RESPONSE OF A DOUBLE CANTILEVER FRAME SUPPORTED PIPELINE TO INTERNAL TRANSMITTED IMPULSIVE LOADS

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This paper presents experimental results of the response of a double cantilever frame supported pipeline to internal transmitted impulsive loads generated by the propagation of shock, detonation and blast waves, with both open and closed end flange configurations. Time resolved axial displacement responses of specially constructed supports were obtained. These showed the coupling of the impulsive loads transmitted into the longer time scale support oscillations. This paper also reports on the comparison between numerical simulations of the response of the pipeline supports with the experimental results obtained.

Keywords: impulsive, transient, loading, detonation, blast, shock, supports, pipeline

INTRODUCTION

Explosions in industry have been the subject of increasing levels of detailed investigation for nearly 50 years. During this period, factors that give rise to, and which control the development of explosions, have been investigated, and the majority of key parameters have been identified. However, advances in understanding the physical causes and predictions of explosions can usefully inform other disciplines of potential hazard scenarios and assess the associated risks in offshore and onshore process plant design and construction.

One area that has received little attention is the response of pipeline structures and supports to explosions. Small explosions could lead to local structural failure resulting in potential devastating escalation, if they formed critical elements of larger structures. Two escalation paths may arise. Direct failure of the pipe itself, or failure due to the subsequent failure of the pipe supports. The latter possibility is one that is considered far less frequently. Usually supports are designed to withstand the static weight of the pipe section and conventional loads associated with wind and seismic activity only, but not to loads associated with internal transient explosions. Currently there is a considerable amount of interest in the response of pipelines and associated structures to internal explosive loads. Interest has developed because of the distant possibilities, which exist of accidental explosions developing in plant pipeline systems.

The amount of material in the published literature on the mechanical response and failure of pipelines and support structures is very limited. Textbook style references such as Biggs[1] and explosion references such as Baker et al.[2] cover the fundamentals of external explosive loads and detailed analytical treatments of simple structures and response models. Brossard and co-workers[3, 4, 5] have reported several studies of the response and internal loading of pipelines by internal propagating pressure waves. More recently, Thomas and Oakley[6] reported the study of loading of GRP (Glass Reinforced Plastic) and Polyethylene pipes by internal detonations. These experiments were conducted using atmospheric ethylene - air in pipelines of internal diameters of 250mm and 300mm, and observed a catastrophic pipe failure in one particular case. Thomas and Oakley considered the motion and possible failure modes of the pipeline supports and noted their significance of the characteristic load duration to that of the natural resonant period of the coupled pipeline and supports. The response of PVC and stainless steel pipes to internal stoichiometric propane - air propagating detonation waves was studies by Brossard and Renard[7]. A model for the mechanical response of the pipe walls was created and tested against experimental results. Experimental results provide information of the dependence of the transverse and longitudinal strain on the pipe wall due to propagation of the detonation waves. The precursor effects, the oscillations and their frequencies and the end effects agree well with theory. However, the observed increase in the transverse strain behind the detonation front and its amplitude did not agree with predictions of the code. Klein and Wilming[8] investigated the response of a complex 'T' configuration piping system and connected supports to an internal oxy-acetylene detonation. Other variants were considered, including the speed of the detonation wave, three different pipe support designs, additional mass on the pipe bridges due to adjacent pipes and pipes as spring supported system without the mass of the supports. They used a simple explosion-propagating model, but made some sweeping assumptions regarding the nature of the loads.

EXAMPLES OF EXISTING PIPELINE SUPPORTS

Pipeline supports can be divided into two groups by their basic structural design. These include 'pipeline unclamped' and 'pipeline clamped' supports. Both groups actually support the static weight of the pipeline section, but only the 'pipeline clamped' group has the ability, if designed correctly, of being resistant to transmitted loads generated within the pipeline.

Examples of 'pipeline unclamped' supports include half-saddle and cradles. Half-saddles and cradles support the pipeline statically, but do not hold or clamp the pipeline to resist its axial motion. If the problem of transient impulsive loading occurs, there will be no resistance from the support and the pipeline is free to move in the direction of the loading.

Examples of 'pipeline clamped' supports include saddle clamps, beam, welds and I-rods. Saddle clamps work by clamping the pipeline circumferentially by means of two metal semicircular yoke bands. Saddle clamps are widely used, especially on larger diameter pipelines, as they offer excellent static mechanical support. They are often used in both horizontal and vertical pipe runs. Beam supports, which are constructed using a beam or girder perpendicular to the pipeline, are a very common method of supporting multiple parallel pipeline runs. The pipes are usually stabilised, usually with a U-bolt. This is a very attractive support method, due to its inexpensive and flexible nature for pipeline designers, where the U-bolts offer a greater inspection and maintainability to corrosion than saddles.

Adaptations that provide a solution to pipeline support corrosion include Welds and I-Rods. Weld supports involves direct welding or fixing of the support to the pipeline wall, in order to stop the amount of moisture being trapped in-between, which eventually causes corrosion. I-rods are a half semicircular yoke configuration on top, similar to half saddle clamps, and are joined to the bottom of a 'I' shaped girder section, made from a high strength thermoplastic material. These may be easily installed, either in a continuous length across the top of the pipe supports beams or as an integral part of a U–bolt assembly to replace saddle clamps.

