Offshore platform rigid riser span analysis and experimental studies

Ong, Yean Chau

2010

Ong, Y. C. (2010). Offshore platform rigid riser span analysis and experimental studies. Master's thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/41572>

<https://doi.org/10.32657/10356/41572>

**OFFSHORE PLATFORM RIGID RISER SPAN
ANALYSIS AND EXPERIMENTAL STUDIES**

ONG YEAN CHAU
SCHOOL OF CIVIL & ENVIRONMENTAL ENGINEERING
2010

OFFSHORE PLATFORM RIGID RISER SPAN ANALYSIS AND EXPERIMENTAL STUDIES

ONG YEAN CHAU

School of Civil & Environmental Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Master of Engineering

2010

ACKNOWLEDGEMENTS

The author would like to express his gratitude to the people mentioned below who had given much encouragement and assistance during the duration of this project, without which the author would not have seen this report to fruition.

Project Supervisor, Associate Professor Lie Seng Tjhen from the School of Civil and Environmental Engineering, Nanyang Technological University, for his guidance and review of this report.

External Project Supervisor, Dr Gho Wie Min from Marine Engineering Services Pte Ltd. The author is immensely grateful for his constant support, patience and invaluable knowledge rendered throughout every phase of this project.

Dr Waheed Khan and Mr James Goh, Directors of OGI Pte Ltd, Singapore, for their enthusiasm and unwavering support during the project.

Mr Christopher Bridge, Pipeline Engineering Manager of OGI Pte Ltd, Singapore and Mr V. Karunakaran, Senior Consultant of JPK Melbourne, who made time for many lunchtime project review sessions, during which they contributed valuable ideas drawn from their wide industry experience.

And finally, the author would like to thank his parents who have given unconditional support and encouragement throughout his life.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	i
TABLE OF CONTENTS	ii
LIST OF TABLES	v
LIST OF FIGURES	vii
SUMMARY	xi
CHAPTER 1 INTRODUCTION	1
1.1 BACKGROUND	1
1.2 OBJECTIVES	3
1.3 SCOPE OF STUDY	3
1.3.1 Considerations for Rigid Riser Span Design	4
CHAPTER 2 LITERATURE REVIEW	6
2.1 ALLOWABLE SPAN DESIGN	6
2.1.1 Pipeline Span	6
2.1.1.1 Allowable Static Span	7
2.1.1.2 Allowable Dynamic Span	7
2.1.1.3 Allowable Buckling Span	8
2.1.2 Riser Span	9
2.2 VORTEX INDUCED VIBRATION (VIV)	11
2.2.1 DNV Rules for Submarine Pipeline Systems (1981)	11
2.2.2 Analysis Based on DNV-RP-F105 (2003)	15
CHAPTER 3 SEABED PIPELINE AND RIGID RISER SPAN DESIGN	19
3.1 GENERAL	19
3.2 ANALYSES WITH DNV CODES FOR SEABED PIPELINES	21
3.2.1 Pipe Modal Damping Ratio	21

3.2.2	Consideration of Design Parameters	23
3.2.3	In-line Riser Span Vortex Induced Vibration	25
3.2.4	Concluding Remarks	25
3.3	DESIGN FOR SEABED PIPELINE AND RIGID RISER SPAN	25
CHAPTER 4	RESEARCH PROGRAM	29
4.1	OUTLINE OF RESEARCH PROGRAM	29
4.1.1	Experiments that Had Been Performed on Pipeline Vibrations	30
4.1.2	Previous Experimental Set-up	31
4.1.3	Proposed Experimental Set-up and Methodology	31
4.1.4	Instrumentation and Measurements	40
4.2	DETERMINATION OF PARAMETERS	41
4.2.1	Proposed Test Program	43
CHAPTER 5	PRESENTATION OF RESULTS	52
5.1	GENERAL	52
5.2	ANALYSIS OF RESULTS	53
5.2.1	Calculation for Root Mean Square Strain, $\epsilon_{R.M.S}$	54
5.2.2	Calculation for Acrylic Pipe Centre Deflection, Δ_{MAX}	54
5.2.3	Calculation for Reduced Velocity Parameter, V_R	55
5.3	PRESENTATION OF RESULTS	57
5.3.1	R.M.S Deflection/Diameter versus Reduced Velocity Graphs	57
5.3.1.1	<i>Experimental Results For 25mm Acrylic Pipe</i>	57
5.3.1.2	<i>Experimental Results For 40mm Acrylic Pipe</i>	59
5.3.2	Sensitivity Study on Boundary Condition Assumptions	61
CHAPTER 6	CONCLUSIONS	65
6.1	GENERAL	65
6.2	OBSERVATIONS AND RECOMMENDATIONS	65

6.2.1	Principal Observations	65
6.2.1.1	<i>Observation 1</i>	65
6.2.1.2	<i>Observation 2</i>	66
6.2.1.3	<i>Observation 3</i>	67
6.2.2	Limitations of Experimental Studies	68
6.2.2.1	<i>Limitation 1</i>	68
6.2.2.2	<i>Limitation 2</i>	69
6.2.2.3	<i>Limitation 3</i>	70
6.2.2.4	<i>Limitation 4</i>	70
6.2.3	Lessons Learnt and Recommendations for Improvements	71
6.2.3.1	<i>Lesson Learnt 1</i>	71
6.2.3.2	<i>Lesson Learnt 2</i>	71
6.2.3.3	<i>Lesson Learnt 3</i>	72
6.3	CONCLUSIONS	73
	REFERENCES	74
APPENDIX A	SAMPLE RESULTS FOR 25MM ACRYLIC PIPE	
APPENDIX B	SAMPLE RESULTS FOR 40MM ACRYLIC PIPE	
APPENDIX C	ALLOWABLE SPAN CALCULATIONS FOR 25MM ACRYLIC PIPE AND 40MM ACRYLIC PIPE	
APPENDIX D	PIPE SPAN SAMPLE CALCULATIONS FOR NORMALIZED DEFLECTION AND REDUCED VELOCITY	

LIST OF TABLES

	Page
Table 3-1	Pipe Parameters and Environmental Conditions 21
Table 3-2	Comparison of Boundary Conditions and Effect On Effective Span Length 24
Table 4-1	Pipe Parameter For Design and Environmental Conditions 41
Table 4-2	Natural Frequencies and Span Lengths For 25mm Diameter Acrylic Pipe With 1mm Wall Thickness Under Different Conditions 42
Table 4-3	Natural Frequencies and Span Lengths For 40mm Diameter Acrylic Pipe With 1mm Wall Thickness Under Different Conditions 43
Table 4-4	Pipe Span A - 25mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 3mm Plate Thickness and 3mm Damping Thickness 44
Table 4-5	Pipe Span B - 25mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 6mm Plate Thickness and 3mm Damping Thickness 44
Table 4-6	Pipe Span C - 25mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 9mm Plate Thickness and 3mm Damping Thickness 45
Table 4-7	Pipe Span D - 25mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 3mm Plate Thickness and 6mm Damping Thickness 45
Table 4-8	Pipe Span E - 25mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 6mm Plate Thickness and 6mm Damping Thickness 46
Table 4-9	Pipe Span F - 25mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 9mm Plate Thickness and 6mm Damping Thickness 47

Table 4-10	Pipe Span G - 40mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 3mm Plate Thickness and 3mm Damping Thickness	47
Table 4-11	Pipe Span H - 40mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 6mm Plate Thickness and 3mm Damping Thickness	48
Table 4-12	Pipe Span I - 40mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 9mm Plate Thickness and 3mm Damping Thickness	48
Table 4-13	Pipe Span J - 40mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 3mm Plate Thickness and 6mm Damping Thickness	49
Table 4-14	Pipe Span K - 40mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 6mm Plate Thickness and 6mm Damping Thickness	50
Table 4-15	Pipe Span L - 40mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 9mm Plate Thickness and 6mm Damping Thickness	50
Table 5-1	End Boundary Conditions Equations	62
Table 6-1	Trend Table For 25mm and 40mm Acrylic Pipes	68

LIST OF FIGURES

	Page
Figure 2.1 Pipeline Span On Seabed	7
Figure 2.2 Rigid Riser Attached To Platform Jacket	10
Figure 2.3 Onset of In-line Motion	14
Figure 2.4 In-line Motion Versus Stability Parameter	14
Figure 3.1 Stability Parameter Versus Modal Damping	23
Figure 3.2 Riser Span Length Versus Modal Damping	23
Figure 3.3 Typical Sketches Of Riser Fixed Clamps	26
Figure 3.4 Typical Sketch Of Riser Adjustable Clamp	27
Figure 3.5 Saipem Pipe Laybarge Castoro II Setting The Riser For Trans Thai Malaysia (TTM) Gas Pipeline Project, 2003	28
Figure 4.1 21m Flume In The Hydraulic Laboratory	32
Figure 4.2 Flume With Acrylic Sheet Laid Out To Create Even Base (Shows Granite Cubes Used To Hold The Sheet)	33
Figure 4.3 Sectional and Plan Views of Test Set-up	33
Figure 4.4 Wood Pieces Used To Simulate Varying Boundary Conditions For Acrylic Pipe	34
Figure 4.5 Experimental Set-up Before The Current Flume Was Flooded With Water	35
Figure 4.6 Acrylic Pipe With The Fixed-fixed End and Acrylic Panel To Prevent Boundary Interference	36
Figure 4.7 Elevation View Of Test Set-up	36
Figure 4.8 Gate At The End Of Current Flume	37
Figure 4.9 Location Of Strain Gauges On Acrylic Pipe Used In Test	37
Figure 4.10 Strain-meter With Wires For Connecting To Strain Gauges On Acrylic Pipe	38

Figure 4.11	Another View Of The Strain-meter	38
Figure 4.12	Acrylic Pipes With Strain Gauges Attached	39
Figure 4.13	View Of The Experimental Set-up Showing Acrylic Pipe and Strain Gauges	40
Figure 4.14	Instrumentation For Capturing Measurements From The Experiments	41
Figure 5.1	Dynamic Strain Plot For A 25mm Diameter Acrylic Pipe In Air	52
Figure 5.2	Dynamic Strain Plot For A 25mm Diameter Acrylic Pipe In Steady Current	53
Figure 5.3	In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 25mm Diameter Acrylic Pipe with 3mm Neoprene Thickness and 3mm End Plate Thickness	58
Figure 5.4	In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 25mm Diameter Acrylic Pipe with 3mm Neoprene Thickness and 6mm End Plate Thickness	58
Figure 5.5	In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 25mm Diameter Acrylic Pipe with 3mm Neoprene Thickness and 9mm End Plate Thickness	58
Figure 5.6	In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 25mm Diameter Acrylic Pipe with 6mm Neoprene Thickness and 3mm End Plate Thickness	58
Figure 5.7	In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 25mm Diameter Acrylic Pipe with 6mm Neoprene Thickness and 6mm End Plate Thickness	58
Figure 5.8	In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 25mm Diameter Acrylic Pipewith 6mm Neoprene Thickness	

	and 9mm End Plate Thickness	58
Figure 5.9	In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 40mm Diameter Acrylic Pipe with 3mm Neoprene Thickness and 3mm End Plate Thickness	60
Figure 5.10	In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 40mm Diameter Acrylic Pipe with 3mm Neoprene Thickness and 6mm End Plate Thickness	60
Figure 5.11	In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 40mm Diameter Acrylic Pipe with 3mm Neoprene Thickness and 9mm End Plate Thickness	60
Figure 5.12	In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 40mm Diameter Acrylic Pipe with 6mm Neoprene Thickness and 3mm End Plate Thickness	60
Figure 5.13	In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 40mm Diameter Acrylic Pipe with 6mm Neoprene Thickness and 6mm End Plate Thickness	60
Figure 5.14	In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 40mm Diameter Acrylic Pipe with 6mm Neoprene Thickness and 9mm End Plate Thickness	60
Figure 5.15	Sensitivity Study For Pipe Span B Considering Pinned-Pinned and Fixed-Fixed End Boundary Conditions	63
Figure 5.16	Sensitivity Study For Pipe Span H Considering Pinned-Pinned and Fixed-Fixed End Boundary Conditions	63
Figure 6.1	Comparison Of Experimental Results With Established Studies	66

Figure 6.2 Graph 4.1 From DNV-OS-F105, Free Spanning
Pipelines

72

SUMMARY

A rigid riser mechanically clamped to an offshore wellhead platform experiences vortex induced vibration due to actions of seawater waves and currents. If occurring at the natural frequency of free span, it will induce a large amplitude vibration that may lead to fatigue failure at the girth welds of pipe joints. To assess if the maximum riser span between the clamps is acceptable, the current practice is to determine based on the same methodology for analyzing the free span of submarine pipelines on the seabed. These methods for assessment have been well described in detail in the MULTISPAN project carried out by Norsk Agip and Statoil (Mørk, Vitali and Verley, 1997) and subsequently in Det Norske Veritas (DNV) standards, Guidelines No. 14 and DNV-RP-F105.

