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14. ABSTRACT
The objective of this one-year research project is to investigate the feasibility of using well-controlled shock waves to remove calcareous fouling organisms (e.g., barnacles) from surfaces painted with a silicone-based fouling release (FR) coating, without damaging the coating. We have developed a fluid-solid coupled simulation model and performed a series of exploratory simulations. We have also conducted a series of laboratory experiments using barnacle models (i.e. pseudobarnacles). Both the simulations and the experiments have shown that a sequence of shock waves with peak pressure in the range of 5 to 45 MPa and duration of 1 to 5 μs can remove pseudobarnacles from silicone-based FR coatings, without damaging the coating. Our simulations also suggest that tuning the waveform and magnitude of the shock wave can improve the efficiency. This project has led to one research article published in the International Journal of Solids and Structures, and several conference presentations.

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PROJECT REPORT

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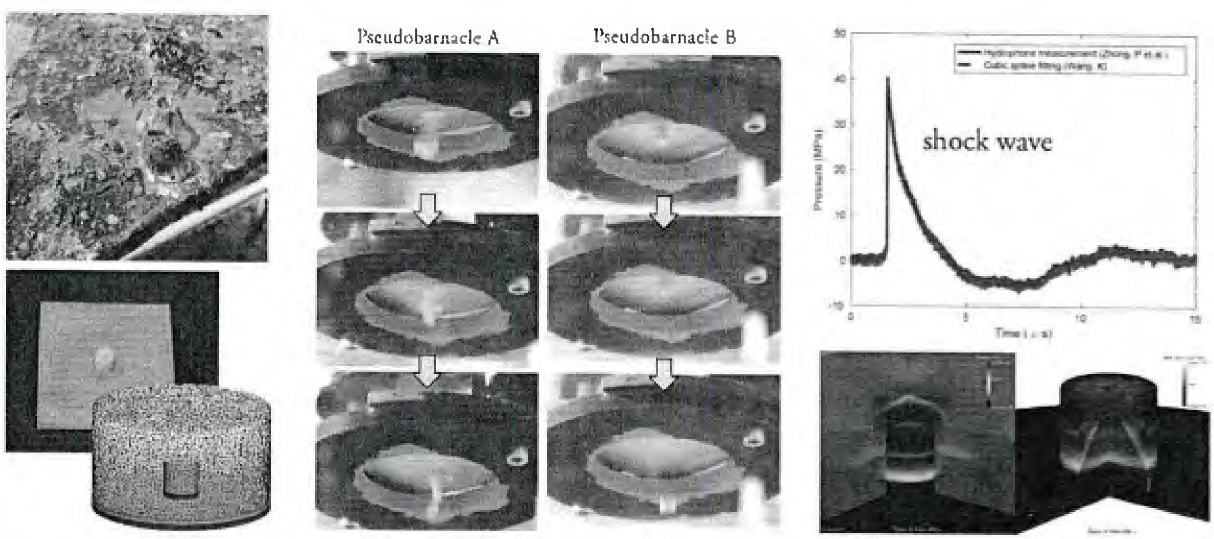
A Pilot Study on the Feasibility of Using Shock Waves for Hull Grooming



Modeling Experiment Computation

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Contents

1. Major goals

The goal of this research project is to investigate the feasibility of using well-controlled shock waves to remove calcareous fouling organisms (e.g., barnacles) from surfaces painted with a silicone-based fouling release (FR) coating, without damaging the coating. It has been hypothesized that several physical processes, such as shock-induced pull-off, fracture, and cavitation, may contribute to the removal of calcareous fouling organisms. It has also been proposed that the significantly different acoustic and elastic behaviors of the fouling and coating materials may be exploited to design shock loads that are effective for releasing biofouling, yet do not inflict damage to the coating. This project is designed to assess the above hypothesis and idea through a joint computational and experimental research framework.

2. Accomplishments under these goals

In this section, we summarize the major project activities and accomplishments, without providing too many details. We present additional technical details of these activities and accomplishments in Section 8.

2.1. Background: In our proposal, we proposed two major research tasks:

- **Task 1:** Model development and verification (Months 1 – 4); and
- **Task 2:** Parameter studies and hypothesis testing (Months 5 – 12).

The main objective is to develop a new simulation model of pseudobarnacle with realistic material properties (Task 1); and to predict the optimal range of shock wave parameters (e.g., magnitude, waveform, etc.) through numerical simulations (Task 2).

2.2. Major Activities: We have completed Task 1, and the majority of Task 2, in consistency with the schedule. (We are currently in Month 10). The remaining work — to be completed by the end of the performance period (08/31/2018) — is the numerical parameter study of the effect of angle of incidence (i.e. the angle between the shock wave and the normal direction of the hull surface).

Motivated by the findings from planned Tasks 1 and 2, we have performed the following additional tasks (not included in the original proposal) to demonstrate the feasibility and explore the optimal parameters.

- **Task 3:** Laboratory experiment of shock wave hull grooming using pseudobarnacle specimens.
- **Task 4:** Numerical study of the optimal shock waveform: effect of trailing tensile phase.

Videos of a few example simulations and experiments:

- https://www.youtube.com/watch?v=htq5-CuB6Ps
- https://youtu.be/mWI4Au6w1EI
- https://youtu.be/ITqr6fKdiRk

Figure 1 presents some example simulation and experiment results.

Details of the project activities and accomplishments are presented in Section 8.

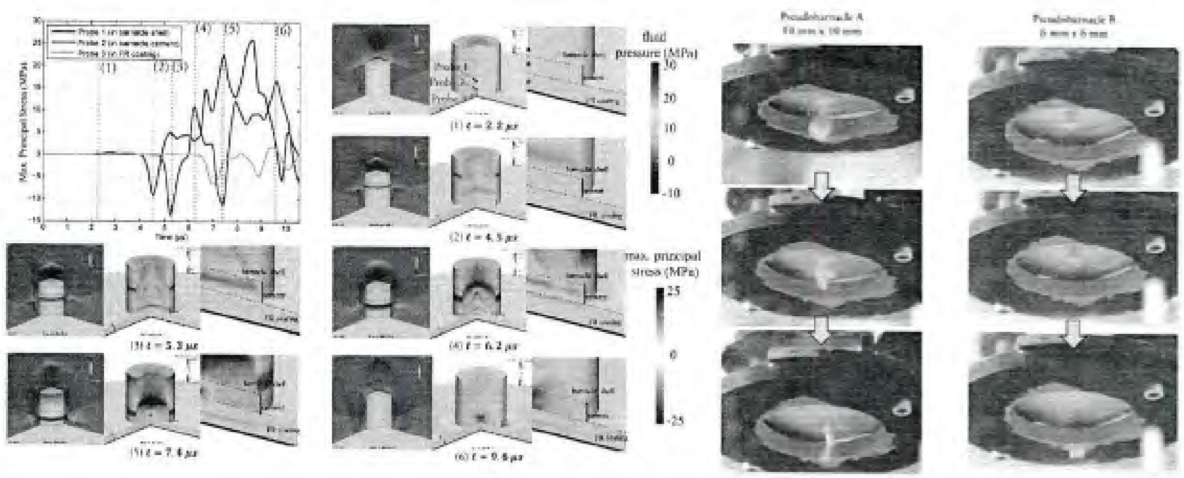


Figure 1: Examples of pseudobarnacle simulations (left) and experiments (right). Details are presented in Section 8.

2.3. Significant findings: Here we briefly summarize the most significant findings obtained from our computational and experimental studies. Details are provided in Section 8.

A. **An open question:** Through literature review, we found that despite related research and development in controlling biofouling in piping systems and heat exchangers (featuring uncoated surfaces and confined space); the feasibility, efficiency, and safety of shock waves for hull grooming is largely unknown.

B. **Feasibility:** Through numerical simulations, we found that when subjected to shock pulses with peak pressure $5\ MPa < p_{max} < 45\ MPa$, the maximum tensile stress within the pseudobarnacle is approximately 50% of p_{max}, which is 1 to 2 orders of magnitude (i.e. 10 to 100 times) higher than the experimentally measured adhesive strength (ref. Stein et al., 2003 and others). *This finding indicates that such shock pulses (or even weaker ones) can be effective for hull grooming & cleaning.*

C. **Demonstration of Feasibility**: Through laboratory experiments, we found that when subjected to shock pulses with peak pressure $p_{max} \approx 40\,MPa$, even relatively large pseudobarnacles — 6 to 10 mm in diameter — can be removed from a silicone-based coating (Dow Corning 3140). This finding confirms the feasibility of using shock waves for hull grooming.