Ideally, a pipeline support should be designed to withstand a range of loads transmitted from the pipeline, to which it is clamped. With all examples of clamped pipeline supports, if the support itself has a low elastic limit and easily extends into the plastic region under loading, the supports becomes potentially dangerous, if such a distant and rare event should occur.

EXPERIMENTAL DETAILS

The current experiments were conducted using a 4.3m, 150mm nominal bore, schedule 40 steel pipeline, comprising of a 1m driver section and 3.3m test section, supported by two specially designed supports as shown in Figure 1. Impulsive loads of varying strengths, which could be experienced in an accidental pipeline explosion scenario, were generated within the pipeline and transmitted to the supports. The generation of the impulsive loads were conducted by either shock, detonation and blast wave propagation. In the case of the shock and detonation wave experiments, the pipeline was closed at both ends. With blast wave experiments, both close and open-end flange configurations were considered. The 1m long driver section was attached to the 3.3m test section pipeline to act as either a detonation driver section for both blast and detonation wave experiments or as a high-pressure section for shock experiments.

For the shock wave experiments, the test section was filled with atmospheric air, while the driver section pressure was raised, by filling with compressed air, until the separating diaphragm burst. For detonation wave experiments, the driver section was filled with atmospheric stoichiometric acetylene – oxygen and the test section with atmospheric stoichiometric ethylene – air. For blast wave experiments, the test section was filled with atmospheric air, while the driver section was filled with atmospheric stoichiometric acetylene – oxygen. In the reactive experiments a slide valve was used to separate the test and driver sections. Ignition via a nominal 0.6J spark occurred immediately after opening the slide valve.

INSTRUMENTATION AND DATA COLLECTION

PCB piezo-electric pressure gauges, mounted in the pipeline wall and end flanges, were used to monitor the propagation of the pressure waves. To measure the axial displacement of the pipeline supports L.V.D.T. (Linear Variable Differential Transformers) sensors were used. The L.V.D.T sensors used were RPD type ACT1000 with a range of ± 25mm and were calibrated following the manufactures guidelines. The L.V.D.T. sensors were mounted in specially designed clamps/gimbals supports and the armature of the sensor was fixed to the stand by means of a steel rod and rose joint as shown in Figure 2.

For data acquisition, two 8 bit synchronised transient recording systems were used, to provide optimal sampling of both the pressure wave and pipeline support, which occur over different time scales. Synchronisation was obtained by duplicating reference gauges on both recording systems.

PIPELINE SUPPORT DESIGN CRITERIA AND VALIDATION

The pipeline used in these experiments was mechanically supported using specially designed supports by Wilfred Baker Engineering Ltd, shown schematically in Figure 2. The design criteria for each of these supports was to generate a realistic elastic displacement output to a load generated by a normal reflected stoichiometric ethylene – air detonation, giving a peak pressure of 40 – 45 atmospheres, subjected to a 150mm diameter end flange. Using the cantilever beam equation, the theoretical spring constant for this particular support design is 845N per mm. Adapting this into a theoretical frame cantilever supported pipeline configuration, gives a theoretical spring constant of 3381N per mm.

To experimentally measure the axial spring constant of a single pipeline support and the frame supported pipeline configuration for comparison and later numerical response simulations, both force and displacement measurements should be obtained. This was achieved by placing the pipeline system under static loading by means of a pulley system attached to a structurally static object. Loads were measured by placing an in-line mounted strain-gauge load cell. The load cell used was an Applied Measurements type DDE – 20000. Displacement was measured using the L.V.D.T. sensors described above. The axial spring constant of the single cantilever and double frame supported pipeline system can be seen in Figure 3 and 4, which gave a value of approximately and 860N per mm and 2500N per mm respectively. Therefore, the pipeline and support configuration used and shown schematically in Figure 1., has an experimental characteristic spring constant that is greater than the theoretical value for the two single combined cantilever supports and is less than the theoretical value for the frame supported pipeline configuration. The differences in the theoretical and experimentally measured spring constants are believed to be due to the pipeline supports not behaving with pure cantilever characteristics in this configuration. An additional factor to be considered is the weight of the pipeline, which will affect the spring constant of the entire pipeline and support configuration.

RESULTS

Typical short duration axial displacement response of the pipeline supports and associated end flange pressures can be viewed in Figures 5(a) – (d) for shock, detonation, blast closed end flange and blast open end flange experiments respectively. All show good correlation in both reproducibility and reliability. There is some scatter in the magnitude of the peak spike pressures from the detonation driver. This is due to the unpredictability associated with the deflagration to detonation transition. Pressures of the detonations may be seen to exceed stable values due to detonations tending to be overdriven in some cases. Positive axial displacement refers to the direction of the initial incident wave propagation into the test section (from left to right in Figure 1). It can be seen in Figure 5(a) that the response displacement of the pipeline supports is initiated from the start of the diaphragm burst – increasing due to the rarefaction waves travelling back into the high-pressure section. It can be observed that the reflected shock pressure on the test section end flanges doesn't have a distinctive effect on the short duration response of the pipeline supports.

