Mitigating Effect of Polymer Coating on Deformation From Non-Ideal Explosions

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ABSTRACT

Non-ideal explosions such as those caused by fuel-air explosions or improvised explosive devices (IEDs) are capable of producing extensive damage on neighboring structures. Using detonations of gaseous reactants in closed pipes as a model, we are examining methods to mitigate the amount of plastic deformation (damage) resulting from non-ideal explosions. The highest pressures and the largest deformations are observed to occur at the closed end of the pipe where a reflected shock wave is created to bring the flow to rest. In previous studies, we have quantified the deformations near the closed end of a mild steel tube with no mitigating methods present. In the present study, we examine the effect of introducing a polyurea coating to the exterior of stainless steel pipes. Polymer coatings applied to underwater structures and ship hulls have been shown [1,3,5] to reduce the amount of deformation resulting from blast loadings in some cases. We will compare strain data resulting from detonations propagating in six tubes. Two of the six tubes have no coating to establish a baseline measurement while the other four have coatings of different thickness to examine the effect of polyurea.

1. INTRODUCTION

Fuel-air explosions, improvised explosive devices (IEDs), and other non-ideal explosions may result in extensive damage on nearby structures. Using detonations of gaseous reactants in closed pipes as a model, we are examining methods to mitigate the amount of plastic deformation (damage) resulting from non-ideal explosions. When a detonation reflects from the closed end of a pipe or tube, a reflected shock wave is created to bring the flow immediately behind the detonation to rest; this wave produces a peak pressure approximately 2.4 times the Chapman-Jouget value [17] and travels back towards the location of detonation initiation. Depending on this peak pressure relative to the pipe or tube's strength, three modes of material deformation may be observed. Small pressure-to-strength ratios result in the first mode in which the detonation produces elastic deformation only and thus no permanent damage [4]. Increasing the pressure-to-strength ratio to intermediate values will produce pressure-to-strength ratios that result in plastic deformation of the pipe wall but no tube rupture [9,10]. Extreme pressure-to-strength ratios—which may occur even for modest pressures if the tube strength is sufficiently low as may be the case if there is a flaw or crack in the tube wall—will result in propagating cracks and tube rupture [5].

Polymer coatings have been shown to mitigate damage caused by loading profiles similar to those observed in detonation experiments. Brasek [4] and Chen et al. [7] observed that the amount of plastic deformation was lessened by application of a polymer coating to the side of a structure opposite that of a blast loading. Amini et al. [1] have shown that similar results may be obtained from impulsive blast loadings where the polyurea was applied on the face opposite the applied loading. Sayed et al. [16] have developed and validated a computational model of ballistic impact onto a steel plate retrofitted with a layer of polyurea.

An extensive effort has been conducted to characterize the material response of polyurea with focus on both the static and strain-rate dependent material properties. The strain-rate dependence is of particular importance for our application of strain induced by reflected detonation where strain rates of 10^3 s^{-1} may be obtained [9,10]. Chen et al. [6] modified the traditional split Hopkinson pressure bar to characterize a range of soft materials. Zhao et al. [18,19] advanced the theoretical knowledge and developed a new method for testing the material response of polyurea and were able to achieve strain rates up to 10^5 s^{-1}. Amirkhizi et al. [2] incorporated a wide-range of data and developed a material model that successfully reproduces high strain-rate experiments. Intermediate strain rates up to 573 s-1 were performed by Roland et al. [13] and compared to high strain rate experiments. Sarva et al. [16] observed a transition in the phase of the polyurea for high strain rates.

Herein we examine the effect of a polymer coating on tubes undergoing plastic deformation, but not rupture. We introduce new experiments characterizing the response of thin-walled stainless steel pipes to internal detonation of stoichiometric ethylene-oxygen with initial pressures of 2 and 3 bar. These experiments serve as a control so that strain data may be compared to tubes that have had a coating of polyurea applied to the exterior surface of the tube wall.