There are several shortcomings to determine the allowable free span of rigid risers based on that of submarine pipelines. These methods require pipeline parameters such as the pipe and seabed gap ratio, seabed roughness coefficient and damping effects, which are not applicable in the context for riser span design. Further, the boundary condition of the submarine pipeline free span is normally considered as pinned-fixed in the analysis.

From the experimental investigation performed in the current research, empirical equations have been derived to present the basis in order to properly evaluate the free spanning of a rigid riser. The results generated from the empirical equations are compared with those from the analysis of submarine pipeline to examine the differences for riser span application. The study also highlights the shortcomings of analyzing the rigid riser spans based on the commonly adopted methodologies for submarine pipeline design. A new design approach for free spanning risers, with reference to the available research for pipeline allowable span analysis and, with consideration of pipe geometrical properties and environmental loadings, is proposed. The comparison of the experimental findings with the existing formulations showed that the current methodology to determine the free spanning of submarine pipelines is not suitable for riser span design.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

There exist thousands of offshore installations around the world producing oil and gas through various means of structural and mechanical systems of well manifolds with pipeline transportation to host production facilities for processing. These offshore systems are known to operate in water depths of 2m to almost 3,000m and are subjected to combinations of environmental forces that include winds, waves, ice, tides, currents, mudslides and seismic activities in general. With exploration and production of oil and gas reserves in uncharted territories of harsher environments, offshore petroleum operations are now moving into new dimensions of challenges in the aspect of design and installation of platforms and transportation facilities.

To date, one of the key issues of offshore installations is the phenomenon of vortex induced vibrations (VIV) in structural riser and pipeline.

There are several possible failure modes for pipelines with free spanning. Once a free span initiates, the pipe span will act as a beam supported by the soil at both ends. If this span is sufficiently large, then the pipe would fail through material yielding. This is commonly known as static span failure due to the span's own weight and contents as well as hydrodynamic forces from waves and currents.

The pipeline with free span could also fail by vibration, and this is commonly known as dynamic span failure. This failure behavior involves the vibration mode of pipeline free span due to vortex shedding resulting from the movement of waves and currents. The action of currents and waves in the region of free spans of the offshore structures will generate vortices that cause the affected members to vibrate significantly. At resonance, the

span vibration in the direction of cross flow could have deformation amplitude of almost two times the pipe diameter. It is important to emphasize that even if there is no resonance, the vibration will result in an increase of stress concentration at pipe joints that lead to fatigue damage. Due to load repetitive action, the resulting cyclic stress will lead to microscopic physical damage to pipe and weld materials. This accumulated damage of material generally occurs at a stress level well below the pipe span strength and will eventually lead to crack initiation at girth welds after a number of load cycles. The crack grows under cyclic loading at the region of high stress concentration and gradually propagates until the pipe fractures.

It is therefore important to realize that if the arrest of these vibrations is not properly addressed during the design stage, the affected members could potentially be exposed to risk of fatigue failure and the consequent damage of supporting structures on platforms.

For a rigid riser that attaches to an offshore platform, it obviously experiences the phenomenon of VIV due to waves and currents acting on its free span between supports. The VIV, if occurring at the natural frequency of the riser span, will induce a large amplitude vibration that could lead to fatigue failure, particularly at the girth welds of the riser pipe joints. Currently, design analysis to determine the maximum rigid riser span between supports is commonly based on the methodologies for analyzing submarine pipelines on the seabed due to undulating topography.

There exist uncertainties in determining allowable spans of rigid risers on existing submarine pipeline design methodologies. These existing methods require the input of pipeline parameters such as the pipe and seabed gap ratio, seabed roughness coefficient and damping effects that may not necessarily be suitable for the design of rigid riser span. The boundary conditions for a seabed pipeline span are normally considered pinned-fixed. Such conditions would not be for the case of rigid risers where the supports on the platform are considered to have fixed-fixed support conditions.

Furthermore, the design criteria for a seabed pipeline span allow free vibration at certain conditions that are not necessarily suitable for rigid risers fixed with mechanical connector at supports. It is interesting to note that in submarine pipeline design, the in-line flow vibration at amplitude of almost 18% of pipe diameter may induce excessive stresses that would result in bolt or clamp plate failure at supports of rigid risers.

For the research of rigid riser spans carried out in this study, the application of submarine pipeline span analysis specified in the MULTISPAN Project (Mørk, Vitali and Verley, 1997) will be discussed, with a view towards an evaluation of suitably designed criteria for riser span analysis. The criteria for riser span analysis will be obtained from experimental works. Suitable empirical equations derived would form the basis for assessing rigid riser spans.

1.2 OBJECTIVES

The key objectives of the current research are to highlight the shortcomings of analyzing rigid riser spans based on the commonly adopted methodologies for submarine pipeline design. A newly designed approach, taking account of the effect of pipe geometrical properties and environmental loadings, will be included in the span analysis. From the experimental investigations, empirical equations will present the basis to evaluate rigid riser spans. Results from the empirical equations will be compared with those from submarine pipeline design to examine the differences for riser span application.

1.3 SCOPE OF STUDY

A rigid riser system consists of riser and expansion loop pipe, riser supports, integrated piping components and corrosion prevention system. An overview of recent developments in submarine pipeline span analysis was

presented. The shortcoming of adopting the submarine pipeline design procedures for analyzing the rigid riser span was examined.

A newly designed approach was also attempted to take into account effects of damping and boundary conditions on the natural frequency of a pipe under current-induced, in-line vortex induced vibration. These are pertinent to the situation of a rigid riser span. In actual practice, varying boundary conditions and damping conditions are witnessed in the application of a rigid riser. In this respect, the approach taken up in this research represented a novel proposition that should provide another perspective from those in previously conducted research.

1.3.1 Considerations for Rigid Riser Span Design

(i) Design criteria The current practice for design of rigid riser span is to reference the design criteria of submarine pipelines. There are currently two relevant criteria in submarine pipeline design with one on in-line vibration due to VIV which could likely be used for the design of rigid riser span. In submarine pipeline span analysis, the pipeline and the supporting structures are independently considered and therefore the interaction effect between the two structural components is not considered. However, for a rigid riser connected by means of mechanical clamps, the effect of in-line vibration transmitted via the riser to the members of the platform could be significant.

(ii) Global span analysis One of the major enhancements for submarine pipeline span analysis in recent years is the consideration of interacting effect between the spans of pipelines and the seabed (Mørk, Vitali and Verley, 1997). Prior to this development, the pipeline span was generally considered as a single entity between supports without considering the effect due to supports and adjacent spans. Such an approach for determining the free spanning of submarine pipeline has been deemed to be too conservative. Despite DNV Guidelines No. 14 (1998) and DNV-RP-F105 (2003) providing specific guidance for multi-span analysis of a submarine pipeline

on the seabed, there exists little information available for rigid riser span analysis.

(iii) Boundary condition For a submarine pipeline on the seabed, the boundary conditions of the free span are neither pinned nor fixed. Depending on the soil stiffness and settlement, the effective length factor of pipeline end fixity can be ranging from 1.57 to 3.56 for pinned and fixed support respectively. In current practice, the boundary conditions of a submarine pipeline span are commonly taken as pinned-fixed conditions with average effective length factor of 2.57. Several experimental works previously conducted were based on pipe models with pinned ends to yield conservative results for design. The end fixities of a pipeline in the design standards are mainly calculated using the beam theory. There is no verification with the experimental results in the aspect of pipeline vibrations. In the experimental studies conducted as part of the current research, fixed-fixed boundary conditions were simulated to represent the state at both ends of a rigid riser span, for structural analysis.

(iv) Structural damping effect The stability parameter of a pipeline is a function of pipe diameter, pipe effective mass, fluid density and total modal damping ratio. For a pipeline span on the seabed, the total modal damping comprises the individual effects of structural, soil and hydrodynamic damping ratio. However, for a rigid riser span, the damping effect of neoprene coating on the inner face of riser clamps should be included for vibration analysis. Furthermore, the soil damping should only be considered for the last section of riser on the seabed connecting the pipeline. In the experiments conducted for the current research, the effect of damping of a rigid riser in vortex shedding would be studied with consideration of stiffness of neoprene materials supporting the pipe model under investigation.

CHAPTER 2

LITERATURE REVIEW

2.1 ALLOWABLE SPAN DESIGN

2.1.1 Pipeline Span

The free spanning of a submarine pipeline occurs when it is no longer in contact with the seabed over a considerable distance due to uneven topography. This often occurs when the submarine pipeline is laid over an undulating topography during installation, such as in areas of hard rock outcrop or corals. However, this phenomenon is found less pronounced in soil formations of clay or sand layers as the pipeline settles over time because of its own weight and its contents. In years of service, the soil surrounding the pipeline may be subjected to scouring due to the effects of currents and wave pressure resulting in the development of free spanning. The occurrence of free spanning in this circumstance creates a pressure difference in the upstream and downstream under the flow of current, which causes the pipeline to vibrate. This behavior should be rectified in the analysis to ensure the structural integrity of the pipeline in operation.

In general, the unsupported free span will be analyzed as part of pipeline design based on simple beam theory. The unacceptable span found during installation or on-site inspection during service would have to be rectified to ensure the safe operation of pipeline throughout the years. The allowable free span of a pipeline is occasionally assessed based on water-filled and hydrostatic tests according to design requirements specified in the standards. An example of a submarine pipeline free span on the seabed is illustrated in Figure 2.1.

Figure 2.1 Pipeline Span On Seabed

In reality, several sections of pipelines could be suspended as free spans depending on sea floor irregularities. The excessive deformation of these spanning induces high stresses on the pipeline due to its self-weight and contents. The stress level can further be amplified due to severe vibration from vortex shedding. The following are the typical design requirements to determine the maximum pipeline allowable free span during installation, system hydro-test and in-place operating condition.

2.1.1.1 Allowable Static Span

The allowable static span is determined based on the criterion that the pipe stresses are within the allowable stress limit without excessive material yielding throughout the life span of pipeline in operation.

2.1.1.2 Allowable Dynamic Span

The allowable dynamic span is calculated to determine the maximum span to avoid vortex induced vibration (VIV) due to in-line flow of currents and waves in the region of pipeline spanning.

2.1.1.3 Allowable Buckling Span

The allowable buckling span is the maximum span within the restrained section of a pipeline as a result of axial compressive forces due to combined effects of design temperature and pressure.

There are several methods available to rectify the free spanning of submarine pipelines, and they include the use of pipe supports and grout bags, for example. These methods are generally costly because the works involve the operation of divers and remote operated vehicles to install. More important, the pipeline would have to be temporarily stopped in operation for rectification, which results in unnecessary revenue losses. Hence, it is a common practice in the industry to perform the rectification for free spans after the hydro-test of the pipelines.

As corrections of free spanning involve extensive and expensive work in operations, research and development projects have been performed frequently to intensively investigate the effect of pipelines' interactions with hydrodynamic forces. In particular, VIV affecting the dynamic performance of pipeline spans has recently been a popular research in pipeline engineering. However, despite extensive research in these areas, there still exist considerable amounts of uncertainties in pipeline span design to be clarified. These are further detailed in Chapter 3. The following is a summary of important research performed over the years in the areas of pipeline VIV:

- a. Full-scale laboratory tests of waves and current actions on cantilevered cylinders at Loughborough University in 1974.
- b. The S.V.S. Research Project conducted by Bruschi et al. (1989), which involved an extensive study of the dynamic behavior of free spanning pipelines when exposed to hydroelastic phenomena in various flow conditions.

