Structural Response to Detonation Loading in 90-Degree Bend

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Summary. The structural response due to detonation propagation through a 90-degree bend in a circular tube was experimentally examined. Hoop strain measurements were obtained at key locations along the tube to measure elastic deformation. Dynamic pressure signals at the same locations were also recorded to track the detonation wave and record the peak pressure. Of particular interest are the effects of the bend on the magnitude of the pressure and strain in the material when compared to the straight tubes. These geometrical effects are due to the excitation of multiple modes: a short period detonation driven mode and longer period bending modes within the structure not seen in the straight tubes. The excitation of these bending modes serves to increase the maximum strain observed, which translates to greater hazards for industrial piping systems.

1 Introduction

Process plant piping is characterized by straight runs of pipe connected by elbows, tees, valves, pumps, reactor vessels, holding tanks and other features, including detonation and flame arrestors. In addition, the piping system is suspended or supported from a framework that provides reaction forces and limits the motion of the piping [1]. If detonations are possible within the piping, then a comprehensive analysis of the structural response requires consideration of how the detonation will interact with these features and what structural loads will be created.

When a detonation wave propagates through a tube, flexural waves are created that may result in strains that are significantly higher, up to 4 times greater, than strains that would be observed under simple static loading with the same internal pressure. Several conditions can create these higher strain conditions: resonant excitation, interaction of direct and reflected flexural waves and detonation pressure oscillations coupling with flexural waves [2].

When the detonation reaches a closed end, the peak pressure of the reflected shock wave is about 2.5 times the Chapman-Jouguet (CJ) pressure [3] and the pressure decays as the wave moves away from the reflecting surface. The reflected shock wave will induce flexural waves in the pipe which will interfere with the waves that were created by the incident wave. Constructive interference of these waves leads to the maximum strain values being observed at times corresponding to the passing of the reflected wave [1].

Detonation propagation through an elbow or tee is an example of detonation diffraction [4] which, depending on the direction of curvature, may cause the detonation to intensify or weaken [5]. Thomas [6] has carried out experiments on a plastic piping network, measuring both the forces on the supports and the strains on the pipes. Substantial motion of the pipe supports was observed in these tests, raising the possibility of piping containing the explosion at early times but failing due to excessive distortion of the supports.

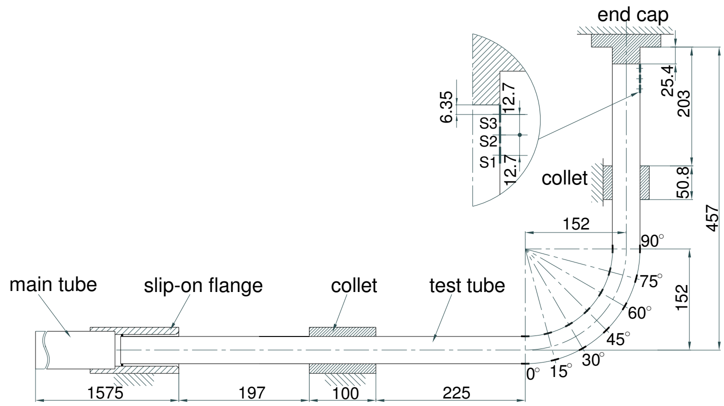


Fig. 1. Schematic of the experimental setup. The length unit is mm.

Previous experiments have been performed in our laboratory to investigate the effects of detonation waves on straight tubes [2, 7]. The focus of the present paper is on detonation propagation through a 90 degree bend, which is part of a larger study [9] in our laboratory examining a range of structural elements including bends and tees.

2 Experimental Setup

The experimental setup consists of a main detonation tube (76 mm ID, 1.5 m long and 6.4 mm thick) connected to a carbon-steel test tube (41.3 mm OD and 0.15 mm thick) by a slip-on flange with an O-ring seal, as shown in Fig. 1. The period of oscillation for the fundamental hoop mode of the test tube is 24 μs, corresponding to a frequency of 41.4 kHz. This is the highest characteristic frequency with which we expect to observe oscillations in the strain signals [2, 1].

The test tube consisted of a 0.61 m (24 in) straight section, a 90-deg bend with a radius of 0.152 m (6 in), and a straight section of 0.305 m (12 in). Two collets were used to support the test tube, one located 0.225 m (8.9 in) before the bend and 0.025 m (1 in) after the bend. The terminating end of the test tube was closed.

