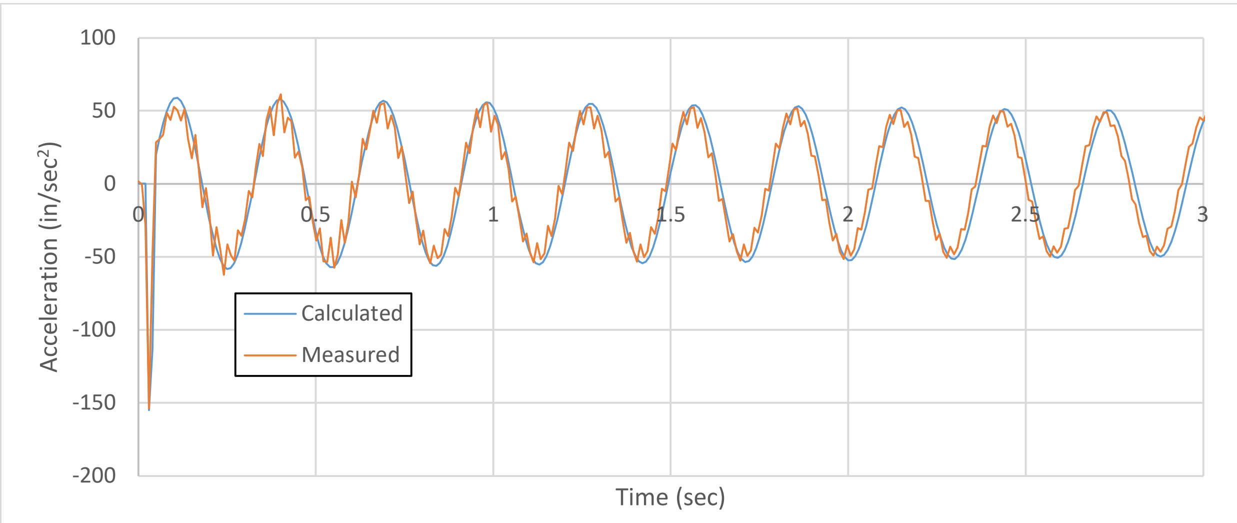

Figure 5. Acceleration response of a one-story model structure subjected to blast loading supplied by toy air cannon (Calculated = Newmark's Method, Measured = iPhone accelerometer).

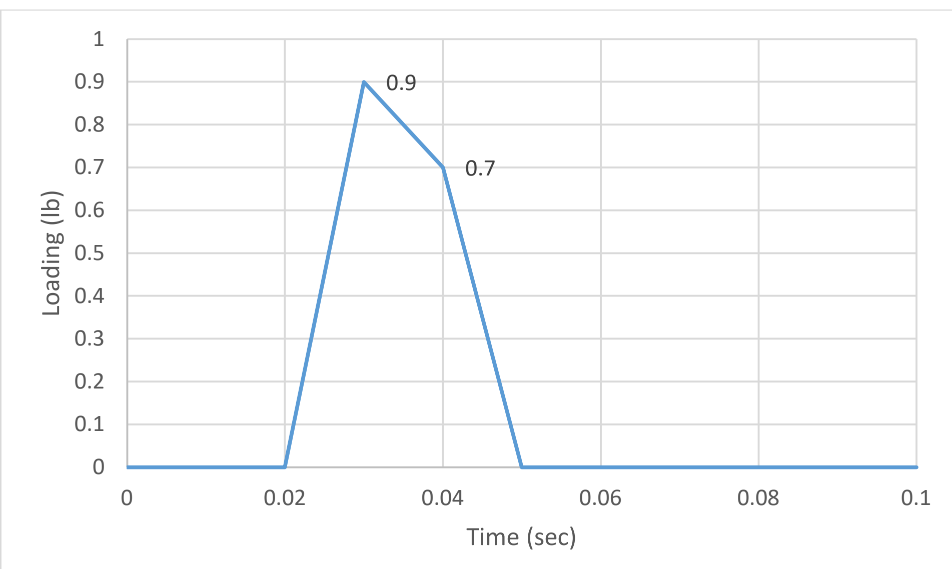

Figure 6. Blast load profile resulting in the best agreement between the measured and calculated acceleration responses.