- c. Bruschi, R., Curti, G., Marchesani, F. and Terselletti, E. (1993). The MASPUS Project: Methodologies for Adapting Submarine Pipelines to Very Uneven Seabeds.
- d. The design experience from the project conducted by Tura et al. (1994) formed a part of the premise for the DNV Guideline for free spanning pipelines and added to the body of knowledge to assist designers with design criteria and guidance on design methods for fatigue in free spans subjected to actions of waves and currents.
- e. The MULTISPAN Project, Design Guidelines for Free Spanning Pipelines, by Mørk et al. (1997).

2.1.2 Riser Span

A rigid riser mechanically clamped to an offshore platform experiences VIV due to the action of waves and currents. These VIV can sometimes be so large in amplitude that failure at the girth weld of pipe joints may occur due to fatigue. The large amplitude vibration occurs when the frequency of vortex shedding coincides with that of the riser span. Hence, there is need to limit the riser span such that its natural frequency is outside the frequency range of vortex shedding under the most extreme environmental conditions. This can be accomplished by adjusting the riser clamps and its accessories to ensure that the in-line VIV on the riser will not take place. An example of a riser free span on the offshore fixed platform can be seen in Figure 2.2.

Figure 2.2 Rigid Riser Attached To Platform Jacket

To determine the maximum allowable riser span between supports, the analyses are usually performed using the same methodology for analyzing submarine pipeline spans on the seabed.

The methodology for analysis of submarine pipeline spans on the seabed assumes that the mean current velocity acting at the middle of unsupported span is uniformly distributed. In the calculation to compute the natural frequency, the span-end conditions of a pipeline are normally considered partially fixed. However, for rigid risers, the allowable span to account for dynamic behavior is designed with reference to pipeline design codes such as DNV Rules for Submarine Pipeline Systems (1981), DNV Guidelines No. 14 (1998) and DNV-RP-F105 (2003). The criterion of “no motion” in the region of riser free spans is normally checked based on the following load cases.

- a. Installation Condition During installation, the riser span is determined based on the new pipe criterion with no internal content. The environmental forces considered are normal and assessment of VIV accounts for actions of currents and waves in the in-line direction.
- b. Hydro-test Condition During hydro-tests, the riser span is determined based on the new pipe criterion with seawater as internal contents. The environmental forces considered are similar to that for riser span design during installation.
- c. Operating Condition During pipeline operation, the riser span is determined based on the corroded pipe criterion filled with products. The extreme environmental design will be considered to prevent any possibility of in-line VIV due to actions of currents and waves.

2.2 VORTEX INDUCED VIBRATION (VIV)

The analytical work for allowable span design is generally performed according to the requirement of DNV Codes. The two most widely used design recommendations for allowable span design are DNV Rules for Submarine Pipeline Systems (1981) and DNV-RP-F105 (2003). The following section presents the methodology to assess the VIV of the submarine pipelines based on the Codes above-mentioned.

2.2.1 DNV Rules for Submarine Pipeline Systems (1981)

Analyses performed to assess the acceptable maximum span length without the risk of flow-induced cyclic loading are based on Appendix A of the DNV Rules for Submarine Pipeline Systems (1981). The natural frequency of the pipeline span is determined from the following relationship.

$$f_n = \frac{C}{2\pi L^2} \left(\frac{EI}{m_e} \right)^{1/2} \quad (1)$$

where,

C	=	Constant for span-end restraints (15.4 for pinned-fixed ends)
E	=	Modulus of elasticity
I	=	2 nd moment of area of pipe
L	=	Allowable span length
m _e	=	Effective mass of pipe

The following aspects are considered in the analysis of the natural frequency:

- a. Mass of pipeline and contents
- b. Hydrodynamics-added mass
- c. Pipeline stiffness
- d. End restraints
- e. Span length

Normally, no marine growth is considered for pipeline or riser span design. The flexural stiffness is determined from the geometrical properties of the pipeline. The contribution of weight coating to the pipe stiffness is not included.

The determination of critical response of pipeline free spans due to flow-induced cyclic loading is based on consideration of the natural frequency of pipeline span with that of vortex shedding induced by environmental loads. In the analysis, the mean reduced velocity (V_r) is generally considered in view of non-uniformly distributed current profile acting on the seabed pipeline. It can be defined as,

$$V_r = V/(f_n D) \quad (2)$$

where,

$$\begin{aligned} V &= \text{Current velocity} \\ f_n &= \text{Span natural frequency} \\ D &= \text{Pipe outside diameter} \end{aligned}$$

Further, the stability parameter (K_s) that shows the ability of pipelines to sustain a particular mode of vibration under environmental loads is also included in calculations. It can be defined as,

$$K_s = 2 m_e \delta / (\rho D^2) \quad (3)$$

where,

$$\begin{aligned} \delta &= \text{Logarithmic decrement of structural damping} \\ \rho &= \text{Density of seawater} \end{aligned}$$

The effective mass (m_e) is the total mass of pipeline and its content with added masses for vibration analysis. The logarithmic decrement of structural damping (δ) is taken from the established industrial practice that bases on site measurement data. With K_s known, the onset of in-line motion of pipeline can be obtained from the plot of V_r versus K_s , with respect to a “no motion” criterion as shown in Figure 2.3. The amplitude of VIV can then be estimated from the graph in Figure 2.4, which bases on Figure 2.3 for in-line motion.

Figure 2.3 Onset of In-line Motion

Figure 2.4 In-line Motion Versus Stability Parameter

2.2.2 Analysis Based on DNV-RP-F105 (2003)

In the current practice, the allowable span analysis for submarine pipelines and risers is commonly performed based on the requirements in DNV-RP-F105 (2003) to determine the maximum span length, and without considering the effect of in-line VIV. The key objective of the screening process in this recommendation is to assess the possible fatigue damage caused by VIV due to direct environmental forces of waves and currents. However, it is important to realize that the available information for maximum allowable span design based on criteria in DNV-RP-F105 (2003), without in-line VIV, will not be adequate for fatigue analysis of rigid riser span.

The allowable pipeline span in DNV-RP-F105 (2003) is determined based on the relationship of natural frequency (f_0) and length of free span as shown below.

$$f_0 = C_1 \sqrt{1 + CSF} \sqrt{\frac{EI}{m_e L_{eff}^4} \left(1 + C_2 \frac{S_{eff}}{P_E} + C_3 \left(\frac{\delta}{D} \right)^2 \right)} \quad (4)$$

where,

C_1, C_2, C_3	=	3.56, 0.25 and 0.4 respectively for single span on seabed
CSF	=	Stiffening effect of concrete
E	=	Young's modulus for steel
I	=	Moment of inertia for steel
m_e	=	Total structural and added mass per unit length
L_{eff}	=	Effective span
S_{eff}	=	Effective axial force
P_E	=	Euler buckling load, $P_E = \frac{\pi^2 EI}{L^2}$
δ	=	Static deflection
D	=	Pipe outer diameter
L	=	Allowable span length

Furthermore, to avoid amplification of natural frequency of pipeline span due to in-line VIV, the screening criteria in DNV-RP-F105 (2003) recommend that:

$$f_o > \frac{U_{c,100\text{year}}}{V_{R,onset}^{IL} \cdot D} \left(1 - \frac{L/D}{250} \right) \frac{\gamma_{IL}}{\alpha} \cdot \gamma_f \quad (5)$$

where,

$$\begin{aligned} \gamma_f &= \text{Safety factor on the natural frequency} \\ \gamma_{IL} &= \text{Screening factor for inline} \\ \alpha &= \text{Current flow ratio, } \max \left(\frac{U_{c,100\text{year}}}{U_{w,1\text{year}} + U_{c,100\text{year}}} ; 0.6 \right) \\ D &= \text{Pipe outer diameter including coating} \\ L &= \text{Free span length} \\ U_{c,100\text{year}} &= \text{100-year return period current velocity at pipe level} \\ U_{w,1\text{year}} &= \text{Significant 1-year return period wave-induced flow velocity at pipe level corresponding to annual significant wave height } H_{s,1\text{year}} \\ V_{R,onset}^{IL} &= \text{In-line onset reduced velocity} \end{aligned}$$

The boundary condition of pipeline span effective length is considered in the L_{eff} and L in equations (4) and (5), respectively. It is noted that L_{eff}/L decreases with increasing L/D and soil stiffness. The ratio L_{eff}/L is determined from the following equation:

$$\frac{L_{\text{eff}}}{L} = \begin{cases} \frac{4.73}{-0.066\beta^2 + 1.02\beta + 0.63} & \text{for } \beta \geq 2.7 \\ \frac{4.73}{0.036\beta^2 + 0.61\beta + 1.0} & \text{for } \beta < 2.7 \end{cases} \quad (6)$$

where,

$$\beta = \text{Relative soil parameter, } \log_{10} \left(\frac{KL^4}{(1 + CSF)EI} \right)$$

$$K = \text{Vertical and horizontal soil stiffness}$$

$$L, CSF, E, I \text{ have the same definitions as in equations (4) and (5)}$$

The maximum allowable span length of the pipeline can be computed based on the criteria in equation (5), with the parameters determined from equations (4) and (6). The stability parameter, K_s , representing the damping for a given modal shape of a single pipeline free span is expressed as follows:

$$K_s = \frac{4\pi m_e \zeta_T}{\rho_w D^2} \quad (7)$$

where,

$$m_e = \text{Effective mass}$$

$$\zeta_T = \text{Total modal damping ratio}$$

$$\rho_w = \text{Water density}$$

$$D = \text{Pipe outer diameter}$$

The induced reduced velocity due to in-line VIV is defined as,

$$V_{R, \text{onset}}^{\text{IL}} = \begin{cases} \left(\frac{1.0}{\gamma_{\text{on}}} \right) & \text{for } K_{sd} < 0.4 \\ \left(\frac{0.6 + K_{sd}}{\gamma_{\text{on}}} \right) & \text{for } 0.4 > K_{sd} < 1.6 \\ \left(\frac{2.2}{\gamma_{\text{on}}} \right) & \text{for } K_{sd} > 1.6 \end{cases} \quad (8)$$

where,

$$\gamma_{\text{on}} = \text{Safety factor for onset value}$$

$$K_{sd} = \frac{K_s}{\gamma_k}, \text{ Factored stability parameter}$$

$$\gamma_k = \text{Safety factor on stability parameter}$$

The effective axial force for a completely restrained pipeline is given as,

$$S_{\text{eff}} = H_{\text{eff}} - \Delta P_i A_i (1 - 2\nu) - A_s E \Delta T \alpha_e \quad (9)$$

where,

$$\begin{aligned} H_{\text{eff}} &= \text{Effective lay tension} \\ \Delta P_i &= \text{Internal pressure difference} \\ A_i &= \text{Internal cross-sectional area} \\ A_s &= \text{Pipe steel cross-sectional area} \\ \Delta T &= \text{Temperature difference} \\ \alpha_e &= \text{Temperature expansion coefficient} \\ \nu &= \text{Poisson's ratio} \end{aligned}$$

The added mass can be calculated based on the following equation:

$$AM = C_a \left(\frac{\pi}{4} D^2 \rho_w \right) \quad (10)$$

where,

$$\begin{aligned} C_a &= \text{Added mass coefficient} \\ D &= \text{Pipe outer diameter} \\ \rho_w &= \text{Seawater density} \end{aligned}$$

The added mass coefficient can be calculated by considering the following:

$$C_a = \begin{cases} 0.68 + \frac{1.6}{\left(1 + 5 \cdot \left(\frac{e}{D}\right)\right)} & \text{for } e/D < 0.8 \\ 1 & \text{for } e/D \geq 0.8 \end{cases} \quad (11)$$

where,

$$e/D = \text{Span gap ratio}$$

CHAPTER 3

SEABED PIPELINE AND RIGID RISER SPAN DESIGN

3.1 GENERAL

In this section, a comparative analysis of allowable span length of seabed pipelines and rigid risers is conducted based on the recommendations of DNV Codes, DNV-RP-F105 (2003) and its predecessor DNV Guidelines No. 14 (1998), with an objective to assess the suitability of existing guidance for computing the free spanning of rigid risers on offshore fixed steel platforms. It is important to note that the phenomenon of vortex induced vibration (VIV) causing the potential adverse effect on the strength integrity of risers should be carefully investigated and included for riser span design. The comparative analysis was also presented by Gho and Ong (2005).