Three types of test tubes were used. Case 1: plain tubes with strain gauges were placed every fifteen degrees along the bent portion (15-90°), six on the intrados, six on the extrados, and three on the reflecting end. Cases 2 and 3: the tubes were modified with welded pressure transducer adapters at the locations corresponding to the strain gauges in Case 1. Pressure transducers were located at 15° increments along the bend on the extrados for Case 2 and on the intrados for Case 3. A stoichiometric ethylene-oxygen mixture was ignited by an electrical spark at the end of the main detonation tube, and a Schelkin spiral was used to accelerate the flame to a detonation before entering the test section.

3 Results and Discussion

All the tests were carried out at a room temperature 21-23°C and an initial pressure of 1 bar. The ideal detonation [8] for the test mixture has a CJ velocity $U_{CJ} = 2376$ m/s,

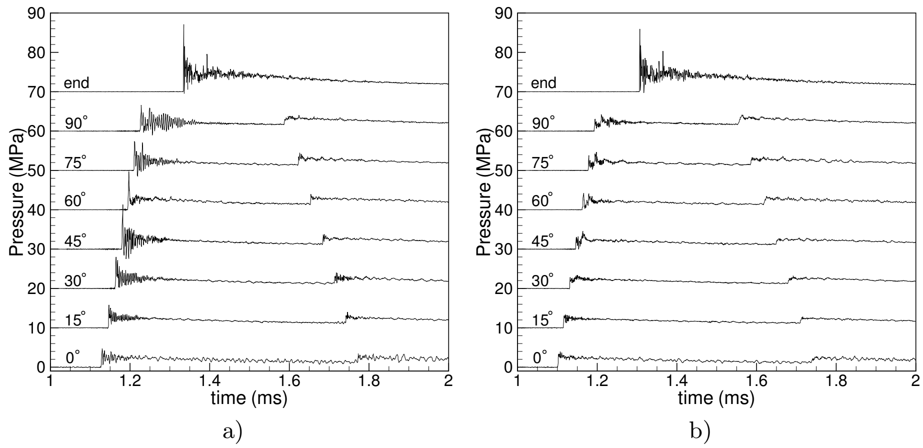


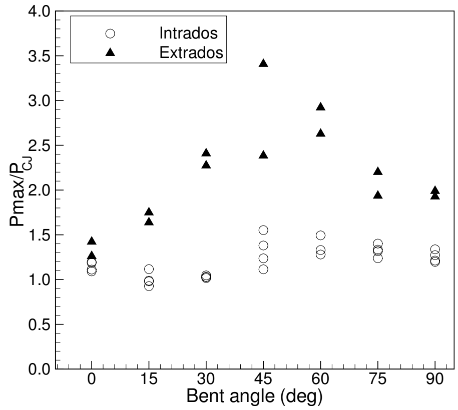
Fig. 2. Pressure histories at locations on the a) extrados and b) intrados. Traces are offset by 10 MPa for visibility.

CJ pressure $P_{CJ} = 3.33$ MPa, and reflected CJ pressure $P_{CJref} = 8.34$ MPa. Replica tests showed good reproducibility of the near-CJ detonation conditions before entering the test tube.

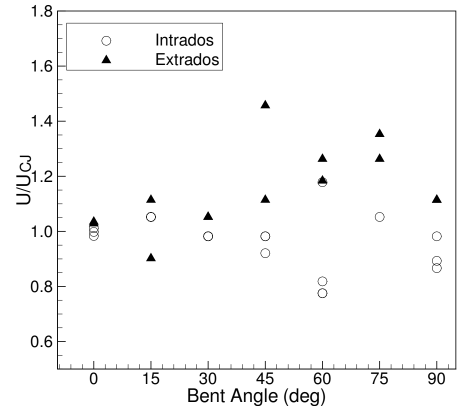
Detonation diffraction through the bend [4] results in the generation of compression waves on the extrados and expansion waves on the intrados, visible in Fig. 2. As a consequence, the peak pressures (Fig. 3a) on the extrados are all larger than those on the intrados. On the intrados of the bend, the peak pressure decreased to a minimum of P_{CJ} at 30°, then increased to $\approx 1.3\ P_{CJ}$ at 90°. On the extrados, the peak pressure increased to a maximum of 3-3.5 P_{CJ} at 45°–60° and decreased to about 2 P_{CJ} at 90°. We believe that this is due to the transverse shock waves generated by the diffraction within the bend and the peak value will be smaller when the length of the extended section after the bend is larger. At the reflecting end, the peak pressure was about twice P_{CJref}, the nominal value for straight tube.