2. EXPERIMENTAL SETUP

The experimental setup is akin to that of [10] wherein a compound tube is created by the joining of two tubes of inner diameter 127 mm and length 1.2 m in the center by a gland seal as shown in Figure 1. The left-hand tube, hereafter termed the driver tube, was thick-walled and does not deform plastically. The right-hand tube, or specimen tube, was a 304L stainless steel welded tube with 1.65 mm wall thickness. Ignition takes place in the driver tube and the combustion wave travels towards the specimen tube and reflecting end. The driver tube contains paddle-shaped obstacles to ensure early DDT. The driver tube is also outfitted with three PCB 113A24 pressure gauges to monitor whether a well-formed detonation propagated into the specimen tube. It should be noted that in all experimental results discussed, DDT occurred before the first pressure gauge. After the detonation passes into the specimen tube, it continues at the theoretical Chapman-Jouget speed [11] to the reflecting end.

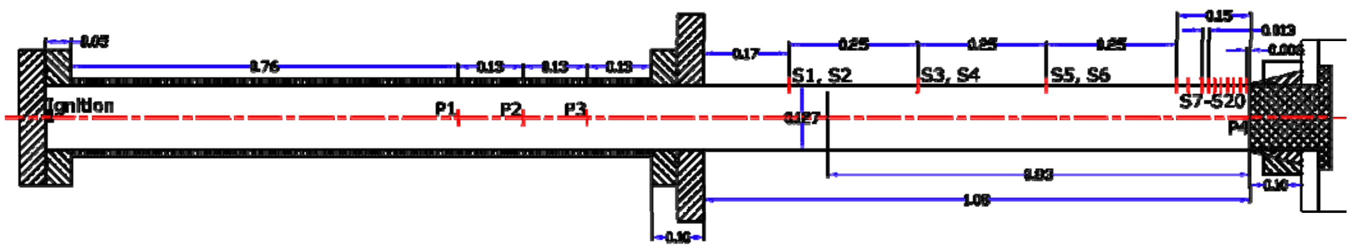


Figure 1. Schematic of detonation tube, dimensions in meters.

The 100 mm of the specimen tube nearest the reflecting end was slipped over an aluminum plug and sealed with an O-ring gland seal. A collet was cut by wire-EDM out of tool steel and hardened. This collet was designed such that, when tightened, it would clamp down on the specimen tube and have the end of the collet be flush with the end of the aluminum plug. A collet ring with an internal taper was used to tighten the collet onto the tube. The collet ring was secured to a steel plate with eight 9/16”-18 bolts with minimum preload of 125 N-m resulting in a clamping force greater than 100 kN. This collet assembly was securely fastened to a 2700 kg mass. This design resulted in a rigid boundary condition at the reflecting end.

Strain and pressure data was recorded at 2.5 MHz during the detonation event. In addition to the three pressure gauges located in the driver tube, one PCB 113B23 pressure gauge was placed in the center of the reflecting end. Up to twenty strain gauges were placed on the specimen tube. Every tube used some strain gauges except for tubes 15 and 16. The precise gauge location and orientation varied between experiments, but in most experiments 20 strain gauges were applied such that the majority of the gauges were located near the reflecting end where the largest deformation was observed to occur. Post shot diameter data was measured using an outside micrometer. For tubes that were coated with polyurea, the polyurea was first removed before the outer diameter data was measured.

In each experiment, the detonation tube was evacuated and filled with stoichiometric ethylene-oxygen to initial pressure 0.5, 2, or 3 bar. The 0.5 bar initial pressure resulted in purely elastic motion and was used to ensure the proper operation of the metrology. The 2 and 3 bar initial pressures resulted in plastic deformation. Testing will be reported for six specimen tubes: Tubes 9, 13, and 15 were filled to 2 bar initial pressure whereas tubes 10, 14, and 16 were filled to initial pressure 3 bar. Tubes 13, 14, 15, and 16 were coated with SPI Ultra Bond-100 Polyurea that was spray applied to the outer surface of the tubes to nominal thickness of 3.9 mm for tube 13, 4.1 mm for tube 14, 2.9 mm for tube 15, and 7.3 mm for tube 16. As this was meant to be a preliminary investigation of the protective properties of polyurea coatings for internal detonations, the tolerance on the thickness of the polyurea was not strict with a maximum variance of 0.35 mm. Tubes 13 and 14 employed both strain gauges and polyurea coating. For these tubes, the gauges were glued and wired before the polyurea was applied. The density of the polyurea was measured to be 952 kg/m^3; the vendor supplied values of 4.7 MPa ± 0.7 MPa for the 100% elastic modulus, a minimum of 20.9 MPa tensile strength, and a minimum elongation of 450%.