The recommendations in DNV Codes are commonly used for design and analysis of seabed pipelines. The traditional approach for seabed pipeline span design is to utilize recommendations from DNV Rules for Submarine Pipeline Systems (1981) to determine the allowable length. These recommendations also include information for riser span design but the application is limited to a single span analysis.

On the contrary, DNV Guidelines No. 14 and DNV-RP-F105 recommendations provide information for seabed pipeline span design analysis based on multiple-spans. It should be noted that the requirements for span design in these two Codes are referenced from the work done in the MULTISPAN Project (Mørk, Vitali and Verley, 1997). One of the key objectives of this joint industry project was to develop appropriate guidelines for pipeline span analysis with reduced design parameters based on turbulent flow, as a result of VIV due to steady current flows. However, provisions for rigid riser span design are not included in these Codes.

DNV Guidelines No. 14 (1998) and DNV-RP-F105 (2003) may not be ideal for riser span design owing to the assumption that the pipelines are on the seabed. A riser is vertically attached on the platform by means of mechanical clamps with one end connected to the topside while the other joining the pipeline on the seabed. The free span of risers in the water is also subjected to VIV, which is similar to that of seabed pipelines but of different magnitudes. However, to determine the allowable length of riser spans during design, designers have referenced the requirements for seabed pipelines in DNV Codes. It is well known that the methodology for seabed pipeline span should not be adopted for rigid riser span design. The reasons are that the boundary condition considered for multiple-span pipelines is different from that for rigid riser span analysis. Further, the equivalent pipe and seabed gap ratio and the seabed roughness coefficient are not suitable as input for rigid riser span calculations. The damping effect at supports of free spanning for seabed pipelines and risers are also not identical.

In view of various design parameters considered in the calculations, the analysis undertaken in this chapter would present results of allowable length of free spanning for seabed pipelines and rigid risers based on the three DNV Codes previously discussed. It has been demonstrated that for a seabed pipeline, a discernible variation of allowable span length and current velocity occurs depending on the parameters considered in the codes. However, this trend of variation should not be observed in the calculation of riser free span. The implication from the analysis revealed that the application of DNV Codes for design of pipeline span length to rigid riser span analyses, is not suitable. The generated results based on DNV Codes suggested that fatigue failure at pipe joints of risers would occur.

3.2 ANALYSES WITH DNV CODES FOR SEABED PIPELINES

To provide insights into the design of allowable rigid riser spans, a 273.1mm (10-in) nominal diameter pipe is considered and assessed under operating conditions, with pipe parameters and environmental conditions as shown in Table 3-1. The in-line vortex induced vibration (VIV) analyses for rigid riser spans were carried out at current-dominated regions with flow velocity ratio greater than 0.8.

Table 3-1 Pipe Parameters And Environmental Conditions

Parameter/ Condition	Property
Pipe Diameter	273.1mm
Pipe Wall Thickness	25.4mm
Corrosion Allowance	12.7mm
Corrosion Coating Thickness	12.0mm
Corrosion Coating Density	1430kg/m ³
Internal Contents Density	85kg/m ³
Steel Density	7850kg/m ³
Seawater Density	1025kg/m ³
Wave Height	15.2m
Wave Period	12.0s
Current Velocity at 5m above Seabed	0.8m/s

3.2.1 Pipe Modal Damping Ratio

The stability parameter to consider the effect of damping at supports for a given modal shape of pipeline is a function of effective mass, seawater density, pipe outer diameter and total modal damping ratio of system. In DNV-RP-F105 (2003), the stability parameter is given as:

$$K_s = \frac{4\pi m_e \zeta_T}{\rho_w D^2} \quad (12)$$

where,

m_e	=	Pipeline effective mass
ξ_T	=	Total damping ratio
ρ	=	Seawater density
D	=	Pipe outer diameter

For seabed pipeline spans, the total damping ratio of the system (ζ_T) comprising the hydrodynamic, structural and soil damping, is considered in the analysis. This is to take account of the effect of soil and pipe interaction at supports. The calculated stability parameter of pipeline spans that indicates the onset of reduced velocity is determined with no in-line VIV motion.

On the other hand, for rigid riser spans, the damping effect due to soil and pipe interaction at supports is also applied. However, as the riser is supported by means of mechanical clamps with layers of neoprene or ethylene propylene diene monomer (EPDM) to overcome vibration, the damping effect will not be identical to that of seabed pipelines. If an assumption of no damping is taken, despite the use of neoprene or EPDM, then the calculated span length for riser design would be very conservative. In reality, the layer of coating at supports of the riser imposes certain degree of damping on the system that could be substantial. As seen from Figure 3.1, despite a linear relationship between the pipe stability parameter and the modal damping ratio, there is no sign of linearity relating the resulting span length and the modal damping ratio of the riser, as illustrated by Figure 3.2, and with values greater than 12m and 0.025 respectively.

Figure 3.1 Stability Parameter Versus Modal Damping

Figure 3.2 Riser Span Length Versus Modal Damping

3.2.2 Consideration of Design Parameters

The effect of boundary conditions on pipeline span analysis is an important aspect to determine the allowable span length for design. To properly simulate the boundary condition of a pipeline on the seabed, several parameters that include the boundary coefficients, soil parameter (β) and effective to actual span length ratio (L_{eff}/L) are considered. However, some of these parameters in the analysis are based on engineering judgment. For the seabed pipeline span analysis, the boundary condition parameters depend on the soil properties and classification.

For the rigid riser span analysis, there is no guideline currently available in the codes and recommendations to determine the allowable span length. In particular, the soil parameter (β) that determines the effective to actual span length ratio is not readily available at all in the analyses for riser allowable span length.

The soil parameter (β) is a function of soil stiffness, span length, pipe properties and concrete stiffness. For rigid riser span design, it is recommended that the soil stiffness be replaced with equivalent stiffness of mechanical clamp materials. However, if the soil parameter is not included, the effective span length of the riser can be taken as the actual span length between supports. This approach of analysis in general yields conservative results for design. To highlight the impact of soil parameters on rigid riser span lengths, a detailed analysis was performed for study, with results presented in Table 3-2. The comparison of results showed that the effective span lengths of the pipeline are sensitive to the boundary conditions at supports. This impact is also considered important for rigid riser span design but the vertical dynamic stiffness of neoprene or EPDM at supports has to be accurately determined.

Table 3-2 Comparison of Boundary Conditions and Effect On Effective Span Length

Boundary Description	Vertical Dynamic Stiffness (MPa)	Soil Parameter, β	Effective Span Length Ratio
Loose Sand	10.9	3.79	1.33
Dense Sand	21.7	4.09	1.28
Very Soft Clay	0.8	2.67	1.64
Very Hard Clay	16.3	3.97	1.30

3.2.3 In-line Riser Span Vortex Induced Vibration

In the event that the riser span is allowed to vibrate, as a result of inaccurate assessment after fatigue analysis has been performed, the significant impact of the vibration on the mechanical clamps should not be underestimated. Based on the recommendations in DNV-RP-F105 (2003), the maximum in-line VIV response amplitude of the pipeline can occur at almost 18% of pipe diameter. In such circumstance, the mechanical clamps of the riser will have to be designed to resist stresses from hydrodynamic forces as well as local deflections at supports. The deflection at mid-span of the riser as a result of in-line VIV creates additional stresses that are normally not included for mechanical clamp design. If a 10m span riser with partial support at both ends is considered, the resultant force on the mechanical clamp could then be as high as 20% of the lateral forces due to hydrodynamic load and support deformation. This additional lateral force must be considered in the mechanical clamp design to prevent any damage of its structural components.

3.2.4 Concluding Remarks

From the preceding discussion, there is merit for developing a separate set of criteria to define the parameters for design such as the modal damping ratio and the boundary conditions in order to better predict the free spanning of rigid risers. Furthermore, the lateral forces due to VIV should also be considered in the design of mechanical clamps to support the riser.

3.3 DESIGN FOR SEABED PIPELINE AND RIGID RISER SPAN

The allowable span length to prevent possible fatigue damage due to VIV is an important criterion for rigid riser design. An inaccurate or unrealistic analysis will lead to an incorrect design approach that may cause unnecessary loss in time and cost. In design, if the allowable span criteria

are not met, the mechanical clamp will have to specifically designed to ensure the riser is securely fixed in position. A typical riser fixed clamp for a 254mm nominal diameter riser weighs about 100kg and is illustrated in Figure 3.3.

Figure 3.3 Typical Sketches Of Riser Fixed Clamps

The connectors supporting the riser from lateral movement are tightly clamped onto the braces of the offshore jacket. Hence, if the riser span did not meet the allowable span criteria, the distance between the support clamps will have to adjust. In this case, adjustable clamps, as illustrated in Figure 3.4, might have to be used to support the riser. A typical adjustable clamp for a 254mm nominal diameter riser weighs about 1,000 kg. However, the material cost can be ten times more than that of fixed riser clamps.

Figure 3.4 Typical Sketch Of Riser Adjustable Clamp

Further, owing to the weight and size of mechanical clamps, professional divers may need to be deployed to fix the riser on-site during installation phase. Specific instructions are also required for pipelay barge to install the riser with adjustable clamps. A typical example showing the difficulty of installing a riser onto a jacket platform is illustrated in Figure 3.5.

Figure 3.5 Saipem Pipe Laybarge Castoro II Setting The Riser For Trans Thai Malaysia (TTM) Gas Pipeline Project, 2003

Apart from cost savings from riser installation and material, a proper design procedure is essential to minimize the risk of fatigue failure of riser pipe due to VIV. It is important to note that a severe vibration due to in-line and cross flow VIV can occur at 18% and 2 times of the riser pipe diameter respectively.

CHAPTER 4

RESEARCH PROGRAM

4.1 OUTLINE OF RESEARCH PROGRAM

As reported in Chapter 3, the dearth of guidelines available for rigid riser span analysis motivated the research in this study. The codes and recommendations that exist currently are biased towards conditions of seabed pipelines and are, in a strict sense, not completely applicable for rigid riser span design. Research projects like the MULTISPAN Project (Mørk, Vitali and Verley, 1997) and work done by Tura et al. (1994), from which guidelines were derived to counsel the design of free span, had considered conditions reminiscent of seabed pipelines instead of rigid risers.

The experimental procedures and analytical work put forward in this chapter are unique in that they had been conceived with a custom view for rigid risers. Suitable experimental works were performed to investigate the effects of damping and boundary conditions on the natural frequency of the pipeline under current-induced in-line vortex induced vibration (VIV). These proposed experimental conditions are pertinent to the situation of a rigid riser span. The theoretical concept behind the experimental works is premised on the seabed pipeline span analysis as detailed in recent works in DNV Rules for Submarine Pipeline Systems (1981).

The objectives of the experimental works were to research the adequacy of model tests using acrylic pipe in free flow conditions to induce in-line vortex shedding vibrations and to compare the results from the experimental works carried out against outcomes derived based on current pipeline codes and standards. The experimental results would be examined alongside formulations proposed by the well-respected industry code, DNV Rules for Submarine Pipeline Systems (1981). Any discrepancies between the experimental and the theoretical works would be discussed in Chapter 6.

In addition, the research program conducted in this study aimed to determine if new criteria could be proposed to eliminate unnecessary conservatism in the design of riser clamps to limit the allowable span due to VIV, and thereby achieve cost savings, which is one of the central themes in practical operations.