D. **Safety to coating**: Through numerical simulations, we found that when subjected to shock pulses with peak pressure $5\,MPa < p_{max} < 45\,MPa$, the maximum tensile stress within a silicone-based coating (RTV 11) is approximately 5% of p_{max}, which is at least 2 orders of magnitude lower (i.e. 1% or below) than the hardness of FR coatings (100 MPa to 1 GPa) and AF coatings (above 1 GPa). *This finding indicates that such shock pulses would not damage fouling-release (FR) and anti-fouling (AF) coatings.*

E. **Demonstration of Safety to coating**: Through laboratory experiments, we found that after more than 150 shock pulses with peak pressure $p_{max} \approx 40\,MPa$, there is still no visible damage to a silicone-based coating (Dow Corning 3140) on a steel plate.

F. **Selection of shock waveform and generation method**: Through numerical simulations, we found that a shock wave with a tensile phase (e.g., generated by electrohydraulic or piezoelectric methods) induces more severe damage to a quasibrittle material ("pseudobarnacle") than a shock wave without a tensile phase (e.g., generated using laser), even if the two carry the same peak pressure and acoustic energy.

2.4. Summary: In summary, our simulations and experiments have shown that shock waves with peak pressure in the range of 5 to 45 MPa and duration of 1 to 5 μs can remove realistic pseudobarnacles from silicone-based FR coatings, without damaging the coating. Our simulations also suggest that tuning the waveform and magnitude of the shock wave can significantly improve the efficiency. In Section 8, we present additional details of our activities and accomplishments.

Despite the above encouraging results, we point out that up to now, all the shock wave simulations and experiments are performed using pseudobarnacles, instead of real biofouling. The approach of starting with pseudobarnacles is proposed in our original proposal, and it has enabled us to obtain useful result in a relatively short amount of time. *Now, we propose to continue and extend the current research project into the next year, working* *on (1) experimentally testing real acorn barnacles and other fouling organisms in a controlled lab environment; and (2) developing a prototypical hull grooming device that generates shock waves using acoustic sparkers.*

3. Dissemination

3.1. Peer-reviewed journal articles:

- S. Cao, A. Main, and K. G. Wang, "Robin-Neumann Transmission Conditions for Fluid-Structure Coupling: Embedded Boundary Implementation and Parameter Analysis," *International Journal for Numerical Methods in Engineering* (in press, https://doi.org/10.1002/nme.5817)
- S. Cao, D. Liao, Y. Zhang, P. Zhong, and K. G. Wang, "Shock-Induced Damage and Dynamic Fracture in Cylindrical Bodies Submerged in Liquid," *International Journal of Solids and Structures* (under review)
- S. Cao, O. Coutier-Delgosha, K. G. Wang, "Multiphase Fluid-Solid Coupled Computational Analysis of Cavitation-Induced Material Damage," Journal of Fluid Mechanics (in preparation; current version: link)

3.2. Conference papers and presentations:

- S. Cao, A. Main, K. G. Wang. "An Embedded Robin Boundary Method for Incompressible Fluid-Structure Interaction Problems," *AIAA AVIATION 2017.* Denver, CO, June 2017
- K. G. Wang, S. Cao, "High-Performance Computational Analysis of Shock-Bubble-Stone Interaction in Shock Wave Lithotripsy," the 173rd Meeting of the Acoustical Society of America and the 8th Forum Acusticum (Acoustics 2017), Boston, MA, 2017
- Cao, S., Zhang, Y., Liao, D., Zhong, P. & Wang, K. G., "Assessing the Effect of Lithotripter Focal Width on the Fracture Potential of Stones in SWL." In 173rd Meeting of the Acoustical Society of America and the 8th Forum Acusticum (Acoustics 2017), Boston, MA, 2017
- Cao, S., Main, A., Wang, K.G., "An Embedded Robin Boundary Method for Incompressible Fluid-Structure Interaction Problems," *14th US National Congress on Computational Mechanics (USNCCM-14).* Montreal, Canada, 2017

- K. Wang, "Multi-Phase Fluid-Material Interaction: Cavitation Modeling and Damage Assessment," the ONR Naval Future Force Science and Technology (S&T) Expo, Washington, DC, 2017
- X. Sun and K. Wang, "Controlled Shock Waves for Underwater Hull Grooming: A Feasibility Study," the 19th International Congress on Marine Corrosion and Fouling (ICMCF), Melbourne, FL, 2018
- S. Cao and K. Wang, "Fluid-Material Coupled Computational Analysis of Cavitation-Induced Material Modification," the 18th U.S. National Congress for Theoretical and Applied Mechanics (USNCTAM), Chicago, IL, 2018

4. Outreach and Collaborations

- Kevin Wang (PI), together with colleagues at Virginia Tech and Naval Undersea Warfare Center, Division Newport (NUWC-Newport), established an Educational Partnership between NUWC-Newport and Virginia Tech. The Partnership Agreement has been signed off by Commanding Officer of NUWC-Newport, Michael R. Coughlin, and Assistant Vice President of Virginia Tech, Linda R. Bucy. Kevin Wang serves as the Program Manager for Virginia Tech.
- In July, 2017, Kevin Wang (PI) discussed the project (including potential collaboration) with Matthew Naiman (NSWC-Carderock) at the ONR S&T Expo.
- In August, 2017, Kevin Wang (PI) paid a two-day visit to the Center for Corrosion and Biofouling Control (CCBC) at Florida Institute of Technology (Melbourne, FL) (Figure 2(a-c)). During the visit, Kevin Wang discussed the project with Geoff Swain, Melissa Tribou, and other memebers of CCBC. A verbal agreement was made regarding future collaborations, including the use of CCBC facilities for testing shock wave hull grooming devices. Kevin Wang also visited the ONR-funded large-scale seawater test facility (LSTF) in Port Canaveral, FL.
- In February, 2018, Kevin Wang (PI) discussed the project (including potential collaboration) with a group of administrators and researchers from NSWC-Carderock Code 80, headed by Department Head Michael Brown.
- Kevin Wang (PI) and his group at Virginia Tech has been collaborating with Pei Zhong and his Therapeutic Ultrasound Lab (TUL) at Duke University over the past three years. During the reporting period, the two groups have discussed extensively on the idea and approach of the current hull grooming project. Kevin Wang and one of his students (X. Sun) "borrowed" a shock wave facility at TUL

to perform pseudobarnacle experiments, at no cost to ONR (Figure 2(d,e)).

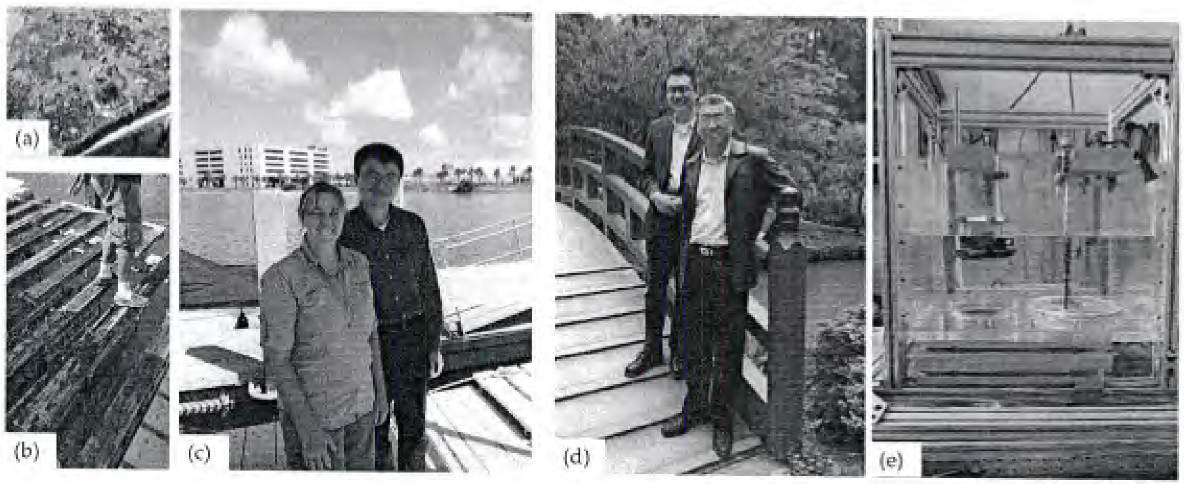


Figure 2: Photos taken by the PI during trips to the Center for Corrosion and Biofouling Control (PI: Geoff Swain) at Florida Institute of Technology and the Therapeutic Ultrasound Lab (PI: Pei Zhong) at Duke University. (a) A specimen with hard and soft biofouling. (b) Geoff Swain presenting the test panels at the large-scale seawater test facility (LSFT). (c) Photo with Melissa Tribou at LSTF. (d) Photo with Pei Zhong on Duke campus. (e) A shock wave lithotripter in Zhong's lab, used for performing the shock wave hull grooming experiments.

5. Student Advising

- **Mr. Xingsheng Sun**, who has been funded by this grant, received his PhD degree in Aerospace Engineering in September, 2018. He is currently a Postdoctoral Scholar at California Institute of Technology, working with Dr. Michael Ortiz.