The axial response profile of the supports from both the detonation and the blast closed end flange experiments is rather different to the response for either shock or blast open-end flange experiments. It can be observed that the same initial response, caused by the recoil load experienced by the ignition end flange, produces a displacement response in the opposite direction of the initial propagating wave. When either the detonation or blast wave meets the test section end flange, a reflected end flange load is created causing a displacement peak in the direction of the initial wave propagation. The bouncing waves within the pipeline transmitted to the supports create a high frequency response over this short time duration. The short duration axial displacement response of the blast open-end flange experiments with ignition end flange pressures can be seen in Figure 5(d). A single recoil load creates a sinusoidal damped oscillation response from the pipeline supports.

Figure 6. shows the long duration axial displacement response of the pipeline supports from shock, detonation and blast waves experiments, with both closed and open end flanges. The difference in long duration axial response of the pipeline supports from closed and open-end flange blast experiments can also be seen in Figure 6. Here it can be observed that with the closed end flange blast experiments, a high frequency response is initially produced from the bouncing decaying blast wave, which is travelling up and down the length of the pipeline. After the blast wave has decayed sufficiently, the natural frequency response of the pipeline system is adopted. The long duration axial response of the open-end blast wave experiment transmitted to the pipeline supports gives a decaying damped sinusoidal displacement history.

Figure 7. shows a slightly out of phase axial displacement response of the two supporting pipeline supports from a detonation wave experiment within the initial high frequency response of the system. This is thought to be the result of the elastic dilatation wave travelling through the steel pipeline wall at its acoustic speed. This develops a slight amount of stretch within the pipe wall, which in turn creates an out of phase axial response between the two supports.

RKM MODELLING

RKM (Runge-Kutta Method) SDOF (Single degree of Freedom) and MDOF (Multiple – degree of freedom) numerical simulation codes are simple elastic-plastic models using tri-linear spring constants. This numerical simulation uses a RKM subroutine to integrate the ordinary differential equations of motion. Using the measured frame supported pipeline configuration spring constant, mass of the system and empirical damping coefficient, the simulation can produce usful values for the axial displacement of the supports.

The RKM SDOF numerical simulation displacement output, using the ignition end wall load history from the blast open-end experiment is plotted against its displacement response for stoichiometric oxygen –acetylene and are shown in Figure 8. It can be seen that the RKM SDOF simulation output is in good agreement with the actual displacement associated with this open-end flange experiment.

Presently, the MDOF simulation can handle dual end flange load histories for closed end flange experiments, but doesn't replicate the initial high frequency response due to the interaction of the pipeline to the fluctuating impulsive loads within. The MDOF code does however simulate the pipe wall stretch causing the out of phase displacement response.

DISCUSSION AND CONCLUSION

The present study represents, what is believed to be a unique series of measurements of the dynamic response of pipeline mechanical supports in a double cantilever frame set-up to transmitted internal impulsive loads. These studies also demonstrate the feasibility of conducting detailed time resolved measurements of the response of pipeline supports to transmitted impulsive loads.

The pipeline supports designed by Wilfred Baker Engineering Ltd. have successfully met their design criteria. These supports, although is a frame configuration, have kept within the elastic region whilst withstanding transient impulsive loads from shocks, detonations and blast wave propagation within the pipeline that they support.

Closed end pipeline experiments, which exhibit large recoil and reflection end flange pressures, develop a high frequency axial displacement response initially. This is due to the internal interaction of the impulsive loads travelling up and down the pipeline colliding with the two end flanges. After the blast or shock wave has sufficiently decayed, normal harmonic oscillations at the systems natural resonant frequency is resumed.

Open-end flange pipeline experiments can be modelled using an equivalent elastic-plastic RKM SDOF numerical simulation. Presently, the elastic-plastic RKM MDOF simulation can handle duel inputted end flange load histories, as for the case of the detonation experiments. This initially high frequency displacement response from the interaction of the fluctuating impulsive loads within the pipeline cannot be modelled presently, but the simulation is giving sensible numerical results for the out of phase displacement between the two supports due to pipeline stretch.

The transient Von Neumann pressure spikes associated with the detonation generated experiments, vary in magnitude due to deflagration to detonation transition, and do not have an observable effect on the displacement response of the pipeline supports. Only the longer duration of the detonation load history affects the magnitude of the axial displacement response of the supports.

In all of the experiments conducted, the pipeline supports did not exceed their linear elastic proportional limit. However, the importance of the characteristic load duration to the natural period of the structure must be considered. In the present study, the duration of the internal impulsive loads were short in comparison to the natural period of the double cantilever frame supported pipeline configuration used. It is possible however that more deformation, or even failure of the supports may have occurred if a less severe, but longer duration explosion had been used. More damage might result in this case, even through the peak pressure would have been less than that observed in this study.

The overall conclusion from this work presented, is that when considering the potential hazards from internal transmitted impulsive loads, not only pipelines must be sufficiently robust to withstand these loads, but also the pipeline supports to withstand potential failure if the pipeline doesn't fail.

FUTURE RESEARCH OPTIONS

Intended future research will consist of a detailed experimental program using a variety of pipeline and support configurations subjected to impulsive internal transient loads form shock, detonation and blast wave propagation within the pipeline. Configurations will include a single supported pipeline, double frame supported pipeline and a double frame supported pipeline including a bend configuration, to investigate the two dimensional response from the waves travelling around a 90° 1.5 radius pipeline bend. Instrumentation will include, in addition to that described above, accelerometers attached to the supports and end flanges, and strain gauges fitted to the supports and pipeline walls to measure the travelling wall flexural waves, generated by the gaseous waves within the pipe.