4.1.1 Experiments that Had Been Performed on Pipeline Vibrations

To better understand the effects of vibration in pipelines, several development projects, mainly funded by oil and gas exploration companies, had been carried out through the years. Laboratory and full-scale tests had been done at Loughborough University to study the effects of VIV on cantilevered cylinders (King, 1974). In 1993, JP Kenny Corporation, together with Hydraulic Research Ltd, conducted full-scale tests on pipelines to quantify the effects of pipe clearance of the seabed, pipe roughness and flow velocity on VIV. In more recent times, the MULTISPAN Project (Mørk, Vitali and Verley, 1997), performed through the collaborative efforts of the Danish Hydraulic Institute, Statoil, Snamprogetti and SINTEF Civil and Environmental Engineering, formed the basis for the widely used pipeline spanning codes in the industry, DNV Guidelines No. 14 (1998) and DNV-RP-F105 (2003).

Despite the above-mentioned experimental efforts, very little guidance had been proposed for determining the allowable span for a rigid riser attached to the platform jacket. Even available research for pipeline spans provided results that are contradictory to one another. The lack of guidelines for application of the pipeline span analysis did little to discourage pipeline and riser designers to apply the design guidelines to rigid riser span analyses. This resulted in unnecessary conservatism in the design of the riser clamps to limit the allowable span due to vortex induced vibration.

4.1.2 Previous Experimental Set-up

The work performed in this research program was heavily skewed towards experimental studies. Hence, previous experimental set-up are discussed here as comparison. Prior to the MULTISPAN Project (Mørk, Vitali and Verley, 1997), in-line VIV had been mainly investigated using vertical cylinders, both in on-site experiments and also in laboratory experiments. However, it has been well documented that current flows about a vertical cylinder differ significantly from that of a free pipeline span and vibrations are mainly prevalent in hydrodynamic loading than in vortex shedding.

The MULTISPAN Project attempted to overcome these limitations by carrying out experiments where steady current is passed over a horizontal pipe. The experimental set-up consisted of a rigid aluminum pipe segment suspended over a current flume via two vertical arms that could rotate about a hinge. It was assumed that the pendulum movement of the pipe section mirrored the horizontal translation of a vibrating pipe due to the magnitude of the movement and the length of the suspension arm. A spring system provided the restoring force for the movement and the pipe was provided with sand roughness to achieve the required turbulence. There were also special arrangements made to minimize the flow disturbance at the hinge ends.

For the MULTISPAN Project, factors investigated included the vortex shedding region for the reduced velocity for a current-dominated seabed, the influence of incident flow angle, and flow gradient. The research results were utilized for the design code, DNV-RP-F105 (2003).

4.1.3 Proposed Experimental Set-up and Methodology

The experimental works were conducted in the Hydraulic Laboratory of the School of Civil and Environmental Engineering, Nanyang Technological University. The experimental set-up includes the following items:

- a. Use of acrylic pipe instead of metallic pipe to provide a greater reduced velocity range for vortex induced vibration.
- b. Use of varying thicknesses for pipe ends to study the impact of pipe boundary conditions on the onset of vortex induced vibrations.
- c. Use of strain gauges in the acrylic pipe to accurately measure vibrations induced by current flow.

A current flume of length, 21m, is used. The flume consists of a 2-stepped bottom base as shown in Figure 4.1. The difference in depth at the bottom is not anticipated to cause any variation to the results as a layer of acrylic material is laid across the bottom to create a base of even level. Granite cubes are used to hold the acrylic sheet at the bottom of the flume in position. This is shown in Figure 4.2.

Figure 4.1 21m Flume In The Hydraulic Laboratory

Figure 4.2 Flume With Acrylic Sheet Laid Out To Create Even Base (Shows Granite Cubes Used To Hold The Sheet)

An acrylic pipe is suspended in the current flume with two vertical arms. The ends of the vertical arms attached to the acrylic pipe were fabricated such that different boundary conditions could be represented in the experimental works. The sectional and the plan views of the test set-up are shown in Figure 4.3.

Figure 4.3 Sectional and Plan Views of Test Set-up

The ends of the vertical arm, which held onto the acrylic pipe, are pieces of wood, as shown in Figure 4.4. Each of the wood pieces was 1mm thick. By

using different number of wood pieces, the thickness of the ends of the acrylic pipe could be changed. For example, for a 3mm fixed-end, 3 pieces of wood would be put together. This was a simple method to simulate different pipe boundary conditions for the pipe ends.

Figure 4.4 Wood Pieces Used To Simulate Varying Boundary Conditions For Acrylic Pipe

Figure 4.5 shows the experimental set-up before the current flume was flooded with water. Measurements were made using a needle ruler at five points across the flume to confirm that the acrylic pipe was leveled across the flume set-up. This was done to ensure that the current velocity that the pipe would be exposed to is as constant as possible across the experimental set-up.

Figure 4.5 Experimental Set-up Before The Current Flume Was Flooded With Water

The ends of the pipe, held in a fixed-fixed end boundary condition by the vertical arms, were covered by pieces of transparent paper to prevent any turbulent effects across the boundary ends. Any 3-dimensional flow around the pipe boundary ends would affect the experimental results. An acrylic panel, as shown in Figure 4.6, was installed at each end of the pipe boundary to minimize the flow disturbance. The gap between the acrylic pipeline model and the flume bed would be sufficiently large to ensure that there would be no effect on the acrylic pipeline. An elevation view of the experimental set-up is provided in Figure 4.7.

Figure 4.6 Acrylic Pipe With The Fixed-fixed End and Acrylic Panel To Prevent Boundary Interference

Figure 4.7 Elevation View Of Test Set-up

The “gate” at the end of the current flume, as shown in Figure 4.8, controlled the amount of water that flowed out of the flume and in turn controlled the velocity of the current across the acrylic pipe. Throughout the experiments, the position of the gate determined the current velocity and it was not possible to get specifically desired current velocities for each set of conditions in the experiments.

Figure 4.8 Gate At The End Of Current Flume

Strain gauges were used to measure the strain experienced in the acrylic pipe during vortex induced vibration. With the vibrating pipe exhibiting vortex induced vibration, dynamic strain measurement would be performed. The strain gauges were positioned at the two ends and at the centre of the pipe as shown in Figure 4.9.

Figure 4.9 Location Of Strain Gauges On Acrylic Pipe Used In Test

The readings captured by the strain gauges, and reflecting the strain experienced by the acrylic pipe, were measured using a strain-meter shown in Figure 4.10 and Figure 4.11. The readings were extremely sensitive. The

strain gauges on the acrylic pipe were connected back to the strain-meter via wires. Figure 4.12 shows acrylic pipes with strain gauges attached, ready for testing.

Figure 4.10 Strain-meter With Wires For Connecting To Strain Gauges On Acrylic Pipe

Figure 4.11 Another View Of The Strain-meter

Figure 4.12 Acrylic Pipes With Strain Gauges Attached

When the strain gauge achieved a reading of 20 or below, as depicted by the strain-meter, it would be assessed that the strain gauge was able to record measurements stably. A layer of waterproofing epoxy would then be applied onto the strain gauge so that they could be used underwater. This process was difficult as the strain gauges used for measuring strain for acrylic material are extremely sensitive.

An illustration of the actual experiment set-up is shown in Figure 4.13.

Figure 4.13 View Of The Experimental Set-up Showing Acrylic Pipe and Strain Gauges

4.1.4 Instrumentation and Measurements

The instrumentation used for the experimental works involved the following apparatus:

- a. One electromagnetic current meter to measure the mean current velocities in the horizontal direction.
- b. One dynamic strain-meter with analog data and recorder to measure the dynamic strain that varied with time.

For the calibration of the current flume, the current velocity will be measured across the cross-section at different depths prior to the various sets of test so that information on flow uniformity could be obtained. During testing, the electromagnetic current meter will be installed in an upstream location with respect to the acrylic pipe for the measurement of reference flow velocities. Figure 4.14 shows a picture of the instrumentation used for capturing the measurements from the experiments.

Figure 4.14 Instrumentation For Capturing Measurements From The Experiments

4.2 DETERMINATION OF PARAMETERS

To provide initial estimates of the parameters required for the experimental works and also to act as a source of comparison with the results from the experimental works in later stages, calculations were manually performed. These calculations were carried out in accordance with the design codes, DNV Rules for Submarine Pipeline Systems (1981) and DNV-RP-F105 (2003).

The design parameters, based on vendor-provided data for apparatus used in the experimental works, were utilized in the calculations to provide accurate analyses. The design data used in the analysis are listed in Table 4-1.

Table 4-1 Pipe Parameter For Design and Environmental Conditions

Parameters/ Conditions	Property	
Pipe Diameter	40mm	25mm
Pipe Wall Thickness	1.0mm	1.0mm
Corrosion Allowance	0mm	0mm

Parameters/ Conditions	Property	
Internal Contents Density	1000kg/m ³	1000kg/m ³
Acrylic Density	1100kg/m ³	1100kg/m ³
Fluid Density	1000kg/m ³	1000kg/m ³
Current Velocity	0.5m/s –1.1m/s	0.4m/s –1.0m/s

Based on the above information, the span lengths at which in-line vortex induced vibration would occur were obtained for both a 25mm diameter acrylic pipe and a 40mm diameter acrylic pipe. The detailed calculations are attached in Appendix C for reference. The results for the pipeline span analyses are as presented in Table 4-2 and Table 4-3. These calculation results would serve as a source of comparison against the experimental results.

Table 4-2 Natural Frequencies and Span Lengths For 25mm Diameter Acrylic Pipe With 1mm Wall Thickness Under Different Conditions

No.	Current Velocity (m/s)	Boundary Condition	DNV-RP-F105		DNV 1981	
			Natural Frequency (Hz)	Span Length (m)	Natural Frequency (Hz)	Span Length (m)
1	0.1	Pinned – Fixed	4.62	1.29	2.752	1.67
2	0.1	Fixed – Fixed	4.32	1.61	2.752	2.02
3	0.2	Pinned – Fixed	10.00	0.88	5.505	1.18
4	0.2	Fixed – Fixed	9.63	1.08	5.505	1.43
5	0.3	Pinned – Fixed	15.49	0.71	8.257	0.97
6	0.3	Fixed – Fixed	15.05	0.86	8.257	1.16
7	0.4	Pinned – Fixed	21.02	0.61	11.009	0.84
8	0.4	Fixed – Fixed	20.53	0.74	11.009	1.01

Table 4-3 Natural Frequencies and Span Lengths For 40mm Diameter Acrylic Pipe With 1mm Wall Thickness Under Different Conditions

No.	Current Velocity (m/s)	Boundary Condition	DNV-RP-F105		DNV 1981	
			Natural Frequency (Hz)	Span Length (m)	Natural Frequency (Hz)	Span Length (m)
1	0.5	Pinned - Fixed	16.78	0.77	8.601	1.08
2	0.5	Fixed - Fixed	16.48	0.94	8.601	1.30
3	0.7	Pinned - Fixed	23.81	0.65	12.041	0.91
4	0.7	Fixed - Fixed	23.46	0.79	12.041	1.10
5	0.9	Pinned - Fixed	30.87	0.57	15.482	0.80
6	0.9	Fixed - Fixed	30.47	0.69	15.482	0.97
7	1.1	Pinned - Fixed	37.95	0.51	18.922	0.73
8	1.1	Fixed - Fixed	37.52	0.62	18.922	0.88

4.2.1 Proposed Test Program

The test program established for the experimental works to be performed would involve the determination of the effects of damping and boundary conditions on the vortex induced vibration of the pipe. The different boundary conditions would be simulated by testing the pipe model with the ends being held by plates of varying thickness. The effect of damping would be tested using different thickness of neoprene layers between the acrylic pipe and the plates holding onto the pipe. The test program would be carried out in two phases where the diameter of the pipe test specimen and the flume channel current velocity would be varied. The following tables summarize the two phases for the test program that was to be performed. The experimental investigation was further published by Ong and Gho (2007).