3. RESULTS FOR INITIAL PRESSURE 2 BAR

Three tubes (tubes 9, 13, and 15) were subjected to detonations of initial pressure 2 bar. Tube 9 had no external coating so that a baseline measurement could be obtained. Tubes 13 and 15 had polyurea coatings of nominal thickness 3.9 and 2.9 mm respectively. Two types of strain gauge orientations were used. Most of the gauges were oriented in the circumferential or “hoop” direction; all of the data presented here are from these hoop gauges as this direction records the largest strains. The remaining gauges were oriented in the longitudinal direction but will not be discussed herein.

Tube 9 was tested with 11 detonations to examine the effect of strain ratcheting. Of these, 6 experiments were 0.5 bar initial pressure detonations that resulted in purely elastic strain and 5 experiments were 2 bar and yielded plastic strain. Comparable to the data presented in [9,10] for detonations in mild steel tubes, we observed a significant degree of strain hardening for repeated experiments as shown in Figure 2 by the diminishing strain amplitudes for repeated experiments. The dashed line indicates the location of the detonation as predicted by Chapman-Jouget theory [11]. The speed of the reflected shock wave is not constant as discussed in [9], but the location of the shock may be discerned from the second increase in strain amplitudes. These results are typical to those obtained in all experiments. Flexural waves are excited by and travel at the speed of the detonation. The largest pressures and hence the largest strains are observed immediately after the detonation reflects.

Tubes 13 and 15 were each coated with polyurea and tested with a single detonation that resulted in plastic deformation. Tube 13 was instrumented with strain gauges in a similar configuration to that of tube 9, and Figure 3(a) illustrates the difference in the strains. We see that the strains induced by the incident detonation were comparable for both tubes. It was only when the reflected shock wave arrives that substantial strain differences were observed. The one gauge that departed from this behavior is the gauge located only 6.35 mm from the reflecting end, which actually measured an increase in strain.

Figure 3(b) displays the differences in outer diameters for tubes 9, 13, and 15 after one 2-bar detonation. Observe that the magnitude of strains significantly decreased for the tubes with polyurea coatings. Tube 13 saw an 8.7% and tube 15 yielded a 14.3% reduction in residual plastic compared to the baseline case of tube 9. Surprisingly, decreasing the polyurea thickness in tube 15 resulted in a decreased strain. This may indicate that the mechanism by which polyurea mitigates damage is more complex than the polyurea acting as structural reinforcement and added mass. Alternatively, it may be that the presence of strain gauges and associated wiring underneath the polyurea coating in tube 13 diminished the ability of the polyurea to mitigate damage.