In addition to this above experimental program, to extend and complete the range of structural response histories of pipelines and support configurations, experiments using load durations that would vary from quasi-static to the impulsive regime should be conducted. A method, which could enable this, is to use a range of flame velocities to induce a lower pressure, but longer duration load to the structure in question, than that of an impulsive load. Using a method like the one described, it could be possible to tune the load duration to the natural period, to develop the maximum displacement response from the pipeline and support configuration used.

Additional future work will be conducted on developing the MDOF numerical simulation code. Using this simulation as a basis, a more complicated two-dimensional simulation will be created, which will solve the loading associated for a bend configuration and the transmitted loads to the supports.

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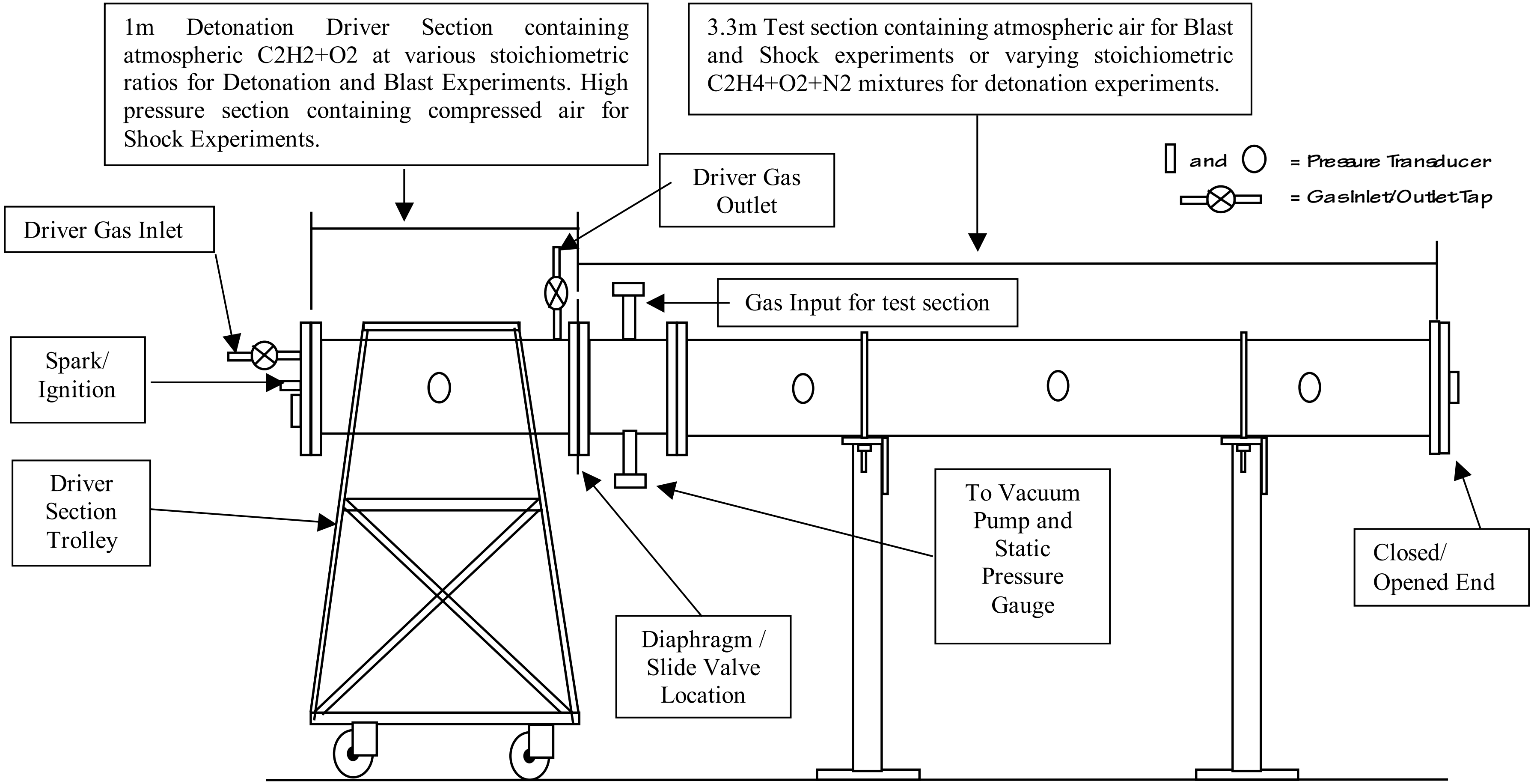

Figure 1. Schematic of pipeline layout showing supports and pipe instrumentation positions