Table 4-4 Pipe Span A - 25mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 3mm Plate Thickness and 3mm Damping Thickness

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP1	001	TP1-001-1	Pinned-Pinned	3mm each side	3	0.06
TP1	001	TP1-001-2	Pinned-Pinned	3mm each side	3	0.09
TP1	001	TP1-001-3	Pinned-Pinned	3mm each side	3	0.12
TP1	001	TP1-001-4	Pinned-Pinned	3mm each side	3	0.15
TP1	001	TP1-001-5	Pinned-Pinned	3mm each side	3	0.18
TP1	001	TP1-001-6	Pinned-Pinned	3mm each side	3	0.21

Table 4-5 Pipes Span B - 25mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 6mm Plate Thickness and 3mm Damping Thickness

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP1	002	TP1-002-1	Pinned-Pinned	6mm each side	3	0.06
TP1	002	TP1-002-2	Pinned-Pinned	6mm each side	3	0.09
TP1	002	TP1-002-3	Pinned-Pinned	6mm each side	3	0.12
TP1	002	TP1-002-4	Pinned-Pinned	6mm each side	3	0.15
TP1	002	TP1-002-5	Pinned-Pinned	6mm each side	3	0.18

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP1	002	TP1-002-6	Pinned-Pinned	6mm each side	3	0.21

Table 4-6 Pipe Span C - 25mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 9mm Plate Thickness and 3mm Damping Thickness

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP1	003	TP1-003-1	Pinned-Pinned	9mm each side	3	0.06
TP1	003	TP1-003-2	Pinned-Pinned	9mm each side	3	0.09
TP1	003	TP1-003-3	Pinned-Pinned	9mm each side	3	0.12
TP1	003	TP1-003-4	Pinned-Pinned	9mm each side	3	0.15
TP1	003	TP1-003-5	Pinned-Pinned	9mm each side	3	0.18
TP1	003	TP1-003-6	Pinned-Pinned	9mm each side	3	0.21

Table 4-7 Pipe Span D - 25mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 3mm Plate Thickness and 6mm Damping Thickness

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP1	004	TP1-004-1	Pinned-Pinned	3mm each side	6	0.12
TP1	004	TP1-004-2	Pinned-Pinned	3mm each side	6	0.15

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP1	004	TP1-004-3	Pinned-Pinned	3mm each side	6	0.18
TP1	004	TP1-004-4	Pinned-Pinned	3mm each side	6	0.21
TP1	004	TP1-004-5	Pinned-Pinned	3mm each side	6	0.24
TP1	004	TP1-004-6	Pinned-Pinned	3mm each side	6	0.27

Table 4-8 Pipe Span E - 25mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 6mm Plate Thickness and 6mm Damping Thickness

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP1	005	TP1-005-1	Pinned-Pinned	6mm each side	6	0.12
TP1	005	TP1-005-2	Pinned-Pinned	6mm each side	6	0.15
TP1	005	TP1-005-3	Pinned-Pinned	6mm each side	6	0.18
TP1	005	TP1-005-4	Pinned-Pinned	6mm each side	6	0.21
TP1	005	TP1-005-5	Pinned-Pinned	6mm each side	6	0.24
TP1	005	TP1-005-6	Pinned-Pinned	6mm each side	6	0.27

Table 4-9 Pipe Span F - 25mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 9mm Plate Thickness and 6mm Damping Thickness

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP1	006	TP1-006-1	Pinned-Pinned	9mm each side	6	0.12
TP1	006	TP1-006-2	Pinned-Pinned	9mm each side	6	0.15
TP1	006	TP1-006-3	Pinned-Pinned	9mm each side	6	0.18
TP1	006	TP1-006-4	Pinned-Pinned	9mm each side	6	0.21
TP1	006	TP1-006-5	Pinned-Pinned	9mm each side	6	0.24
TP1	006	TP1-006-6	Pinned-Pinned	9mm each side	6	0.27

Table 4-10 Pipe Span G - 40mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 3mm Plate Thickness and 3mm Damping Thickness

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP2	001	TP2-001-1	Pinned-Pinned	3mm each side	3	0.09
TP2	001	TP2-001-2	Pinned-Pinned	3mm each side	3	0.12
TP2	001	TP2-001-3	Pinned-Pinned	3mm each side	3	0.15
TP2	001	TP2-001-4	Pinned-Pinned	3mm each side	3	0.18
TP2	001	TP2-001-5	Pinned-Pinned	3mm each side	3	0.21

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP2	001	TP2-001-6	Pinned-Pinned	3mm each side	3	0.24

Table 4-11 Pipe Span H - 40mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 6mm Plate Thickness and 3mm Damping Thickness

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP2	002	TP2-002-1	Pinned-Pinned	6mm each side	3	0.09
TP2	002	TP2-002-2	Pinned-Pinned	6mm each side	3	0.12
TP2	002	TP2-002-3	Pinned-Pinned	6mm each side	3	0.15
TP2	002	TP2-002-4	Pinned-Pinned	6mm each side	3	0.18
TP2	002	TP2-002-5	Pinned-Pinned	6mm each side	3	0.21
TP2	002	TP2-002-6	Pinned-Pinned	6mm each side	3	0.24

Table 4-12 Pipe Span I - 40mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 9mm Plate Thickness and 3mm Damping Thickness

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP2	003	TP2-003-1	Pinned-Pinned	9mm each side	3	0.09
TP2	003	TP2-003-2	Pinned-Pinned	9mm each side	3	0.12

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP2	003	TP2-003-3	Pinned-Pinned	9mm each side	3	0.15
TP2	003	TP2-003-4	Pinned-Pinned	9mm each side	3	0.18
TP2	003	TP2-003-5	Pinned-Pinned	9mm each side	3	0.21
TP2	003	TP2-003-6	Pinned-Pinned	9mm each side	3	0.24

Table 4-13 Pipe Span J - 40mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 3mm Plate Thickness and 6mm Damping Thickness

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP2	004	TP2-004-1	Pinned-Pinned	3mm each side	6	0.12
TP2	004	TP2-004-2	Pinned-Pinned	3mm each side	6	0.15
TP2	004	TP2-004-3	Pinned-Pinned	3mm each side	6	0.18
TP2	004	TP2-004-4	Pinned-Pinned	3mm each side	6	0.21
TP2	004	TP2-004-5	Pinned-Pinned	3mm each side	6	0.24
TP2	004	TP2-004-6	Pinned-Pinned	3mm each side	6	0.27

Table 4-14 Pipe Span K - 40mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 6mm Plate Thickness and 6mm Damping Thickness

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP2	005	TP2-005-1	Pinned-Pinned	6mm each side	6	0.12
TP2	005	TP2-005-2	Pinned-Pinned	6mm each side	6	0.15
TP2	005	TP2-005-3	Pinned-Pinned	6mm each side	6	0.18
TP2	005	TP2-005-4	Pinned-Pinned	6mm each side	6	0.21
TP2	005	TP2-005-5	Pinned-Pinned	6mm each side	6	0.24
TP2	005	TP2-005-6	Pinned-Pinned	6mm each side	6	0.27

Table 4-15 Pipe Span L - 40mm Diameter Acrylic Pipe Of 1mm Wall Thickness With 9mm Plate Thickness and 6mm Damping Thickness

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP2	006	TP2-006-1	Pinned-Pinned	9mm each side	6	0.12
TP2	006	TP2-006-2	Pinned-Pinned	9mm each side	6	0.15
TP2	006	TP2-006-3	Pinned-Pinned	9mm each side	6	0.18
TP2	006	TP2-006-4	Pinned-Pinned	9mm each side	6	0.21
TP2	006	TP2-006-5	Pinned-Pinned	9mm each side	6	0.24

Test Phase	Test Series	Data Reference No.	Boundary Condition	Thickness of End Plate	Neoprene Damping Thickness (mm)	Required Test Velocity (m/s)
TP2	006	TP2-006-6	Pinned-Pinned	6mm each side	9	0.27

CHAPTER 5

PRESENTATION OF RESULTS

5.1 GENERAL

In this chapter, the results of the test program established for the experimental works performed to record vortex induced vibration of the acrylic pipe are presented. A total of 12 sets of test were conducted to obtain 72 sets of results. For each set of results, a total of 1500 dynamic strain data at three locations on the acrylic pipe were recorded over a time span of 120 seconds. A sample of the results for the test performed on a 25mm diameter acrylic pipe under steady current flow is presented in Appendix A.

An example of the graphical representation of strain data for a 25mm diameter acrylic pipe in air is presented in Figure 5.1. It was noted that the acrylic pipe experienced dynamic strain even in air. The magnitude of the dynamic strain ranged from -2μ to $+4\mu$. This can be attributed to the vibrations caused by the surroundings in the laboratory including movements of vehicles and active machinery. This also indicated that the acrylic pipe specimen was extremely sensitive to external vibrations.

Figure 5.1 Dynamic Strain Plot For A 25mm Diameter Acrylic Pipe
In Air

For an acrylic pipe subjected to steady current flows, the dynamic strain was found to be larger in amplitude. In Figure 5.2, a 25mm diameter acrylic pipe

was subjected to a steady current flow. The amplitudes of the dynamic strain ranged from -4μ to $+7\mu$.

Figure 5.2 Dynamic Strain Plot For A 25mm Diameter Acrylic Pipe In Steady Current

For acrylic pipes subjected to even larger current flows, the amplitudes of the dynamic strain recorded by the dynamic strain-meter were correspondingly larger. This observation is in line with the theory that a larger current flow creates a bigger vortex shedding effect causing the acrylic pipe to exhibit more vigorous vibrations and hence larger amplitudes of dynamic strain.

5.2 ANALYSIS OF RESULTS

The main objective of the experimental investigation is to determine the effects of damping and boundary conditions on pipelines due to vortex induced vibration. In the experiments, the boundary conditions were simulated by varying the plate thickness at both ends of the pipe model. The damping effect of the test model was examined by varying the thickness of neoprene layers between the pipe ends and the plates at supports.

Based on the strain data obtained from the dynamic strain-meter, the experiment results were analyzed. The strain data and experimental parameters were processed in accordance with the procedures presented in Sections 5.2.1 to 5.2.3 below.

5.2.1 Calculation for Root Mean Square Strain, $\epsilon_{R.M.S}$

For each set of strain values recorded from the strain-meter, the root mean square strain value is generated based on the following equation:

$$\epsilon_{R.M.S} = \sqrt{\frac{1}{n} \sum_{i=1}^n \epsilon_i^2} \quad (13)$$

where,

$\epsilon_{R.M.S}$	=	Root mean square strain value
ϵ_i	=	Individual strain value
n	=	Total number of strain values (1500)

5.2.2 Calculation for Acrylic Pipe Centre Deflection, Δ_{MAX}

The pipe centre deflection is calculated considering a pinned-pinned end boundary condition and the deflection is assumed to occur within elastic limits of the material.

For a uniform pipe, the maximum deflection at pipe centre is calculated as follows:

$$\Delta_{MAX} = \frac{5WL^4}{384EI} \quad (14)$$

where,

Δ_{MAX}	=	Maximum deflection at centre of pipe
W	=	Uniform distributed load
L	=	Length of pipe
E	=	Young's modulus of material
I	=	2 nd moment of inertia

For a uniform pipe, the maximum bending moment at pipe centre, M_{cen} , is presented as follows:

$$M_{\text{cen}} = \frac{WL^2}{8} \quad (15)$$

Since the maximum deflection at pipe centre is assumed to occur within the elastic limit of the material, the strain at the centre of the pipe, ε_0 , is calculated as follows:

$$\varepsilon_0 = \frac{M_{\text{cen}}}{ZE} \quad (16)$$

where,

$$\begin{aligned} \varepsilon_0 &= \text{Strain at the centre of pipe} \\ Z &= \text{Section modulus} \end{aligned}$$

To calculate the maximum deflection of the pipe at the centre of the span as a function of the strain experienced at its centre, equations (15) and (16) are substituted into equation (14) to obtain the following expression:

$$\Delta_{\text{MAX}} = \frac{10\varepsilon_0 L^2}{96y} \quad (17)$$

where,

$$y = \text{Radius of pipe}$$

5.2.3 Calculation for Reduced Velocity Parameter, V_R

The reduced velocity, V_R , is a commonly utilized dimensionless parameter for reporting measurements for vortex induced vibrations. The reduced velocity has been expressed by the following formula (Palmer and King, 2004, p. 417):

$$V_R = \frac{U}{ND} \quad (18)$$

where,

$$\begin{aligned} U &= \text{Flow velocity across the pipe} \\ N &= \text{Lowest natural frequency of oscillation} \\ D &= \text{Pipe outer diameter} \end{aligned}$$

The lowest natural frequency of oscillation, N , is further defined by the following expression (Palmer and King, 2004, p. 418):

$$N = \frac{C}{L^2} \sqrt{\frac{F}{m_e}} \quad (19)$$

where,

$$\begin{aligned} C &= 1.57 \text{ for pinned-pinned end conditions} \\ F &= \text{Flexural rigidity} \\ m_e &= \text{Pipe effective mass} \end{aligned}$$

For small deflection within elastic limit, the flexural rigidity, F , is defined by the following expression:

$$F = \frac{\pi}{64} [D^4 - (D - 2t)^4] E \quad (20)$$

where,

$$t = \text{Pipe wall thickness}$$

Hence, equation (18) for the reduced velocity parameter, V_R , can be expressed as follows:

$$V_R = A_1 \left(\frac{U}{\left(\frac{D}{L^2}\right) \sqrt{\frac{[D^4 - (D - 2t)^4] E}{m_e}}} \right) \quad (21)$$

where,

$$A_1 = \text{Constant value of 2.875}$$

Sample calculations for the determination of the normalized pipe deflection over diameter and reduced velocity in accordance with the above procedures have been attached in Appendix D for reference.