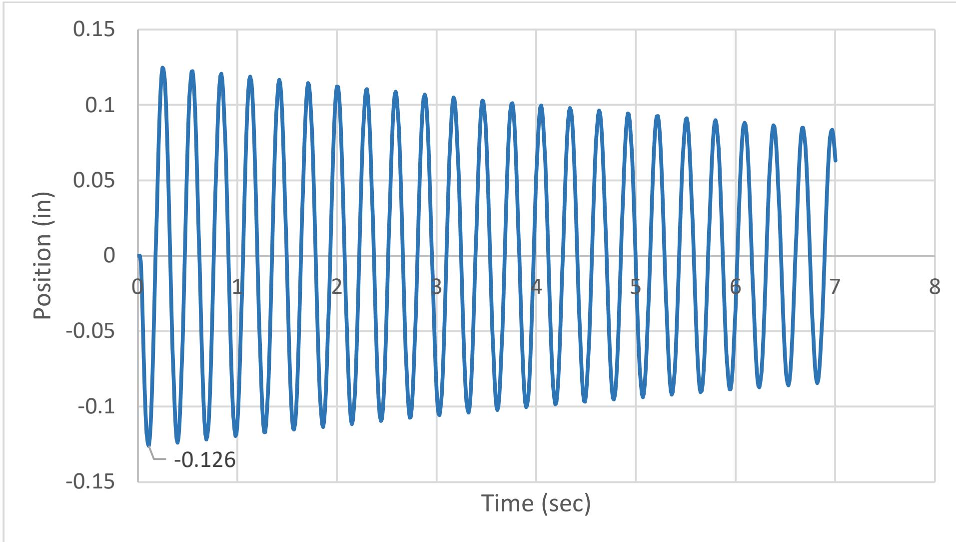

Figure 7. Calculated displacement response of the model structure to blast loading supplied by toy air cannon.

Results and Discussion

While the comparison of exam performance was a goal of this study initially, it was discovered that students performed equally well regardless of the instructional approach to Newmark's Method and blast loading. Given the small sample sizes, a rigorous comparison is not particularly useful and is not provided here. The results of this relatively small study seem to be consistent with much more robust studies of inquiry-based labs: that student learning does not appear to be impacted either positively or negatively, but that student ability to address uncertain situations with creativity in the use of tools is improved [4].

Smith and Holmes [4] suggest that "allowing students to make decisions establishes a spirit of inquiry and provides deliberate practice with the cognitive activities associated with conducting an experiment." But they are careful to point out that "learning requires structure" and that structure should equip students to perform their own experiments. In the case of this study, students had experience prior to the lab with both phone-based tools for measuring dynamic response and an introduction to Newmark's method for calculating dynamic response to arbitrary loading. Thus, the students were well prepared to conduct their own experiment without being faced with uncertainty in all areas of tools, methods, and experimental design; they could focus on the experimental design to achieve a specific goal.

Smith and Homes also point out that "removing all verification goals helps students engage authentically" and that "even a hint of a verification goal can lead students to engage in…questionable research practices" like adjusting numbers to achieve good agreement in results [4]. In the case of this study, adjusting the blast load profile to achieve agreement in measured and calculated response was the primary means of estimating the blast load rather than an attempt to prove theory correct. Thus, the engagement with the subject was indeed authentic.