6. Awards

- Kevin Wang (PI) received an NSF CAREER Award in 2017. The award was reported by Virginia Tech News (https://vtnews.vt.edu/articles/2018/01/012918-aoe-wang-nsf.html).

7. Training

Most of the grant (approximately $60K, including overheads) is used to support Xingsheng Sun, a 4th year PhD student in the PI's lab. During the reporting period, Sun served as a Graduate Research Assistant (GRA). He had one-on-one meetings with the PI on a weekly basis. Under the guidance of the PI, Sun participated in the literature review, and did most of the experimental study, including the design and preparation of pseudobarnacle specimens.

Sun plans to take his PhD final examination (i.e. thesis defense) in the 2018 Fall semester. He has accepted an offer of a Postdoctoral Scholar position at California Institute of Technology (Caltech), conditioning on passing the final exam.

8. Additional Details of Major Activities and Accomplishments

8.1. Literature review: During the reporting period, we have searched publications and patents in the following technical areas.

- The use of acoustic methods, including but not limited to shock waves and cavitation, for antifouling purpose.
- The design and use of shock waves in related engineering and biomedical applications (e.g., shock wave lithotripsy, burst wave lithotripsy, dynamic fracking).
- Data and knowledge of the properties of calcareous fouling organisms (e.g., acorn barnacles) and different antifouling and fouling release coatings.

Through this effort, we have built an EndNote library comprised of more than 200 items (mostly journal and conference papers).

We found that shock waves (and shock-induced cavitation) have been utilized in a number of biomedical and engineering applications to remove or fragment solid materials attached to a surface. Examples include, but are not limited to, extracorporeal shock wave lithotripsy (ESWL) — a first-line, non-invasive therapy of urinary stone disease — and ultrasonic cleaning — a widely used method to clean various material surfaces such as those of jewelry, lenses, and watches. In the context of biofouling control, a few research groups have explored the use of electro-hydraulically generated shock waves (Figure 3) to prevent or remove fouling organisms *in confined spaces*, such as heat exchangers and piping systems. Specifically,

- R. Brizzolara, M. Walch *et al.* (NSWC, Carderock) have used underwater electrical discharge to generate pulsed, low-intensity shock waves (without inducing cavitation). They demonstrated that the continuous application of such shock waves is capable of *inhibiting* microfouling on the surface of titanium pipes. On the other hand, the feasibility of using this approach to *remove* settled fouling organisms was not discussed.

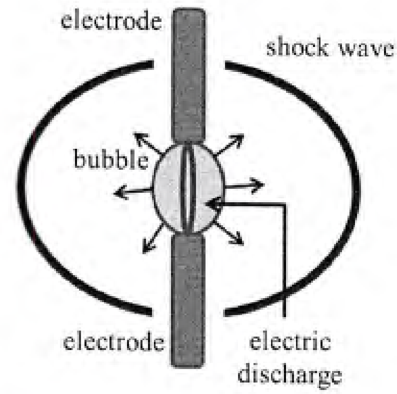


Figure 3: A schematic drawing of an acoustic sparker (adapted from Schaefer et al. 2010).

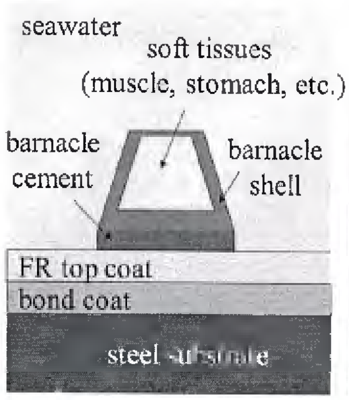
- Mackie *et al.* (US Army Engineer Research and Development Center) have shown that the repeated application of shock waves with higher intensity (specifically, a peak pressure of 0.34 to 2.76 MPa at a distance of 30 cm from the discharge source) is capable of killing and removing adult zebra mussels settled on the wall of polyvinyl chloride (PVC) pipes, as well as producing cracks in mussel shells. Whether the antifouling effect is caused by the prescribed shock wave, the shock-induced cavitation, or the combination of both was unclear. Furthermore, the adult zebra mussels used in this study are significantly larger and harder than most organisms targeted by hull grooming.
- R. Schaefer *et al.* (Phoenix Science and Technology Inc.) have shown that the repeated application of shock pulses with a peak pressure of 0.3 MPa (measured at a distance of 30 cm from the discharge source) is capable of disintegrating clumps of adult zebra mussels suspended in a water pipe, as well as breaking and perforating the shell of individual mussels. Using a hydrophone, they have also recorded the shock waves resulting from the collapse of cavitation bubbles, which are found to have a peak pressure of 0.7 MPa, that is, approximately twice as high as the peak pressure of the prescribed shock wave.
- S. Guo *et al.* (National University of Singapore) studied the effect of individual cavitation bubbles on juvenile barnacles in a well-controlled laboratory environment. They showed that the inertial collapse of *a single cavitation bubble* with maximum radius around 1.8 mm is capable of causing visible damage to a 10-day-old juvenile barnacle settled on a glass substrate, when the peak pressure from bubble collapse (measured at the same distance as from the barnacle) exceeds 18.6 MPa. This finding suggests the potential of using controlled cavitation for hull grooming. Nonetheless, the risk of damaging hull coating was not investigated. Moreover, the feasibility of detaching juvenile barnacles from a surface without

breaking their shells — which could be preferable in the context of hull grooming — was not considered.

- Cioanta *et al.* (Sanuwave Inc., GA) published a patent on "cleaning and grooming water submerged structures using acoustic pressure shock waves (US9840313B2)". Nonetheless, the effectiveness of this approach has not been demonstrated, at least in the public domain.

To our best knowledge, despite related efforts including those reviewed above, *pulsed shock waves have not been applied to hull grooming. Moreover, the transient response and fracture of various hard and soft materials involved in this application — such as barnacle cement, shell, and coating materials — under repeated shock loading is largely unknown.*

Through literature review, we also found that the acoustic and mechanical properties of fouling organisms, such as barnacles, are drastically different from those of FR or AF coatings. For example, Figure 4 presents the different types of materials involved in an acorn barnacle (*Amphibalanus amphitrite*) and an FR-coated steel substrate, together with several important physical properties of the involved materials. For simplicity, but without loss of generality, we consider a duplex FR coating (RTV11 and Silgan J501) instead of newer triplex coatings (e.g., International Intersleek® 900). From Figure 4, it is notable that the Young's modulus of barnacle cement can be three orders of magnitude larger than that of the FR coating. Also, the longitudinal and transverse acoustic impedances of barnacle cement are approximately 4 times larger than those of the FR coating. Therefore, as a shock wave passes through, a fraction of the energy will be deposited into the barnacle cement. Given the different physical properties of the barnacle and the FR coating, *we hypothesize that a shock wave may lead to the removal of a barnacle from an FR coating, without damaging the coating.*



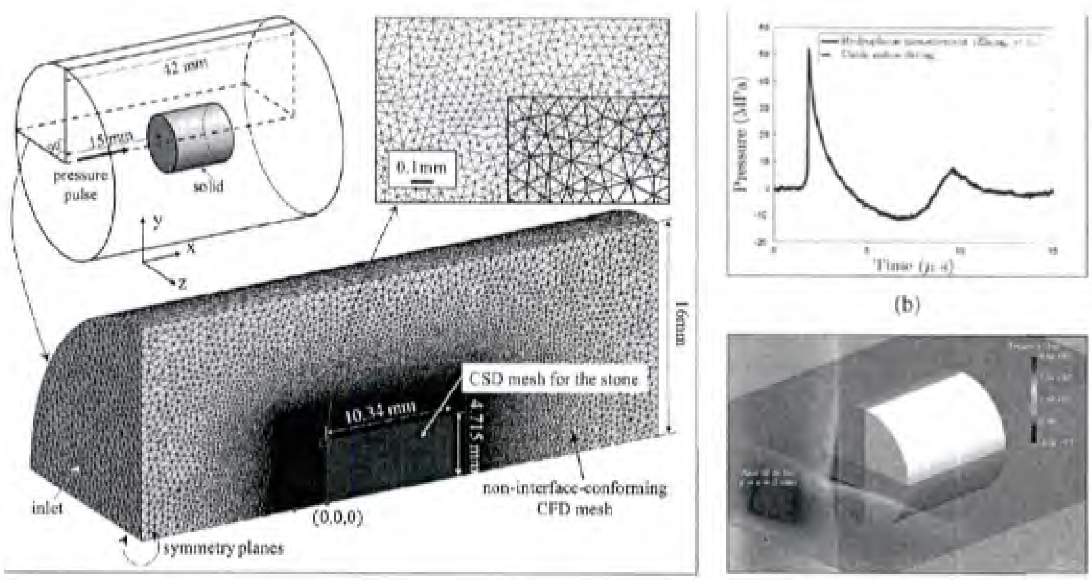
material	density ρ (g/cm^3)	Young's modulus E (GPa)	acoustic velocity		acoustic impedance	
			C_L (m/s)	C_T (m/s)	Z_L (kg/(mm^{2}s))	Z_T (kg/(mm^{2}s))
seawater	1.0	-	1500	-	1.5	-
barnacle soft tissues	1.0	-	1500	-	1.5	-
barnacle shell	1.7	14.7	3170	1870	5.4	3.2
barnacle cement	1.6	2.0	1670	681	2.6	1.1
FR top coat (RTV11)	1.2	0.0023	562	25	0.67	0.03
bond coat (Silgan J501)	1.5	17.3	1390	62	2.1	0.09
structural steel	7.8	210.0	6000	3210	47.1	25.2