5.3 PRESENTATION OF RESULTS

A set of raw data from the experimental study is enclosed in Appendix C. Based on the analysis methodology discussed in Section 5.2, the raw data were analyzed and the results were tabulated. To establish a relationship for the results, non-dimensionalized parameters were proposed. These parameters include the reduced velocity parameter, V_R , and the maximum deflection, Δ_{MAX} , normalized over pipe diameter. The relationships are presented in graphs further detailed in Section 5.3.1 below. The methodology proposed in Section 5.2 has assumed a pinned-pinned end boundary condition for the analyses. Section 5.3.2 presents the sensitivity studies on the result assuming another end boundary condition.

5.3.1 R.M.S Deflection/Diameter versus Reduced Velocity Graphs

The conventional way to report vortex induced vibrations is to present the data in a Deflection/Diameter versus Reduced Velocity graph. This representation has been performed in several research programs including the Polar Gas Project and the UK Department of Energy by Hydraulics Research (Palmer and King, 2004, p. 418, Fig. 14-6) in 1984 and the MULTISPAN Project (Mørk, Vitali and Verley, 1997).

5.3.1.1 Experimental Results For 25mm Acrylic Pipe

Using the equations in Section 5.2, the data from the dynamic strain-meter were processed to produce the following graphs presented in Figures 5.3 to 5.8 below.

Figure 5.3 – In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 25mm Diameter Acrylic Pipe with 3mm Neoprene Thickness and 3mm End Plate Thickness

Figure 5.4 – In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 25mm Diameter Acrylic Pipe with 3mm Neoprene Thickness and 6mm End Plate Thickness

Figure 5.5 – In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 25mm Diameter Acrylic Pipe with 3mm Neoprene Thickness and 9mm End Plate Thickness

Figure 5.6 – In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 25mm Diameter Acrylic Pipe with 6mm Neoprene Thickness and 3mm End Plate Thickness

Figure 5.7 – In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 25mm Diameter Acrylic Pipe with 6mm Neoprene Thickness and 6mm End Plate Thickness

Figure 5.8 – In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 25mm Diameter Acrylic Pipe with 6mm Neoprene Thickness and 9mm End Plate Thickness

The range of reduced velocity based on the analyzed values is from 0.7 to 1.8. Although this range is limited by the maximum current velocity generated within the hydraulic flume, it has adequately covered the established reduced velocity values for onset of in-line vibration usually observed between values 1.0 to 1.4 from previous experimental studies.

From the graphs, it can be reported that the in-line VIV response R.M.S amplitudes experienced by the 25mm diameter acrylic pipe specimens were very small. The maximum deflection observed was in Pipe Span B at 0.1mm horizontal deflection at a reduced velocity value of 1.55. No pipe spans, except for Pipe Span B shown in the graph in Figure 5.4, showed a significant jump in deflection when tested across the reduced velocity ranges, a jump normally associated with the onset of in-line vibrations. The trend represented by the graphs showed that the in-line VIV response R.M.S amplitude increased as the reduced velocity value increased. However, the increase in amplitude was so small that it is difficult to conclude confidently if there is actually a linear relationship between the amplitude and reduced velocity for these test results.

To further analyze the test results, the above graphs were plotted against established test results from reproduced graphs from the Hydraulics Research Report EX 1268 (Palmer and King, 2004, p. 418, Fig. 14-6) and the MULTISPAN project (Mørk, Vitali and Verley, 1997) and presented in Chapter 6 of this report.

5.3.1.2 Experimental Results For 40mm Acrylic Pipe

Using the equations in Section 5.2, the data from the dynamic strain-meter were processed to produce the following graphs presented in Figures 5.9 to 5.14 below.

Figure 5.9 – In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 40mm Diameter Acrylic Pipe with 3mm Neoprene Thickness and 3mm End Plate Thickness

Figure 5.10 – In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 40mm Diameter Acrylic Pipe with 3mm Neoprene Thickness and 6mm End Plate Thickness

Figure 5.11 – In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 40mm Diameter Acrylic Pipe with 3mm Neoprene Thickness and 9mm End Plate Thickness

Figure 5.12 – In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 40mm Diameter Acrylic Pipe with 6mm Neoprene Thickness and 3mm End Plate Thickness

Figure 5.13 – In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 40mm Diameter Acrylic Pipe with 6mm Neoprene Thickness and 6mm End Plate Thickness

Figure 5.14 – In-line VIV Response R.M.S Amplitude/Diameter Versus Reduced Velocity Graph For 40mm Diameter Acrylic Pipe with 6mm Neoprene Thickness and 9mm End Plate Thickness

Compared to the graphs in Figures 5.3 to 5.8, the range of reduced velocity obtained for the graphs in Figures 5.9 to 5.14 was smaller and is between 0.6 to 1.5. Some graphs, namely in Figures 5.11 to 5.14, also did not adequately cover the required range of reduced velocity values (1.0 to 1.4) and this has made it impossible to report any observation of onset for in-line vibrations.

The in-line VIV response R.M.S amplitudes experienced by the 40mm diameter acrylic pipe specimen were even smaller than the amplitudes displayed by the 25mm diameter acrylic pipe specimen. The maximum deflection experienced was in Pipe Span G at 0.06mm horizontal deflection at a reduced velocity of 1.5. This may be attributed to the fact that the 40mm diameter acrylic pipe is more rigid than a 25mm diameter acrylic pipe at similar span lengths. This observation may also imply that the deflections experienced by both pipe spans were caused by hydrodynamic forces including lift and drag forces instead of in-line vibrations. No pipe spans, except for Pipe Span G shown in the graph in Figure 5.9, showed any significant jumps in deflection when tested across the range of reduced velocity. There is no observable trend represented by the graphs and some of the graphs, namely in Figures 5.10 to 5.14, showed no significant increase in in-line VIV response R.M.S amplitudes when the reduced velocity values were increased.

Similarly, to further analyze the test results, the above graphs were plotted against established test results and presented in Chapter 6 of this report.

5.3.2 Sensitivity Study on Boundary Condition Assumptions

The experimental results in Section 5.3.1 were analyzed using pinned-pinned end boundary conditions. Based on this assumption, the maximum deflection at the center of the acrylic pipe was calculated in accordance with equation (17). However, it is not possible to ascertain that the end plates used in the experiments truly reflect pinned-pinned end boundary conditions. Hence, a sensitivity study was carried out to see if analyzing the experimental results using fixed-fixed end boundary conditions would have

any impact on the results. The pinned-fixed end boundary conditions, while most commonly utilized in engineering design, is a “middle” condition between pinned-pinned end boundary conditions and fixed-fixed end boundary conditions. The pinned-fixed end boundary conditions would not be analyzed as part of the sensitivity study.

The sensitivity study was performed based on the following Table 5-1:

Table 5-1 End Boundary Conditions Equations

Parameters	End Boundary Conditions	
	Pinned-pinned	Fixed-fixed
Maximum Deflection at Mid Span of Pipe, Δ_{MAX}	$\frac{5WL^4}{384EI}$	$\frac{WL^4}{384EI}$
Maximum Bending Moment at Pipe Center, M_{cen}	$\frac{WL^2}{8}$	$\frac{WL^2}{24}$
Maximum Deflection as a function of R.M.S. strain	$\frac{10\epsilon_0 L^2}{96y}$	$\frac{\epsilon_0 L^2}{16y}$
Value of constant, C, utilized in Natural Frequency of Pipe Span	1.57	3.56

The notations utilized in Table 5-1 have been defined in equations (13) to (19). The sensitivity study was carried out for the following Pipe Spans:

- Pipe Span B – 25mm diameter acrylic pipe with 3mm neoprene thickness and 6mm end plate thickness.
- Pipe Span H – 40mm diameter acrylic pipe with 3mm neoprene thickness and 6mm end plate thickness.

The results of the sensitivity study were plotted on Deflection/Diameter versus Reduced Velocity graphs and were presented in Figures 5.15 and 5.16 below.

Figure 5.15 Sensitivity Study For Pipe Span B Considering Pinned-Pinned And Fixed-Fixed End Boundary Conditions

Figure 5.16 Sensitivity Study For Pipe Span H Considering Pinned-Pinned And Fixed-Fixed End Boundary Conditions

Based on the graphs, it can be shown that the calculated in-line VIV R.M.S amplitudes for a pipe span considering fixed-fixed end boundary conditions are smaller than the amplitudes for pinned-pinned end boundary conditions. The reduced velocity ranges have also been “compressed” for the fixed-fixed end boundary conditions. In addition, it can be noted from the graphs

that the general shapes of the curves for both fixed-fixed and pinned-pinned end boundary conditions are similar.

The pinned-fixed end boundary condition graph is expected to be in between the pinned-pinned and fixed-fixed end boundary condition graphs. From the sensitivity analyses, for the purpose of these experiment studies, it is concluded that the choice of the type of end boundary conditions will not have an impact on the findings of the experimental study.

CHAPTER 6

CONCLUSIONS

6.1 GENERAL

In this chapter, the observations from the experimental test program will be compared against established results obtained from previous experimental studies to draw conclusions. The limitations of the current experimental studies will be highlighted. Finally, lessons learnt from these studies, which could be used to improve future research, will also be elaborated.

6.2 OBSERVATIONS AND RECOMMENDATIONS

6.2.1 Principal Observations

6.2.1.1 Observation 1

The graphs in Section 5.3.1 presented the R.M.S deflection amplitudes experienced by the 25mm and 40mm acrylic pipes when exposed to current flow in a flume.

To compare the experimental results with previously established experimental results, the Amplitude/Diameter versus Reduced Velocity curves for the Hydraulics Research Report EX 1268 (Palmer and King, 2004, p. 418, Fig. 14-6) and the MULTISPAN project (Mørk, Vitali and Verley, 1997) were reproduced and superimposed onto the generated graphs shown in Figures 5.3 to 5.14 in Chapter 5. The combined results are shown in the graph in Figure 6.1 below:

Figure 6.1 Comparison Of Experimental Results With Established Studies

Based on the graph in Figure 6.1, it is obvious that the experimental studies did not produce any significant vibrations compared to the established experimental results. The experimental studies were conducted across the established reduced velocity values for onset of in-line vibrations but there was no significant increase in the acrylic pipes' deflection amplitudes.

While the acrylic pipes exhibited deflections, the deflections were extremely small when compared to the established experimental results. Hence, it can be concluded that the acrylic pipes did not experience any vortex induced vibrations over the tested reduced velocity range.

Some possible explanations have been proposed to why the acrylic pipes did not experience any vortex induced vibrations and are listed in Section 6.2.3.