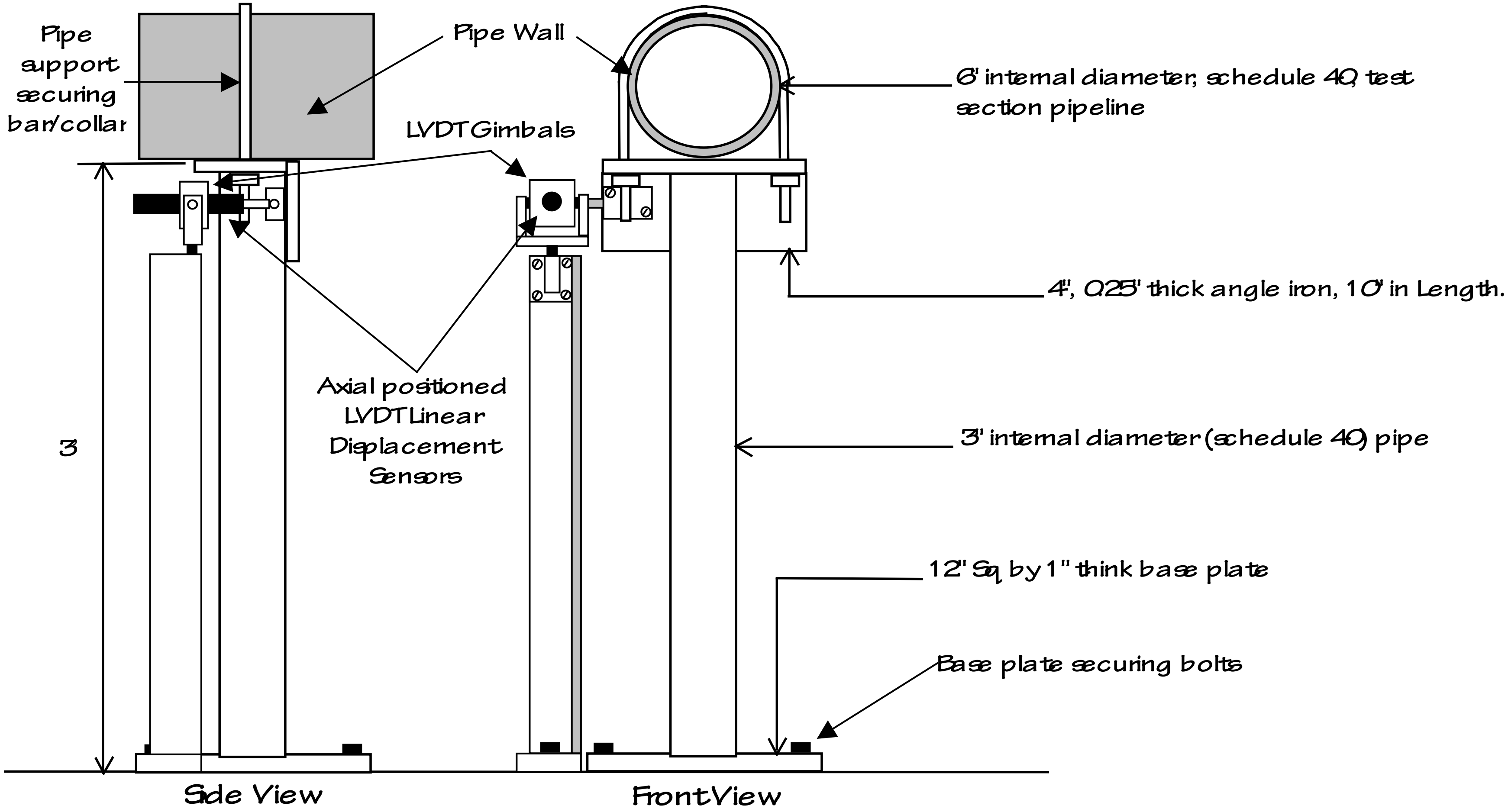

Figure 2. Schematic of supports and mounting arrangements for the (L.V.D.T.) linear displacement sensors.

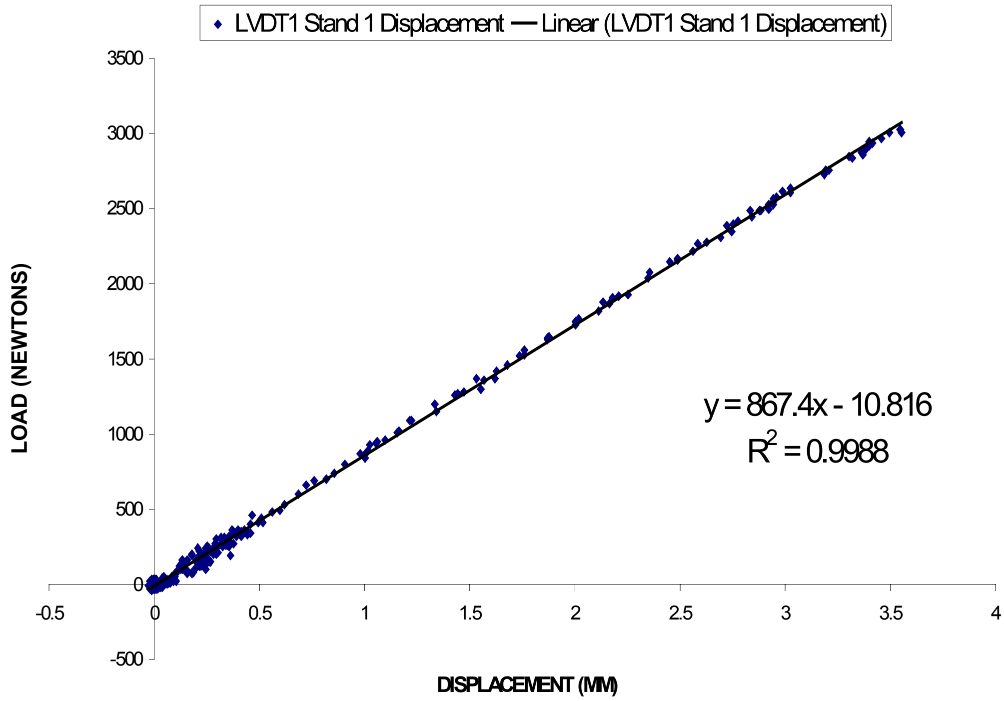

Figure 3. Axial spring constant of a single pipeline support.