Figure 4: Left: A schematic cross-section of an acorn barnacle attached to a substrate coated with duplex FR coating. Right: Measured or estimated values of some physical properties of the involved materials. Specifically, the properties of barnacle soft tissues are estimated basing on seawater. The properties of barnacle cement are estimated basing on Loctite Hysol® 1C, an epoxy adhesive that has been used by some research groups as "pseudobarnacle". Its value of Young's modulus (2.0 GPa) is close to that of the cement of adult acorn barnacle (*Amphibalanus amphitrite*), as measured by Ramsay *et al.* (Naval Research Lab and Duke Univ.) and Raman *et al.* (IIT, India). The properties of barnacle shell are estimated basing on gypsum (Ultracal-30). Properties of the duplex FR coating (RTV11 and Silgan J501) are obtained from J. Kohl et al., 1999 and I. Singer et al., 2000. The subscripts "L" and "T" of acoustic velocity (***C***) and acoustic impedance (***Z***) refer, respectively, to "longitudinal" and "transverse".

<u>**8.2. Development and validation of a fluid-solid coupled computational model:**</u> Over the past decade, the PI has developed with collaborators and students a three-dimensional (3-D), CFD (computational fluid dynamics) - CSD (computational solid dynamics) coupled numerical solver capable of predicting the interaction of shock waves, cavitation, and deformable solid materials submerged in water, including shock-induced material damage and fracture. The development was largely supported by ONR through an MURI project and an FNC project, for analyzing underwater implosion. Before the start of the present project, the solver (referred to as "FIVER", now open-source) was limited to simulating shock impacts on ductile materials (e.g., metals) and thin-walled structures.

To be able to simulate shock-induced damages and fracture in calcareous fouling (quasibrittle materials), we have completed the following algorithm and software development and validation.

- We have implemented and parallelized a multi-scale continuum damage mechanics (CDM) model in our in-house finite element computational solid dynamics (CSD) solver. This model allows us to simulate the accumulation of damage and fracture in quasibrittle materials (e.g., calcareous fouling) due to multiple shock doses.
- We have extended the implementation of the element erosion methods in our CSD solver to handle macroscopic fracture (i.e. cracks that can be resolved by the the CSD mesh) in solid bodies (vs. thin-walled structures in the past), resulting from the accumulation of microscopic damage.
- We have calibrated and validated the CDM model and element erosion method mentioned above by simulating experiments of shock-induced fracture in BegoStone (a representative quasibrittle material) conducted at the Therapeutic Ultrasound Lab at Duke University (PI: P. Zhong), and comparing simulation and experimental results (Figures 5 to 7).
- We have developed a new mathematical model of shock wave and implemented the model in our CFD solver. This model allows us to predict the effect of shock waveform (e.g., with or without a tensile phase), magnitude, and duration on fouling and coating materials.



(a) (c)

Figure 5. Setup of a typical CFD-CSD coupled simulation. (a) The computational domain and meshes (the computational fluid dynamics (CFD) and computational solid dynamics (CSD) meshes are shown in black and blue, respectively). (b) The cubic spline fitting of the shock waveform measured at the focal point. (c) The shock wave prescribed as an initial condition to the fluid governing equations.

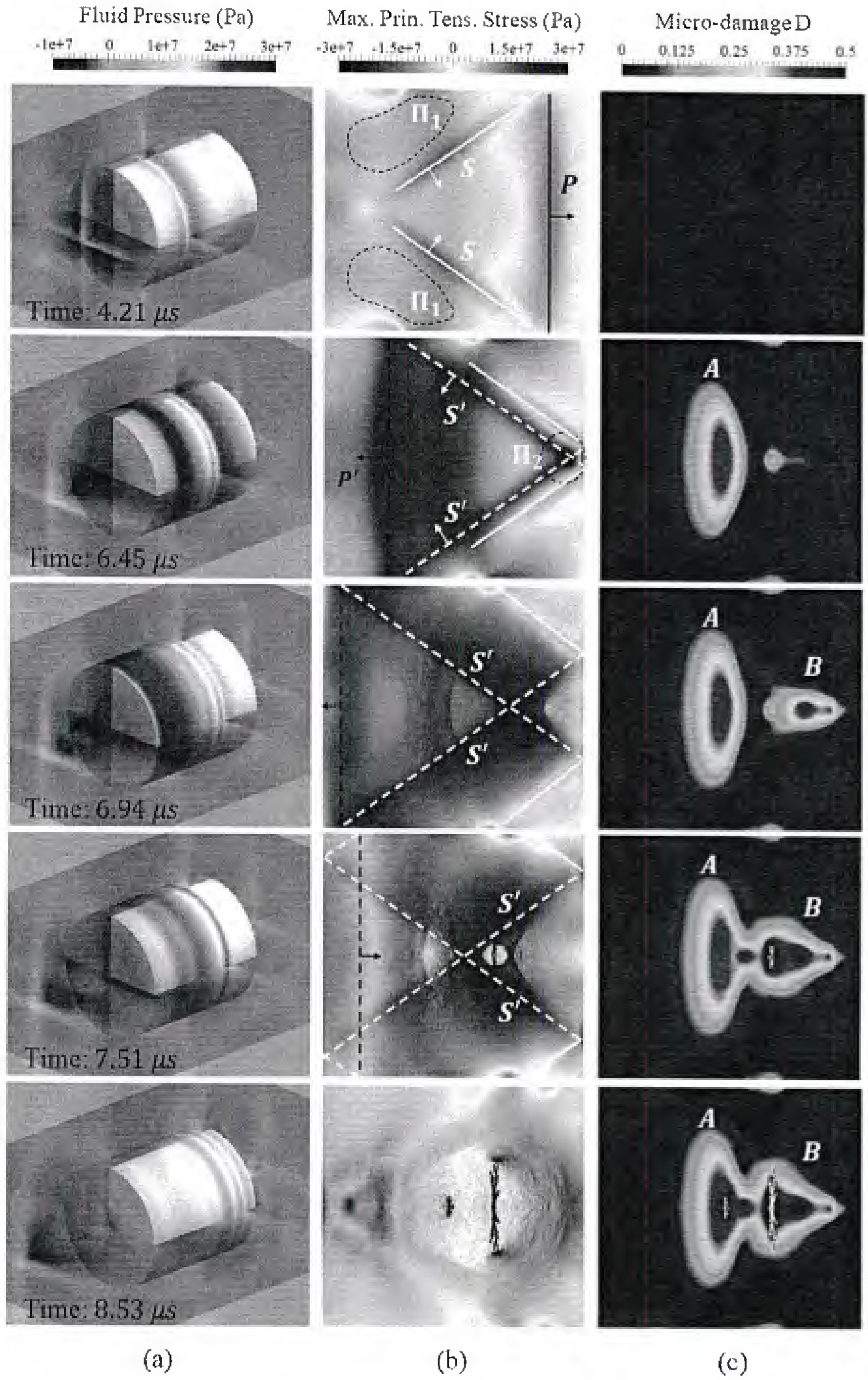


Figure 6. Predicted elastic fields, material damage, and fracture in a representative quasibrittle material (BegoStone) resulting from prescribed shock loading.