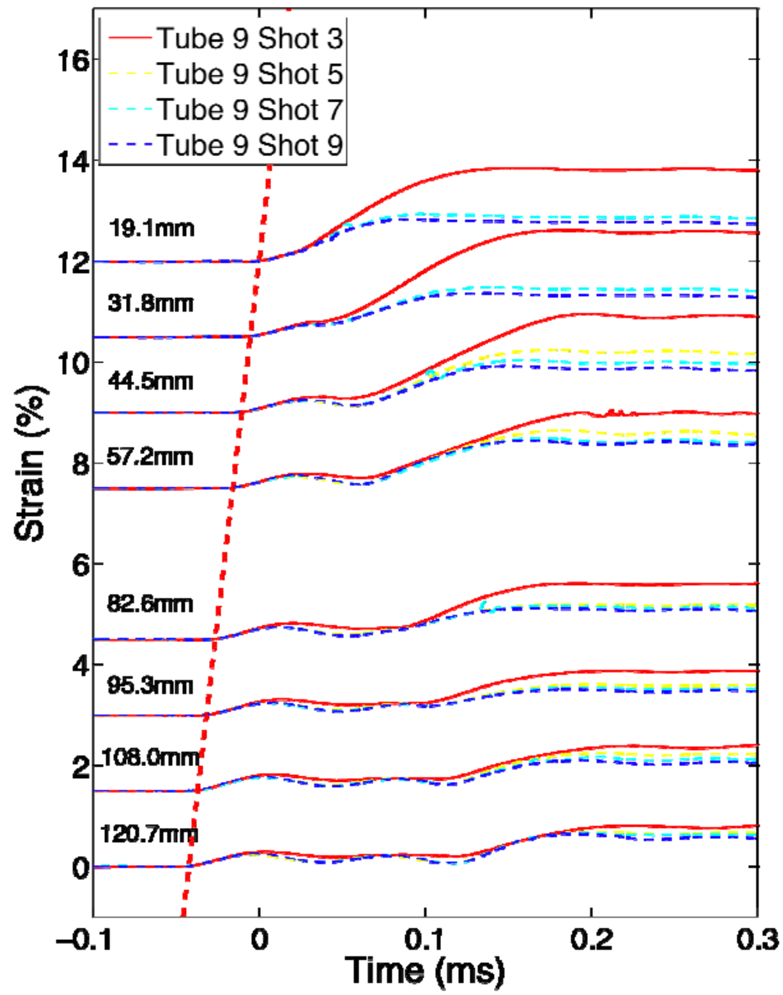


Figure 2. Hoop strain data recorded for 5 subsequent detonations of initial pressure 2 bar. The gauge locations are given as distance from the location of detonation reflection.

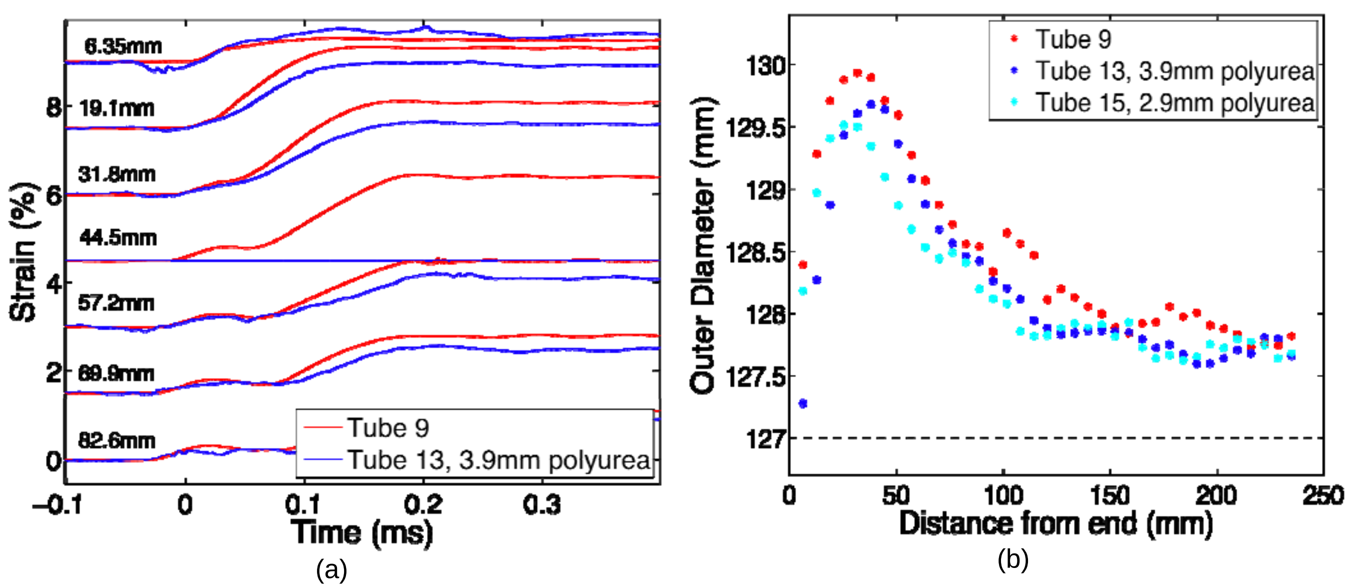


Figure 3. (a) Hoop strain for the first detonation of initial pressure 2 bar for tubes 9 and 13 displaying the strain mitigating effect of polyurea. Labels represent gauge distance from location of detonation reflection. (b) Post-shot outer diameter measurements for tubes 9, 13, and 15. The dashed line indicates the undeformed tube diameter.