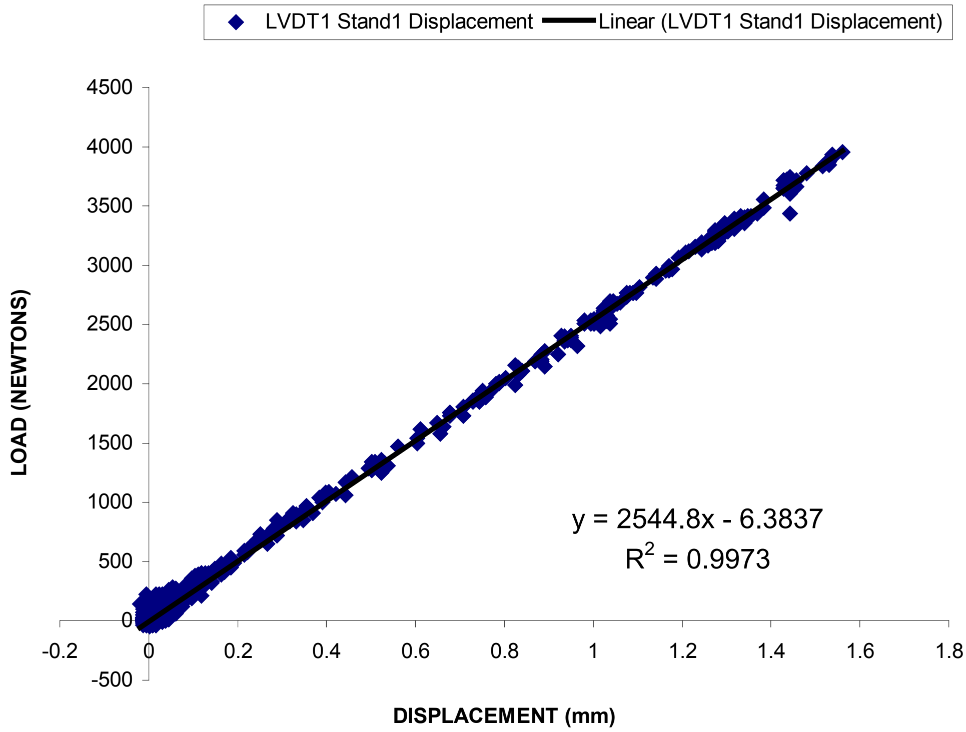

Figure 4. Axial spring constants of the frame supported pipeline system.

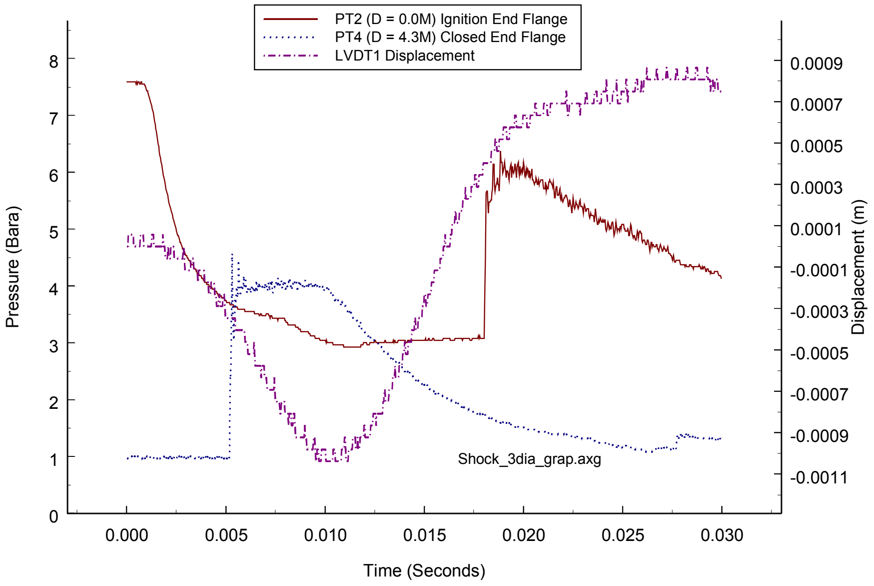

Figure 5(a). Typical shock wave experiment, showing the two end flange pressure histories and the short duration motion of the pipeline supports.