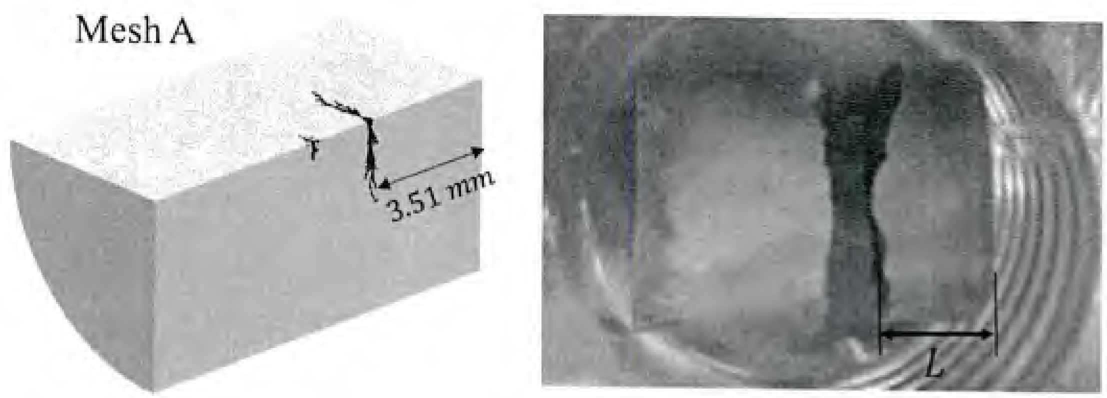


Figure 7: Validation of the CFD-CSD coupled computational framework for shock-induced fracture in a representative quasibrittle material (BegoStone). **The location and shape of the simulation result (left) agrees with the experimental result (right).**

8.3. Numerical simulations of shock wave hull grooming using pseudobarnacles: Using the computational framework described above, we have conducted trial simulations for pseudobarnacles attached to an FR coating. Figure 6 presents the simulation setup, including the dimensions of the computational domain, the modeled materials, the local mesh refinement, and the prescribed shock waveform. We model seawater as a compressible, inviscid fluid flow, governed by the Euler equations and the Tait equation of state. For the ease of validation and interpretation, we model acorn barnacle as a gypsum cylinder with an epoxy base (i.e., a "pseudobarnacle"). Gypsum is a reasonable model for the calcareous (i.e. composed of calcium carbonate) barnacle shell, as it is also a calcium-based brittle material. Epoxy (e.g., Loctite Hysol® 1C) has been widely used in the past to model barnacle cement. In particular, the Young's modulus of Loctite Hysol® 1C (2.0 GPa) is found to be close to that of barnacle cement, as measured by Ramsay *et al.* (Naval Research Lab and Duke Univ.) and Raman *et al.* (IIT, India).

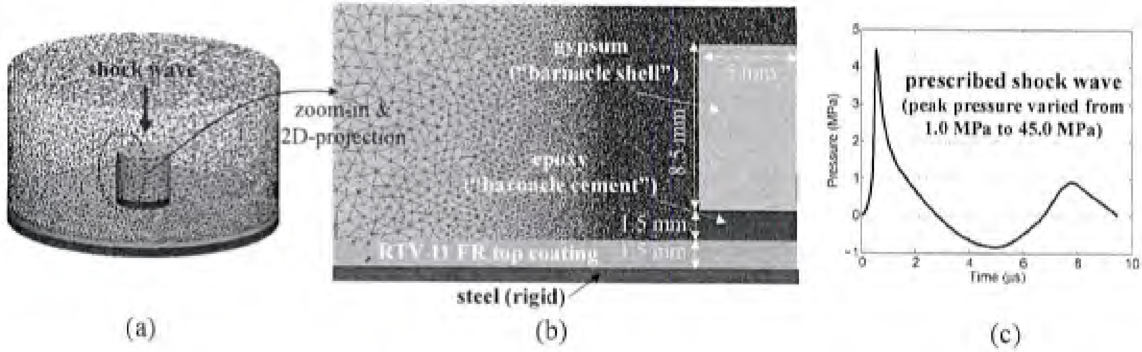


Figure 8: Setup of the computational model. **(a)** the fluid and solid computational domains. **(b)** a local 2D projection of the computational domain, showing the mesh resolution and the dimensions of the pseudobarnacle and the FR coating. **(c)** the prescribed shock waveform.

In a series of simulations, we have varied the peak pressure of the prescribed shock wave (p_{max}) from 1.0 MPa to 45 MPa (see Figure 9 for a few examples). Within this range, the peak values of maximum principal stress inside the barnacle shell (σ^*_{shell}), the cement (σ^*_{cement}), and the FR coating (σ^*_{coat}) are found to be approximately linear functions of p_{max}. (The maximum principal stress is the most tensile component of the principal stresses, therefore can be used as an indicator of tensile failure.) Specifically, we found $\sigma^*_{shell} = 0.55\, p_{max}$, $\sigma^*_{cement} = 0.38\, p_{max}$, and $\sigma^*_{coat} = 0.04\, p_{max}$. This finding suggests that under shock wave loading, the stress inside the barnacle shell and cement may be significantly higher than the stress inside the hull coating, which *supports our hypothesis that controlled shock waves may be able to release biofouling with damaging the coating.*

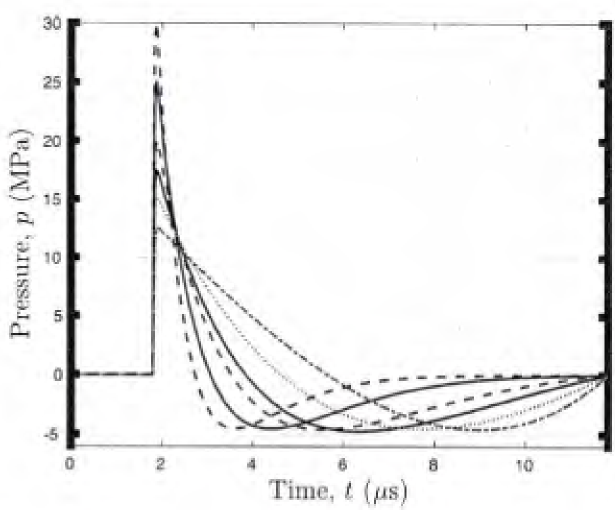


Figure 9: Numerical parameter study: shock waves with different peak pressures, yet the same duration and acoustic energy.

As an example, Figure 10 presents the predicted dynamic response of the pseudobarnacle and the coating, for a prescribed shock wave with $p_{max} = 45$ MPa. To characterize the complex multi- material interaction, we have visualized the pressure field in seawater, and the maximum principal stress in the pseudobarnacle and the coating. We have also examined the time history of maximum principal stress at three probes, which are located, respectively, in the barnacle shell (near the cement), in the cement, and in the FR coating. The following observations are noteworthy.

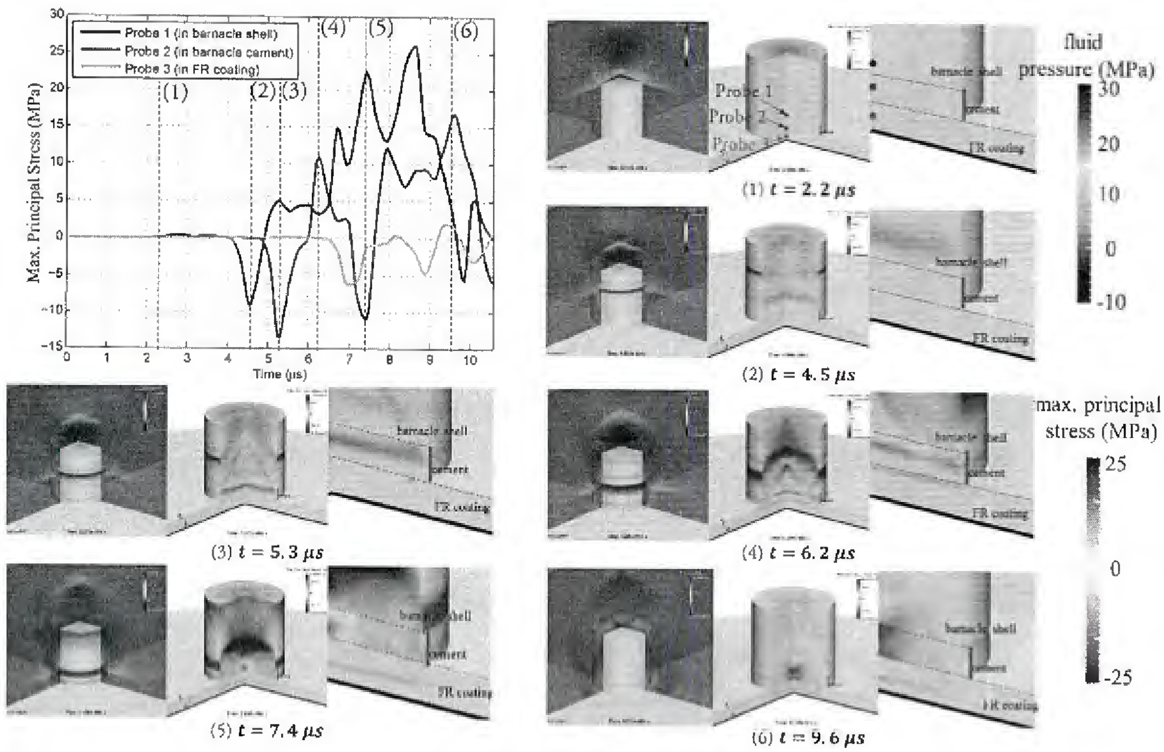


Figure 10: Preliminary pseudobarnacle simulation. The upper-left plot shows the time-history of maximum principal stress (MPS) at three probe locations. The seawater pressure and MPS at six time instances (marked in the plot) are also visualized. At $t = 2.2\ \mu s$, the shock front just reaches the top surface of the barnacle, initiating a longitudinal wave and a shear wave. At $t = 4.5\ \mu s$, The compressive longitudinal wave has reached Probe 1 inside the barnacle shell. At $t = 5.3\ \mu s$, it propagates into the barnacle cement, and also reflects back as a tensile wave. At $t = 6.2\ \mu s$, the compressive longitudinal wave reflects against the cement-coating interface as a tensile wave. At $t = 7.4$ and $9.6\ \mu s$, the shear wave propagating over the barnacle surface leads to compressive and tensile waves at Probe 2 inside the barnacle cement. The complete simulation video can be found at https://www.youtube.com/watch?v=htq5-CuB6Ps