Student comments in submitted lab reports are more helpful in considering the benefits of the inquiry-based approach of the lab. Confirming the problem and reiterating is a valuable first step in this process: *"The first challenge in conducting this experiment was that we did not possess explicit instructions on how to directly mimic a blast load, or how to measure the magnitude and duration of that load."* It was also wonderful to see recognition that this lab was different and that development of the experimental procedure is an opportunity that students are not often granted in engineering labs: *"What differentiated this lab from previous experiments was the lack of direction for how to go about measuring our experimental results."*

Experimental design requires some degree of prototyping and refinement. The students worked effectively through this aspect of the development of the experiment to attempt to control for perceived uncertainty before realizing and confirming that variation of multiple applied loadings was not a goal: *"We attempted to secure the AirZooka to apply this load, however every attempt to do this was ineffective. As such, the AirZooka was simply held a few inches from the structure, drawn, and released."*

The exploration of various methods of measurement was also useful to compare the effectiveness of different tools and tradeoffs in ease of use and precision: *"The primary unknown throughout this lab was the magnitude of the blast force and the time history. There were a few methods that were tried to find the duration of the blast load, such as an acoustic stopwatch on a phone capturing the sound created when the tension chord of the AirZooka was released. It was hard to measure the actual duration of the blast load to the simple structure because of the limitation of our devices."*

Some students recognized the analogous nature of the scale model to larger structures: *"This lab had very few parts but was helpful to understand how real loads affect structures."*

Some students explored confidence in their tools, both the phone-based sensor technology and numerical modeling approach: *"For this lab there was not a whole lot to it but there were a lot of things that were assumed. One is trusting Newmark's Method. Another is we only collected one set of data that we tested. Our methods were sound, we used a method for collecting acceleration data that has been proved accurate."*

Other students unfortunately still found reason to question the phone-based sensor technology, even after previous experience with it and good comparison with more precise sensors: *"Due to the uncertainty in precision of the cellular application to measure the acceleration of the model after being subjected to the blast loading, it is unclear whether the application or Newmark's Method is to blame for asymmetric behavior of acceleration vs time of the model."* In this case, the "asymmetric behavior" the student is referring to is the large acceleration of the structure during the blast compared to the free vibration response after the blast, an indication that there is still some post-hoc discussion of the results that would be valuable.

Many students commented on the value and accuracy of Newmark's Method as an analysis tool with thoughts similar to this: *"If engineers are confident in their assumed or measured blast force and blast profile, Newmark's Method provides engineers with an extremely accurate way to predict a structure's response to a blast load."* Thus, a primary goal of the laboratory was reached: to demonstrate the benefits of numerical time-stepping procedures in dynamic response calculation.

Comparison of experimental and numerical results was the focus of this lab, but analytical results could – and probably should – be included to provide a complete picture. After reflecting on the lab, the instructor offered the students a comparison with the analytical approaches to estimating response to blast loads in the following lecture period. Since t_d/T_n is very small in this lab experiment (0.02 sec/0.2907 sec = 0.069), the displacement response factor, R_d, can be expressed as [9]

$$R_d = 2\sin\left(\pi \frac{t_d}{T_n}\right)$$

Evaluating this equation results in a value of $R_d = 0.429$, which means that the displacement response of the dynamically applied load is 0.429 times the static response. If the 0.8 lb (average loading) were simply applied statically to a structure with a stiffness of 2.68 lb/in, the displacement $(u_{st})_o$ would be (0.8 lb)/(2.68 lb/in) = 0.2985 in. The dynamic response, u_o, would then be $R_d(u_{st})_o$ = (0.429)(0.2985 in) = 0.128 in, which compares wonderfully with the results of the Newmark analysis with a 0.126-in maximum response (Figure 7).

Conclusions

This paper described the implementation of a laboratory module for structural dynamics that incorporated student development of an experiment, including selection of measurement methods, configuration of the loading apparatus, exploration of a numerical analysis method, and discussion of uncertainty in the experimental method. Student interest was motivated using a toy air cannon to apply a blast load to a small single-degree-of-freedom frame structure. Student comments in the submitted lab reports indicated strong engagement with the experimental design and numerical modeling approach while exam performance compared to a control group was effectively unchanged. These results seem to be consistent with the conclusions of more robust studies that demonstrate the value of inquiry-oriented experimentation laboratories compared to verification labs.

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