Figure 3b demonstrates the change of the average wave speed, computed using the pressure wave arrival times, along the bend. The wave propagated at near-CJ velocity at the beginning of the bend (0°). The velocity decreased to $\approx 0.8\ U_{CJ}$ at 60° on the intrados, and increased to $\approx 1.4\ U_{CJ}$ at 75° on the extrados. After the peak, the wave speed on the extrados decreased to $\approx 0.8\ U_{CJ}$, the wave speed on the intrados was nearly U_{CJ}, and the wave at 90° was slightly overdriven ($\approx 1.1\ U_{CJ}$), consistent with the pressure profile and the wave being tilted at the exit of the bend. The measured hoop strains (Fig. 4) show the effects of incident and reflected waves as structural oscillations over a range of time scales. The radial oscillations induced by the incident detonation result in peak hoop strains on both the extrados and intrados of about 300 μstrain and 350– 575 μstrain due to the reflected shock wave.

The strain gauges near the end (Fig. 4c) show traces that are nearly identical to those obtained with straight samples (not shown in this paper). This suggests that although the peak reflected pressure is higher than for a straight tube, the next effect of the bend on radial structural motion is negligible after a propagation distance of two bend radii. The maximum hoop strain magnitude near the end was approximately 600 μstrain.



a)



b)

Fig. 3. a) Peak pressure (normalized by P_{CJ}) and b) detonation speed (normalized by U_{CJ}) vs. the bend angle.

In addition to radial oscillations, a bending mode is excited due to the forces created by the change in direction of the detonation wave as it passes through the bend. This results in a long-period (≈4 ms) oscillation (Fig. 4d) observed in the hoop strain. This period corresponds to the flexure of the tube in a beam-like mode between the two collets (Fig. 1) holding the tube fixed to the support structure.

The bend in the pipe results in time-dependent forces on the pipe due to both the internal pressure acting on the bend and the change in flow direction. As shown in Fig. 5, forces F_x and F_y will be generated in the plane of the elbow in the direction of the pipe segments upstream and downstream of the bend. During the passage of the detonation wave through the bend, these forces will have a complex time dependence due to the waves created by the diffraction processes. Later, once these waves have died down, the forces can be estimated from the momentum balance for a steady flow. In terms of the average properties, the forces will be $F_x = A_1(P_1 + \rho_1 u_1^2)$ and $F_y = A_2(P_2 + \rho_2 u_2^2)$. Immediately behind the detonation front, the dynamic pressure ρu^2 is of the same order as the static pressure P so that the force will be a factor of two higher than computed on the basis of pressure alone. As the Taylor wave propagates through the bend, the flow will eventually come to rest and only the pressure will contribute to the forces.

We have analyzed the measured strain signals by computing the dynamic load factor (DLF), the ratio of the measured peak strain to the peak strain expected in the case of quasi-static loading $DLF = \epsilon_{max}/\epsilon_{static}$ where $\epsilon_{static} = \Delta PR/Eh$. For our test tubes, the parameters are E=210 GPa, R=20 mm (mean of inner and outer radius), h=1.5 mm (wall thickness), ϵ_{max} is the measured peak strain. The DLF values shown in Table 1 were computed in two ways. The values for DLF_{exp} were based on the static strain that would be expected from the experimentally measured peak pressure (ΔP=P_{max}) and the values for DLF_{CJ} were based on the calculated CJ pressure (ΔP=P_{CJ}-P_a).

The average peak pressures (Table 1) are always smaller on the intrados than on the extrados, but the maximum strains are larger on the intrados than the extrados between 0–60°. Using the experimental peak pressures, we find values of the DLF that are between 1 and 2, indicated the loading is in the regime intermediate to impulsive and "sudden loading" [1]. For the purposes of estimating peak deformations the dynamic load factor