- As expected, the maximum principal stress at the three probe locations vary significantly as the shock wave passes through. *The fact that their tensile (i.e. positive) and compressive (i.e. negative) phases do not coincide supports our general hypothesis that the shock wave may induce vibration in a barnacle and eventually "shake it off" the coating.*
- The maximum principal stresses at Probes 1 and 2 (i.e., within the barnacle shell and cement) exhibit strong tensile phases after the initial compression, which *provides a support of our "pull-off" hypothesis.*

<u>8.4. Shock wave experiments using pseudobarnacles</u>: The numerical simulations have indicated that shock waves with peak pressure in the range of 5 to 45 MPa and duration of 1 to 5 μs can remove realistic pseudobarnacles from silicone-based FR coatings, without damaging the coating. To verify this finding, we have conducted a series of experiments using pseudobarnacle specimens fabricated in our own lab and an electromagnetic shock wave lithotripter at the Therapeutic Ultrasound Lab at Duke University (at no cost to ONR).

Figure 11 shows two representative pseudobarnacle specimens. Each specimen includes a 7 cm x 7 cm rectangular steel plate. The plate is coated with Dow Corning 3140 (recommended by CCBC@FIT), a silicone-based coating. After applying the coating, the specimens are placed within a vacuum chamber to release bubbles. The average thickness of coating is 0.17 mm. At the center of the plate, a cylindrical BegoStone (the "pseudobarnacle") is attached to the surface using the LocTite SuperGlue. BegoStone is a hard plaster with properties comparable to those of barnacle shell. The two specimens shown in Figure 10 have pseudobarnacles of 10 mm (diam.) x 10 mm (height) and 6 mm x 6 mm, respectively.

Material properties of BegoStone (power-to-water ratio 5:1, dry) [22]

C_L (m/s)	C_T (m/s)	ρ (kg/m^3)	E (GPa)	ν	Static Strength (MPa)
4159	2319	1995	27.4	0.27	16.3

Figure 11: Two pseudobarnacle experiments fabricated in Kevin Wang's lab at Virginia Tech

Figure 12 presents the experimental setup, including photos of the shock wave lithotripter (i.e. shock wave generator), a representative shock waveform, and schematic drawings of the experimental apparatus.

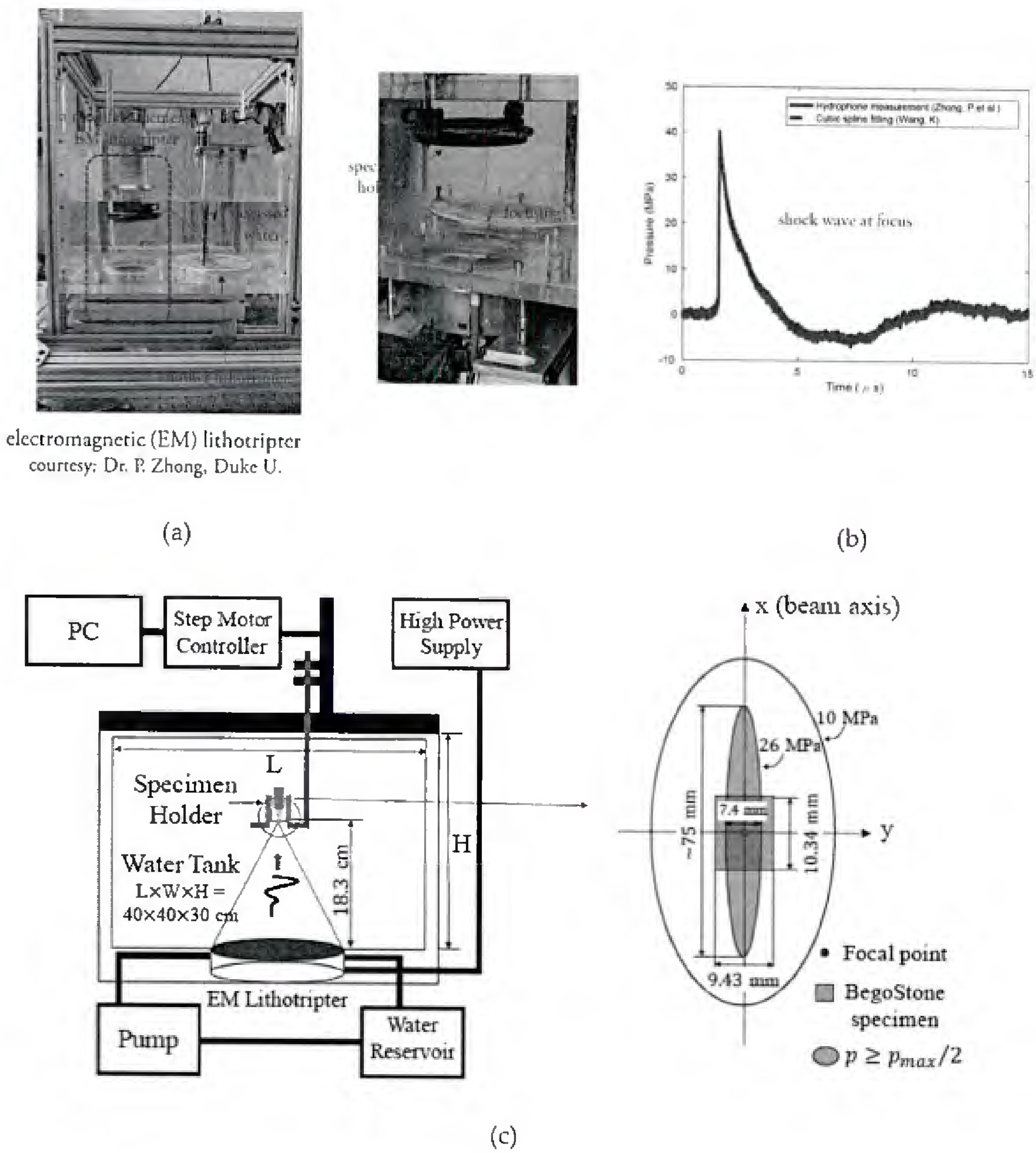


Figure 12: The experiment setup. (a) Photo of an electromagnetic shock wave generator. (b) A representative shock waveform, measured within the focal zone. (c) Schematic drawing of the experimental apparatus.

Specifically, the shock wave generator was mounted at the bottom of a Lucite tank (40 x 40 x 30 cm), filled with 0.2 μm filtered and degassed water (< 3 mg/L concentration, 23°C). The shock wave generator is operated at 14.8 kV with a pulse repetition frequency (PRF) of 0.5 – 1.0 Hz. The pseudobarnacle specimens are fixed at the focus of the generator, where the intense shock wave is generated. The axis of cylindrical pseudobarnacle is aligned with the central axis of the shock wave generator.

Figure 13 presents several snapshots obtained during the experiment. For Pseudobarnacle A (10 mm x 10 mm), we observed an initial fracture inside the pseudobarnacle body after 8 shock doses (~10 s). Additional fractures were observed