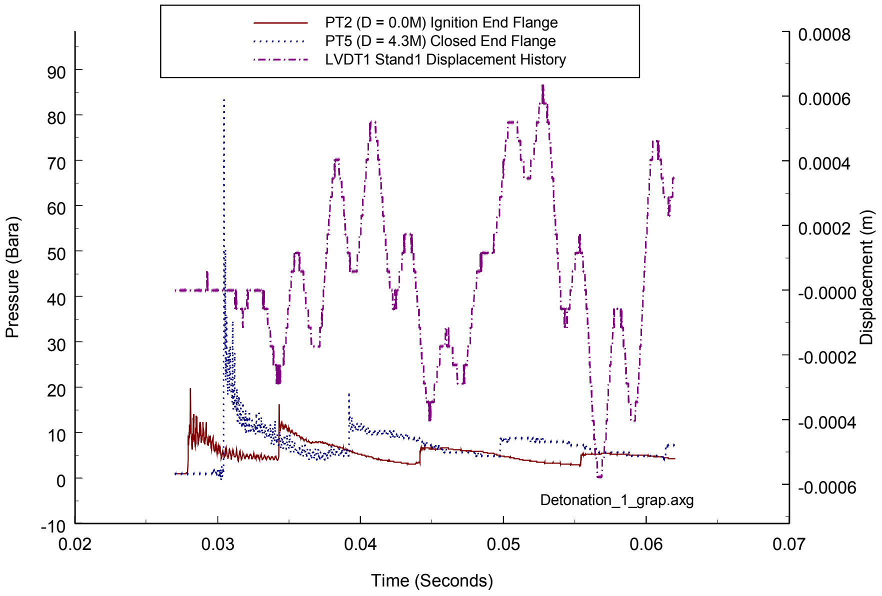

Figure 5(b). Typical detonation wave experiment, showing the two end flange pressure histories and the short duration motion of the pipeline supports.

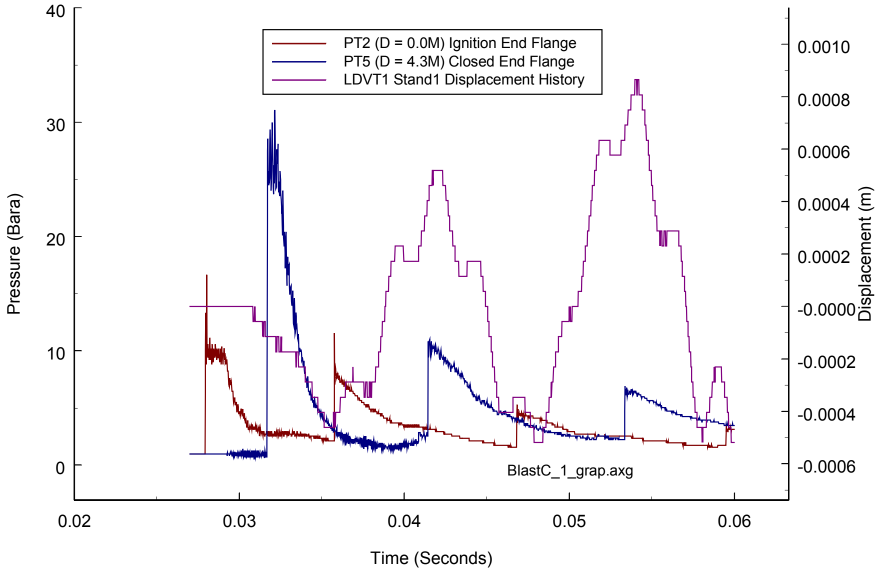

Figure 5(c). Typical closed end flange blast wave experiment, showing the two end flange pressure histories and the short duration motion of the pipeline supports.

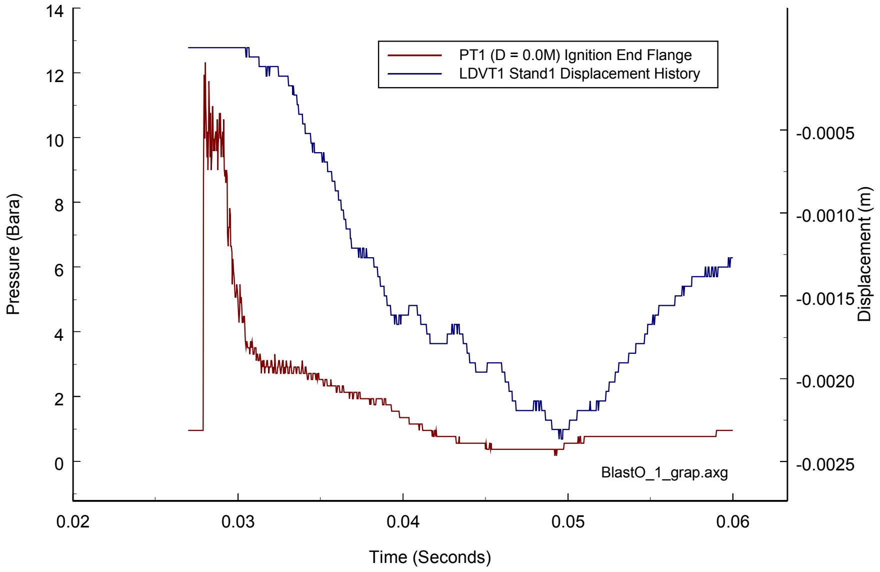

Figure 5(d). Typical open-end flange blast wave experiment, showing the two end flange pressure histories and the short duration motion of the pipeline supports.