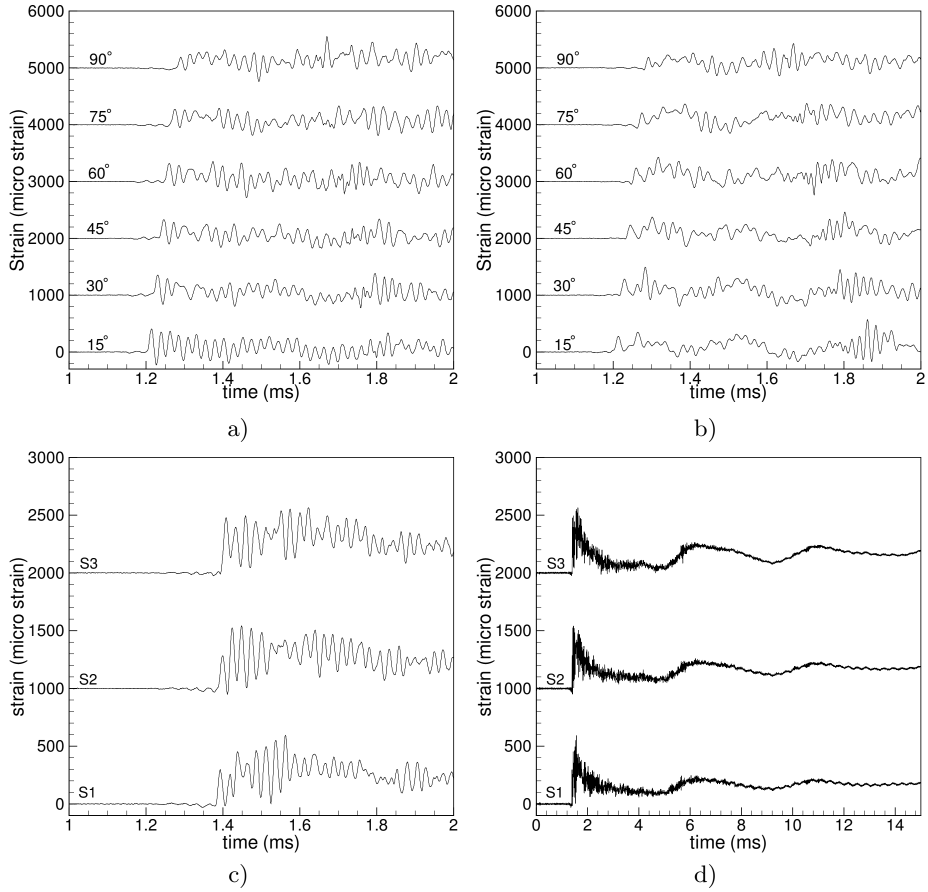


Fig. 4. Strain histories at locations along the bend on the a) extrados, b) intrados, c) reflecting end, and d) over a longer time scale for S_1-S_3. Traces are plotted with a vertical offset of 1000 μstrain.

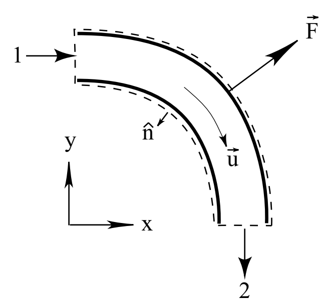


Fig. 5. Forces on pipe bend created by pressure and flow.

DLF_{CJ} based on the CJ pressure is most useful since it does not require experimental measurements. From the present data, we see that $1.7 < DLF_{CJ} < 2.4$ depending on the location of the measurement. This is valid for both the short duration hoop oscillations and the longer-duration beam oscillations.

Table 1. Average values of measured peak pressure P_{max}, peak strains ϵ_{max} and the corresponding dynamic load factors.

angle	extrados				intrados			
	ϵ (μstrain)	P (MPa)	DLF_{exp}	DLF_{CJ}	ϵ (μstrain)	P (MPa)	DLF_{exp}	DLF_{CJ}
15°	423	5.63	1.18	1.99	513	3.34	1.43	2.42
30°	366	7.79	0.74	1.72	500	3.43	1.01	2.36
45°	390	9.63	0.63	1.84	448	4.39	0.73	2.11
60°	382	9.23	0.65	1.80	485	4.55	0.82	2.29
75°	406	6.88	0.93	1.91	396	4.40	0.90	1.87
90°	479	6.51	1.15	2.26	366	4.18	0.88	1.83

4 Conclusion

The structural response due to detonation propagation through a 90° bend was examined. Due to the detonation diffraction process, the peak pressure on the extrados was substantially larger than on the intrados of the bend. The peak values of strain on the extrados and intrados were comparable. Oscillatory hoop strains were observed with short periods similar to the flexural modes observed with straight tubes and a longer period mode corresponding to beam bending excited by the change in wave direction through the bend. A maximum dynamic load factor (based on P_{CJ}) of 2.4 was measured. The peak hoop strains associated with the bending mode were comparable to those created by detonation wave reflection from a closed end.

References

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