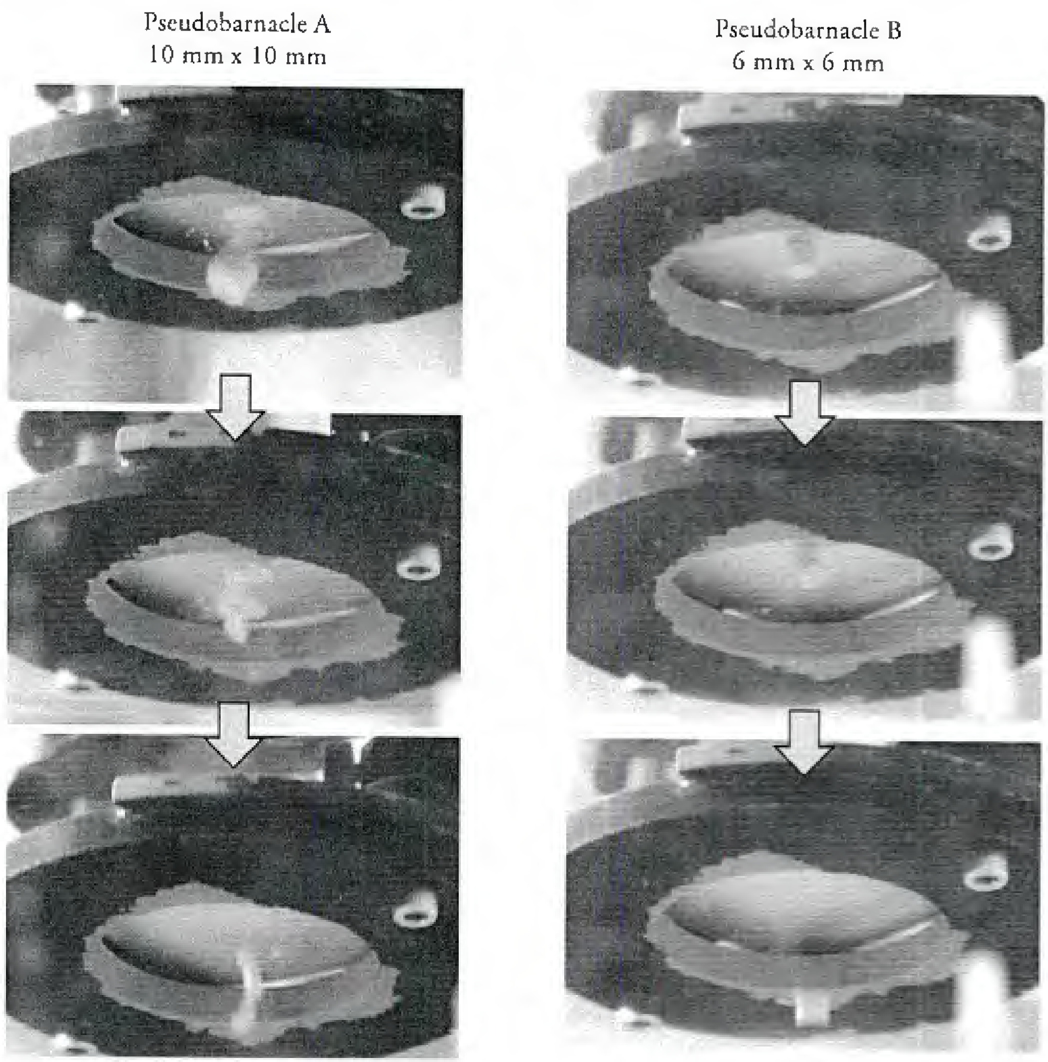


Figure 13: Snapshots from the experiment video showing the detachment of pseudobarnacles under shock wave treatment. The original videos are at https://youtu.be/mWI4Au6w1EI and https://youtu.be/ITqr6fKdiRk

afterwards. *After 48 shock doses (~1 min), the pseudobarnacle is completed removed from the coated steel plate.* For Pseudobarnacle B (6 mm x 6 mm), we observed *a direct detachment after 10 shock doses (~10 s).* Figure 14 presents a comparison of the specimens before and after shock wave treatment. In both cases, there is no visible damage to the coating.

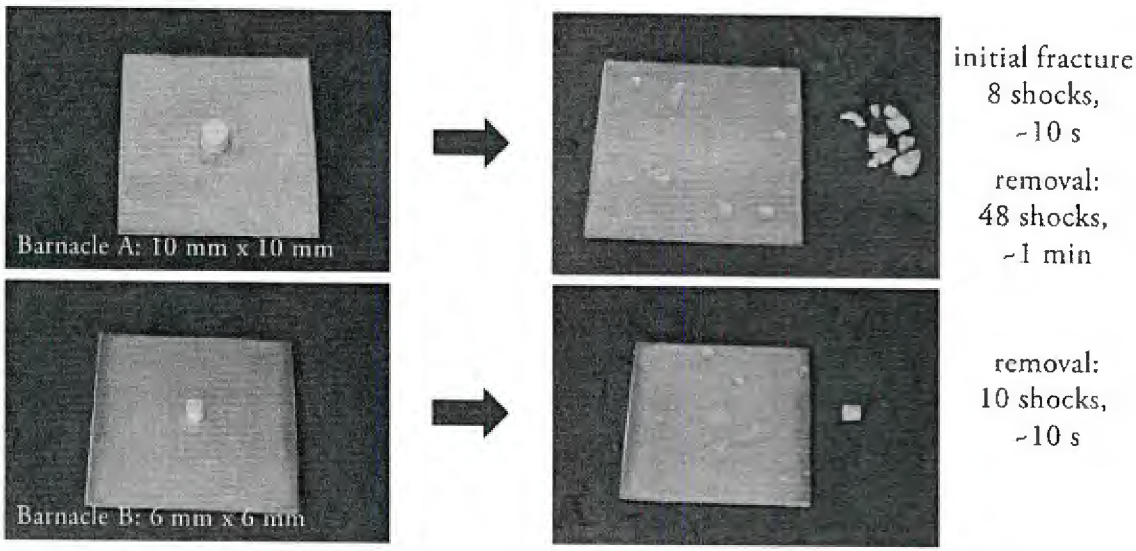
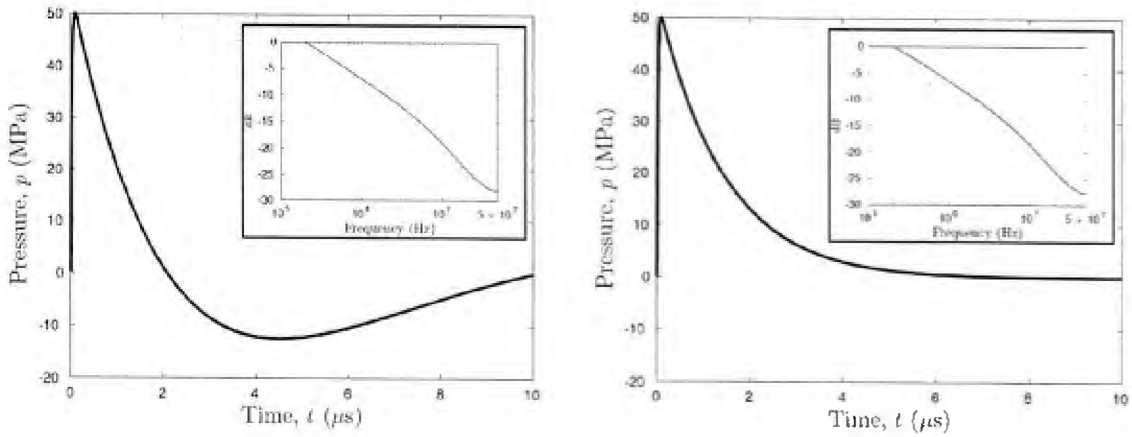


Figure 14: Two pseudobarnacle specimens before and after shock wave treatment. In both cases, the pseudobarnacles were detached, without visible damage to the coating.

To verify the safety to coating, we have also conducted longer experiments with more than 150 shock doses. Again, no coating damage was observed.

<u>8.5. Numerical study of the effect of shock waveform</u>: The waveform, magnitude, and duration of a shock wave depend sensitively on the generation method and the parameters specified therein. In particular, two distinct waveforms are often observed in different applications: one that features a non-monotonic decay and a tensile phase (Figure 15(a)), and one that exhibits monotonic decay, without a tensile phase (Figure 15(b)). The former waveform can be generated, for example, by focusing one pulse of acoustic wave, while the latter can be obtained by inducing a rapid bubble expansion using laser (or even detonation).



(a) (b)

Figure 15: Two shock waves with the same magnitude (i.e., peak pressure), the same acoustic pulse energy, similar spectrum, approximately the same duration, yet clearly di erent waveforms: (a) with non-monotonic decay and a tensile phase; (b) with monotonic decay, without a tensile phase.

We have conducted a numerical parameter study where we gradually vary the shock waveform from one that features a non-monotonic decay and a tensile phase to one that exhibits monotonic decay, without a tensile phase (Figure 16). Figure 16 compares the transient results of two representative cases. Overall, we found that when the size of the target (i.e. the pseudobarnacle) is of the same order of magnitude to the width of the shock wave, due to complex wave interactions, a trailing tensile phase may induce

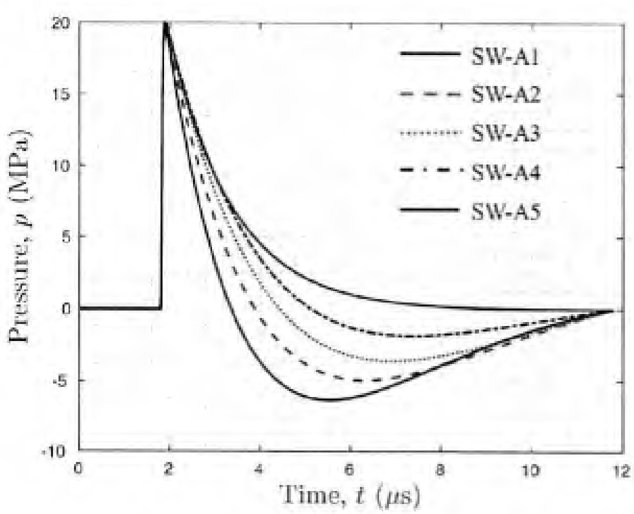


Figure 16: Five shock waveforms with different tensile phases, yet the same peak pressure, duration, and acoustic energy.

significantly larger damages in the target. Additional details of this finding are provided in an upcoming paper in the International Journal of Solids and Structure (link).