A novel observation as seen in Figure 4 is the presence of ripples on the tube surface after a detonation has been performed. These were also observed by [9,10] and shown to be an interference of the elastic oscillation induced by the incident detonation with the reflected shock wave. The amplitude of this ripple pattern was observed to decrease for the tubes with polyurea as observed when comparing the outer diameter data in Figure 3(b). This is likely due to the polyurea having a damping effect on the elastic oscillation. Figure 5 shows strain comparisons for two 0.5 bar initial pressure experiments that resulted in purely elastic motion. Observe that the polyurea significantly decreases the amplitude of the elastic oscillation. It is also of interest that we observe the first oscillation cycle appears identical with and without polyurea. This seems to indicate that, for very short times, the polyurea does not follow the steel. This may be due to an adhesion issue, or simply that the polyurea has such a low modulus compared to the steel that there is little initial effect. Later times reveal that the diminished oscillations of the polyurea have a longer period as expected by the added mass of the polyurea. The increase in mass would suggest a decrease in frequency of approximately 14%; from the data plotted in Figure 5 we observe a frequency decrease of 13% indicating that the added mass is of primary importance in reducing the frequency of the oscillations. The ripple pattern observed in the stainless steel tubes is substantially more extensive than that observed in mild steel tubes under identical detonation loadings [10]. This is possibly due to the different strain rate dependencies between 304 stainless steel [12,15] and C1010 mild steel [14] as reported by Rusinek et al. Further studies are necessary to be able to fully predict the extent and amplitude of the ripple effect.

Figure 4. Post-detonation photographs of tubes 9 (left) and 10 (center).

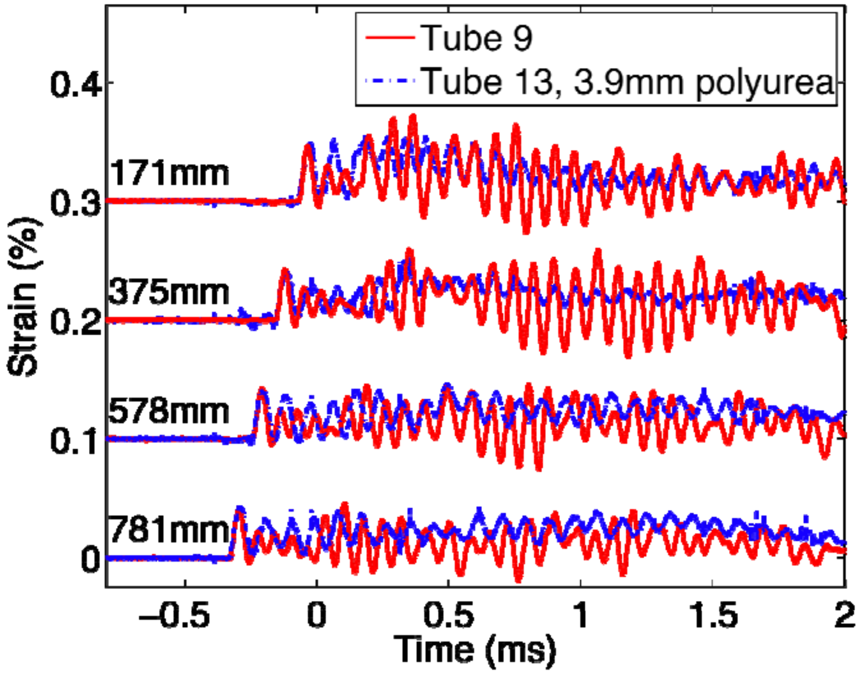
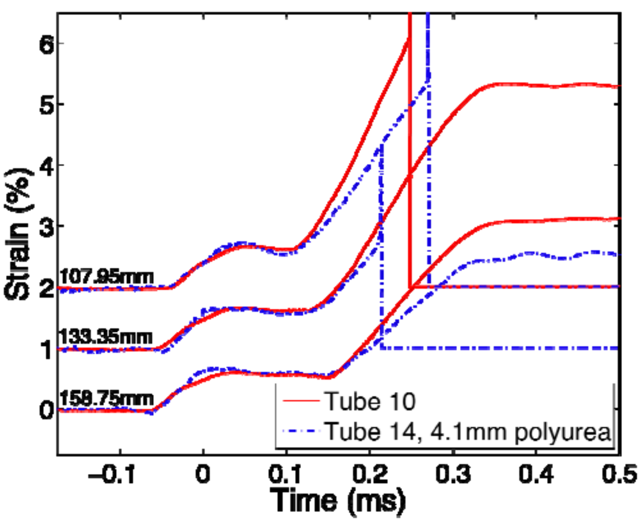