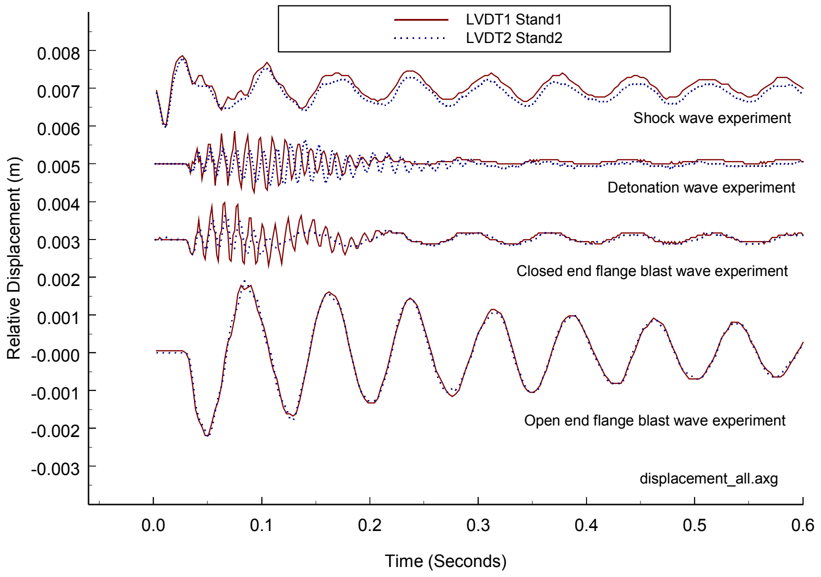

Figure 6. Comparison of the long duration support responses for the shock, detonation and blast wave experiments with both open and closed end flange configurations.

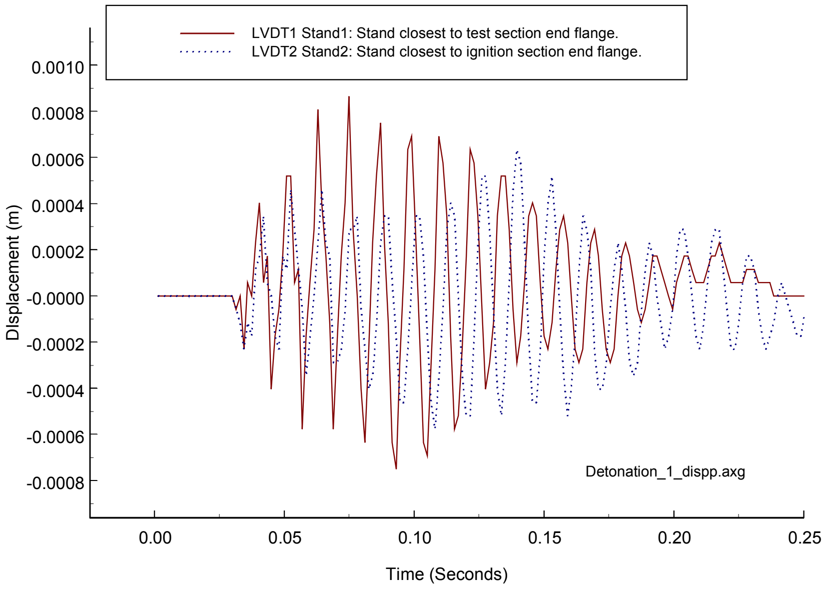

Figure 7. Comparison between axial displacement responses for the two pipeline supports subjected to a detonation experiment showing the out of phase response.

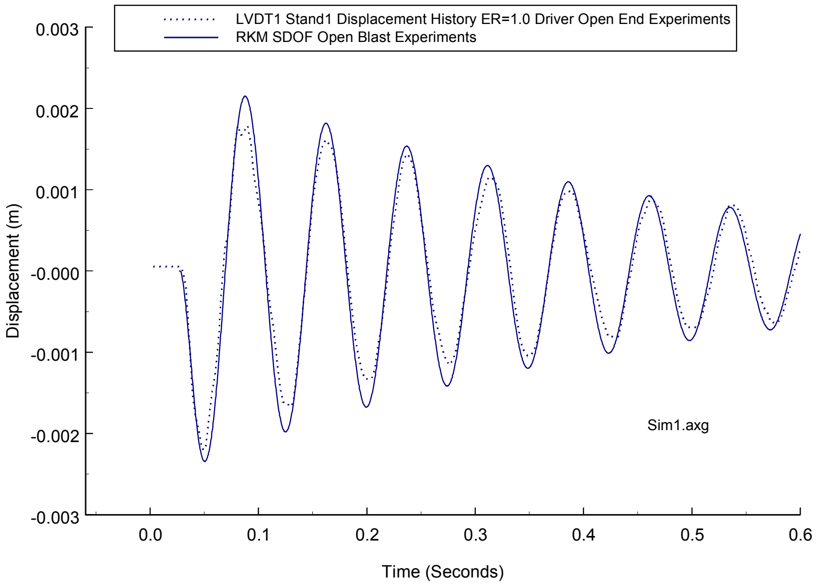

Figure 8. Comparison between RKM SDOF numerical simulation and the long duration response of the supports for an open-end blast wave experiment.