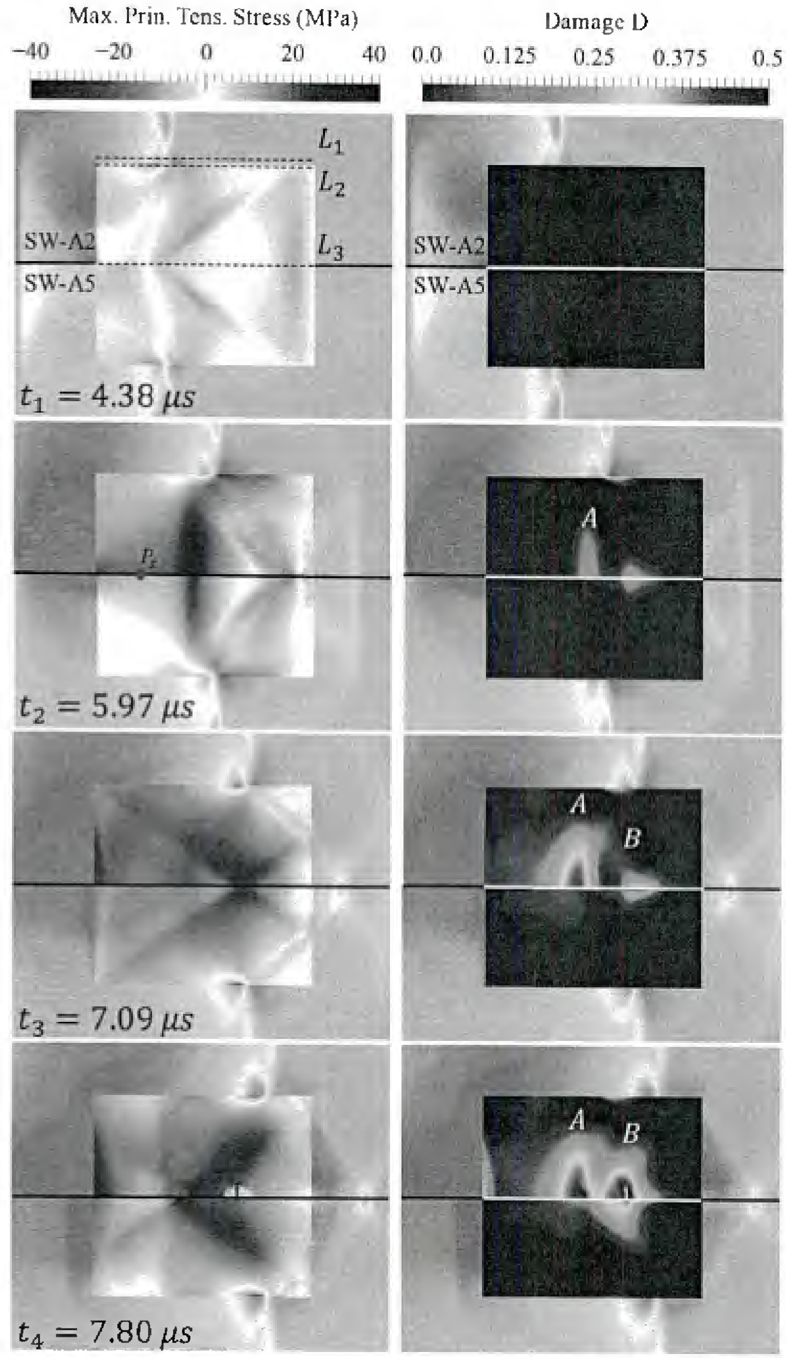


Figure 17: Comparison of simulations with SW-A2 and SW-A5 (see Figure 14), showing the significant impact of a trailing tensile phase on the target solid material. Link.

8.6. Numerical simulation of the dynamic response of pseudobarnacle and FR coating to shock-induced cavitation: As one step towards understanding the effect of cavitation in this application — specifically, the trade-off between the erosion of hard fouling organisms and the risk of damaging hull coating — we have employed FIVER to simulate the collapse of an air bubble (initial radius $R_0 = 50\ \mu m$) near a gypsum cylinder (representing hard fouling), a silicone-based FR coating (RTV 11), and a rigid wall (for reference). In these simulations, the collapse of bubble is triggered by a shock wave with peak pressure $p_{max} = 45.0$ MPa. Overall, the result shows that when the same bubble collapses near different materials, the speed of collapse, the transient flow field, the pressure loads on the material's surface, and the transient stress in the material all vary significantly (Figures 17, 18).

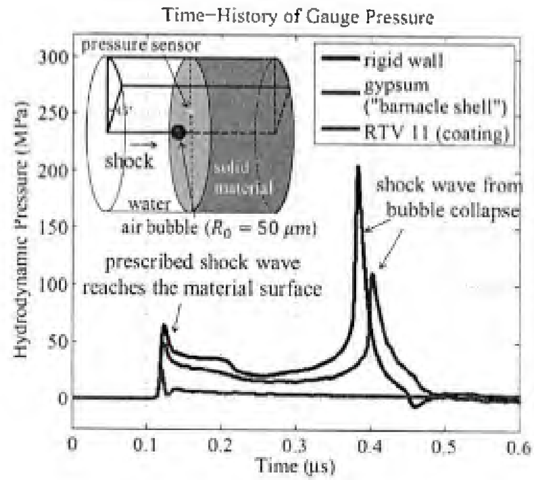


Figure 17: Numerical simulation of the collapse of cavitation bubble near different solid materials: time-history of pressure at a sensor near the material surface.

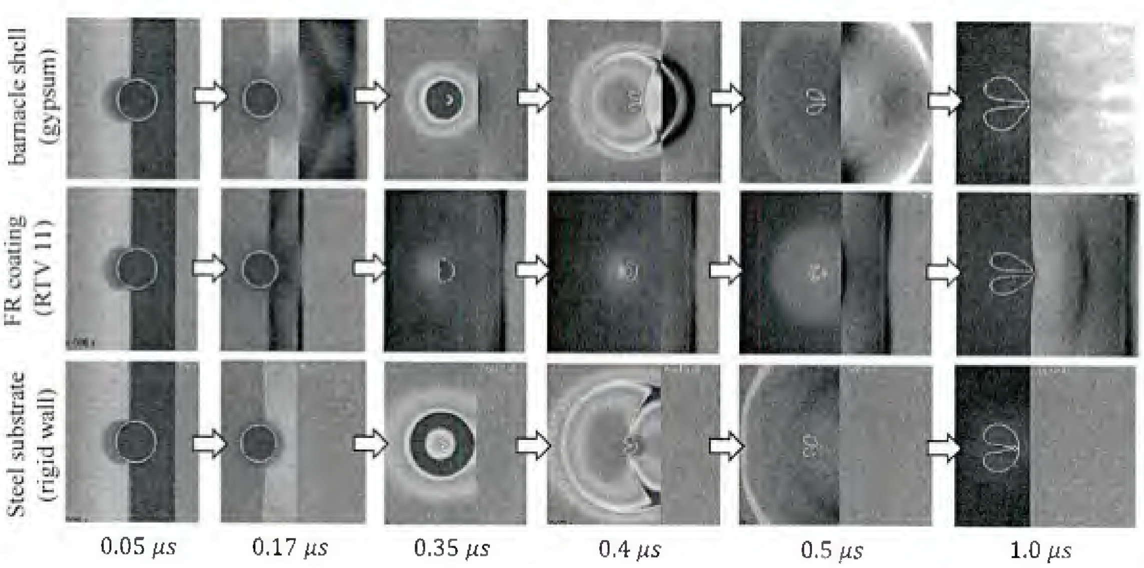


Figure 18: Numerical simulation of the collapse of a bubble ($R_0 = 0.05\ mm$) near different types of materials. Dynamic pressure is visualized in the (two-phase) fluid domain. The maximum principal tensile stress is visualized in grayscale in the solid material.

In particular, the polymer FR coating significantly reduces the speed of bubble collapse (Figure 18); and as a result, the shock wave resulting from bubble collapse is largely suppressed (Figure 17). This is due to the fact that the acoustic impedance of the polymer ($0.67\ kg/mm^2s$) is lower than that of water ($1.5\ kg/mm^2s$) (Figure 4). Therefore, the material reflects the compressive front of the shock wave as tensile wave. The reflected wave interacts with the bubble, significantly reducing its speed of collapse and the magnitude of the shock wave resulting from its collapse. *This finding indicates that silicone-based FR coatings may be resistant to pulsed cavitation, which supports our hypothesis that well-controlled shock waves may be effective for hull grooming, without damaging the coating.*