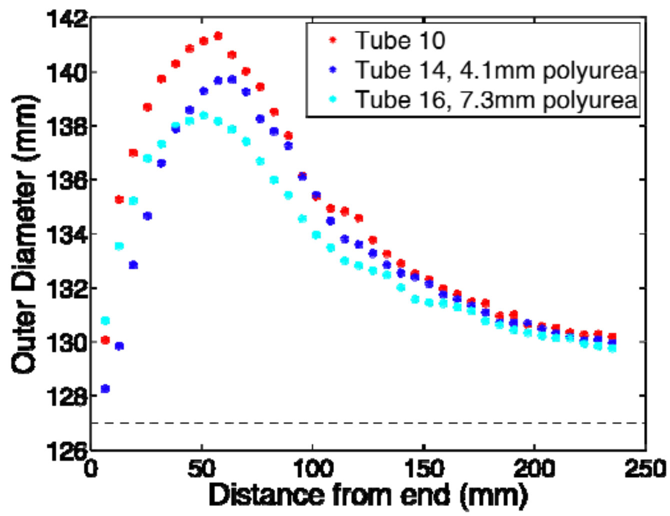
Figure 5. Purely elastic hoop strain for detonations of initial pressure 0.5 bar. Labels represent gauge distance from location of detonation reflection.

4. RESULTS FOR INITIAL PRESSURE 3 BAR

Three tubes (tubes 10, 14, and 16) were subjected to detonations of initial pressure 3 bar. Analogous to the 2-bar experiments, tube 10 was uncoated for a baseline and tubes 14 and 16 had polyurea coatings of nominal thickness 4.1 mm and 7.3 mm respectively. The strain data is less useful here because the degree of strain observed in experiments was such that most strain gauges did not survive the experiment, as observed in Figure 6(a) by signals abruptly jumping to zero strain. The best comparison in data is seen in the post-shot outer diameter data shown in Figure 6(b). Here we observe that, like the 2-bar initial pressure experiments, the polyurea significantly lessens the observed deformation: The peak strains are reduced by 11.3% and 20.5% for tubes 14 and 16 respectively.



(a)



(b)

Figure 6. (a) Hoop strain for the first detonation of initial pressure 3 bar for tubes 10 and 14 displaying the strain mitigating effect of polyurea. The sudden drops in strain correspond to gauge failure. Labels represent gauge distance from location of detonation reflection. (b) Post-detonation outer diameter measurements for tubes 9, 13, and 15. The dashed line indicates the undeformed tube diameter.

5. CONCLUSIONS

It is clear from our reflected detonation experiments that an external coating of polyurea mitigates the plastic deformation of the tubes. The amount of mitigation varies by polyurea thickness and detonation strength, but reduced residual plastic strain by a minimum of 8.7% as observed in the 2-bar, 3.9 mm thickness shot and as much as 20.5% as seen on the 3-bar, 7.3 mm thickness experiment. The polyurea thickness clearly has an impact on the damage mitigation provided, with the most mitigation being observed for the thickest polyurea coating. However, the precise benefits of thinner coatings are not clear as demonstrated by the decrease in strain for tube 15 which had the thinnest polyurea coating. We also conclude that the polyurea serves to decrease the amplitude of the ripple pattern reported in [9,10]. Considering the theory developed in [9,10], this is likely due to the dampening of the elastic oscillation that results from the incident detonation. Future computational work to be performed will use a more precise tolerance on the polyurea thickness and an existing constitutive model for polyurea (e.g., [2]) to develop a numerical simulation of the expected material response of the polyurea coated tubes subject to internal reflected detonation in the manner of [10].

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