6.2.1.2 Observation 2

Two experimental studies presented in the graphs shown in Figures 5.4 and 5.9 in Section 5.3.1 demonstrated a "jump" in R.M.S amplitude when tested

across the reduced velocity values of 1.4. These increases in amplitude are typically observed in behaviors of pipe spans experiencing onset of in-line vortex induced vibrations at certain reduced velocities. Pipe Span B in the graph in Figure 5.4 exhibited an increase of 142.99% in deflection amplitude when tested across reduced velocity value of 1.4 while Pipe Span G in the graph in Figure 5.9 exhibited an increase of 68.78% in deflection amplitude when tested across a similar range. The remaining experimental studies exhibited increases of less than 50% in deflection amplitudes.

However, while Pipe Span B registered a huge increase in deflection amplitude across reduced velocity of 1.4, the subsequent deflection amplitude registered was a drop of 48.98%. There was no further data point available for Pipe Span G beyond reduced velocity value of 1.508 and its behavior beyond could not be ascertained. In addition, when the graphs in Figures 5.4 and 5.9 were superimposed against established experimental results in the graph in Figure 6.1, it can be seen that the increase in amplitude for the two pipe spans seemed negligible.

It can be concluded that while the two pipe spans exhibited behavior consistent with vortex induced vibrations when tested across the onset of in-line vibrations, it is unlikely that they were experiencing any vibration due to the size of the deflections. It is possible that the sudden increase in amplitude may have been caused by some instability within the strain gauges during the experimental studies.

6.2.1.3 Observation 3

For each experimental study, the acrylic pipe experienced deflections although the amplitude of the deflections was very small. As concluded in Observation 1, it is now agreed that these deflections were unlikely to be caused by vortex induced vibrations. A linear regression study based on the data points in the graphs in Figures 5.3 to 5.14 was performed and the following trend in Table 6-1 has been observed.

Table 6-1 Trend Table For 25mm and 40mm Acrylic Pipes

Referenced Figure	Relationship Between Amplitude/Diameter and Reduced Velocity Based On Linear Regression
5.3	Linear
5.4	Linear
5.5	Linear
5.6	Linear
5.7	Linear
5.8	Linear
5.9	Linear
5.10	Inverse
5.11	Linear
5.12	Linear
5.13	Linear
5.14	Linear

Table 6-1 shows that nearly all the graphs exhibited a linear relationship between the magnitudes of the deflection experienced by the acrylic pipe and the reduced velocities of which flow velocity is a component. It is possible that the deflections exhibited by the acrylic pipes may have been caused by hydrodynamic loading of drag and inertia forces imposed onto the pipe span under the uniform current flow.

6.2.2 Limitations of Experimental Studies

6.2.2.1 Limitation 1

Opportunities to measure the natural frequency of the pipe span length and the modal damping of the system were lost when the system was not set into vibration in air and in water. The natural frequency of the pipe span for each

experimental study could still be calculated using equation (19) but the damping effect of the neoprene layer at the end boundary plates on the system could not be ascertained.

The stability parameter, K_s , could not be determined without the measured modal damping ratio and this parameter has an impact on the onset of in-line vortex induced vibrations. Since no vibrations had been observed from the experimental data, it is not possible to back-calculate for the stability parameter. Based on DNV-RP-F105 (2003), Figure 4-1 in the Code, it is likely that the stability parameter will be greater than 1.2.

Had the damping effect been measured at the start, the ranges of reduced velocities which would generate vortex induced vibrations could be ascertained and the experimental studies could then be performed along these ranges.

6.2.2.2 Limitation 2

The reduced velocities for each set of experimental study tested did not manage to cover a very large range. The range of reduced velocities tested for the 25mm diameter acrylic pipe started at 0.680 and terminated at 1.914 while the range of reduced velocities tested for the 40mm diameter acrylic pipe was even shorter from 0.632 to 1.583. This did not allow for further comparisons with established experimental studies where the pipe specimens were tested up to reduced velocity values of 6.

One reason for the short range was due to the limitations of the flume. The maximum current velocity generated within the flume during the experimental studies averaged 0.33m/s (which results in a reduced velocity value of about 1.51 for a 40mm diameter acrylic pipe span of 1.181m considering pinned-pinned boundary conditions).

While a smaller diameter acrylic pipe could be selected to improve the reduced velocity range, there are difficulties in installing the available strain gauges on the pipe surface of the next available pipe diameter of 10mm size.

6.2.2.3 Limitation 3

As the strain gauges were set up in an in-line horizontal direction along the acrylic pipe specimens, the experimental studies were unable to measure any cross-flow vertical vibrations.

However, this limitation is expected to have no impact on the experimental studies as the reduced velocity at which the onset of cross-flow vibrations would take place is much higher than the onset of in-line vibrations. The experimental studies did not capture any in-line vibrations for the tested reduced velocity range and hence, it is unlikely to measure any cross-flow vibrations at all.

6.2.2.4 Limitation 4

The analyses were performed in accordance with Section 5.2 to calculate the maximum deflections at mid span based on the strain data obtained from the dynamic strain meter. However, during the actual experimental studies, the strain gauges were not totally centered at the mid span due to physical restrictions. The errors measured were recorded up to an average of 0.23cm off centered.

However, it is unlikely that these inaccuracies would have any impact on the final results of the experimental studies.

6.2.3 Lessons Learnt and Recommendations for Improvements

6.2.3.1 Lesson Learnt 1

It is important to ensure that all parameters affecting the outcomes are thoroughly studied before carrying out the experiments. In this case, as mentioned in Limitation 1 in Section 6.2.2, critical parameters including the modal damping ratio for the system were not pre-determined and it is believed that the whole system had been over-damped in relation to the experiment. The physical limitations of the experimental set-up further exacerbated the situation when the acrylic pipe specimens could not be tested beyond the reduced velocity ranges.

The experimental studies failed to register any in-line vortex induced vibrations due to a lack of proper understanding of critical parameters.

6.2.3.2 Lesson Learnt 2

The methodology to determine the damping effect of the neoprene layer on the 25mm and 40mm acrylic pipe specimens in the experimental studies is flawed.

To recapitulate, one of the objectives of the experimental studies was to determine the impact of a layer of neoprene on the riser system and to try to quantify the damping capacity of this neoprene layer in terms of its thickness. To do so, the experimental studies employed two different thicknesses of neoprene (3mm and 6mm) at the two boundary end plates and the acrylic pipe specimens were set in the tank subjected to current flows.

The acrylic pipe specimens were to be tested across a range of reduced velocities to the point where the onset of in-line vortex induced vibrations could be determined. Based on the experimentally obtained reduced velocity values, the stability parameter, K_s , could be determined from established

experiment studies such as the DNV-RP-F105 (2003) graph below and the damping effect of the neoprene layers investigated.

Figure 6.2 Graph 4.1 From DNV-OS-F105, Free Spanning Pipelines

The methodology did not consider the possibility that the experimental studies would be over-damped to the point that no vortex induced vibration would be exhibited by the acrylic pipes within experimental control conditions.

6.2.3.3 Lesson Learnt 3

It was difficult to determine the effect of the boundary conditions on the pipe spans in the experimental studies.

For these studies, unconventional boundary plates modeled after rigid riser clamps were utilized as supports at two ends of the acrylic pipes. The choice of wood as the material for the boundary plates was not suitable as the material contributed further to the damping effect on the overall system. A better material for the boundary end plates would have been steel as this would be the same material used for riser clamps.

It was not possible to measure the effect of the thickness of the boundary end plates on the onset of in-line vibrations as none was exhibited. It is recommended that further studies be carried out on site involving actual rigid risers and real time environmental loading instead. Prior to installation, strain gauges could be installed in the risers and a monitoring program implemented.

6.3 CONCLUSIONS

The work reported in this study represented a contemporary approach to the analysis for allowable pipeline span for a rigid riser attached to a platform jacket. It is hoped that the observations and findings from this study would serve as useful guidance for future work to examine allowable span due to vortex induced vibrations.

The effort of this study contributes towards the objective of capability in pipeline span analysis without undue conservatism in the design of riser clamps to limit allowable span due to vortex induced vibrations. However, the objectives could not be achieved due to the reasons discussed in this chapter. Nevertheless, it is hoped that the observations, limitations and lessons learnt would be of some benefit for realizing cost-effectiveness for pipeline projects.

REFERENCES

1. Bruschi, R., Montesi, M., Tura, F., Vitali, L., and Acerboni, A. (1989), "The SVS Project: Field Tests with Pipeline Free Spans Exposed to Wave Flow and Steady Current", OTC'89, Houston, Texas, pp. 387-396.
2. Bruschi, R., Curti, G., Marchesani, F., Torselletti, E. (1993), "The MASPUS Project. Methods for Adapting Submarine Pipeline to Uneven Seabed", OMAE'93, Glasgow, United Kingdom, Volume V, pp. 83-99.
3. CIRIA Underwater Engineering Group (1977), "Report UR 8: Dynamics of Marine Structures", London.
4. DNV Rules for Submarine Pipeline Systems (1981).
5. DNV Guidelines No. 14 (1998), "Free Spanning Pipelines".
6. DNV-RP-F105 (2003), "Free Spanning Pipelines".
7. Gho, W.M., Ong, Y.C. (2005), "Comparative Study of Allowable Free Span Between Seabed Pipelines and Rigid Risers", TEAM Conference, Singapore, pp. 465-469.
8. King, R. (1974), "Vortex-Excited Structural Oscillations of a Circular Cylinder in Flowing Water", PhD Thesis, Loughborough University.
9. MARC, User Manual and Primer (2001), MARC Analysis and Research Corporation, California, United States.
10. Mørk, K.J., Vitali, L., Verley, R. (1997), "The MULTISPAN Project: Design Guideline for Free Spanning Pipelines", OMAE'97, Yokohama, Japan, Volume V, pp. 31-43.
11. Ong, Y.C., Gho, W.M. (2007), "Experimental Investigation of Free Spanning Submarine Pipeline under Vortex Induced Vibration", International Maritime-Port Technology and Development Conference, Singapore.

12. Palmer, A.C., King, R.A. (2004), "Subsea Pipeline Engineering", Tulsa, Oklahoma: PennWell Books, p. 417, equation 14.17.
13. Palmer, A.C., King, R.A. (2004), "Subsea Pipeline Engineering", Tulsa, Oklahoma: PennWell Books, p. 418, equation 14.18.
14. Palmer, A.C., King, R.A. (2004), "Subsea Pipeline Engineering", Tulsa, Oklahoma: PennWell Books, p. 418, Fig. 14-6.
15. Tura, F., Dumitrescum, A., Bryndum, M.B. and Smeed, P.F. (1994), "Guidelines for Free Spanning Pipelines: The GUDESP Project", OMAE'94, Houston, Volume V, pp. 247-256.
16. Tura, F., Bryndum, M.B., Nielsen, N.J.R. (1994), "Guideline for Free Spanning Pipelines: Outstanding Items and Technological Innovations", Proceedings of Conference on Advances in Subsea Pipeline Engineering and Technology.

APPENDIX A
SAMPLE RESULTS FOR 25MM ACRYLIC PIPE

APPENDIX A

As mentioned in Chapter 5, a total of 12 sets of test were conducted to obtain 72 sets of results. For each set of results, a total of 1500 dynamic strain data at three locations on the acrylic pipe were recorded over a time span of 120 seconds. A sample of the results for the test performed on a 25mm diameter acrylic pipe under steady current flow is presented in this appendix. In Appendix B, a sample of the results for the test performed on a 40mm diameter acrylic pipe is presented.

APPENDIX A

Experimental Data Record No.									
17 Aug 25mmdia 1052-26gate1									
Data Type : Dynamic									
File Comment :									
Record Word : 1500 word									
Sampling Cycle : 40 msec.									
Pretrigger Memory : 0 word									
No.		CH.001	CH.002	CH.003					
Mode		2.0Vrms	2.0Vrms	2.0Vrms					
L.P.F.		PASS	PASS	PASS					
Coeff.		9.43E-01	9.43E-01	9.43E-01					
Unit		μ	μ	μ					
MAX		8.487	11.316	9.43					
MIN		-9.43	-12.259	-11.316					
MEAN		0.943	0	-0.943					

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)	Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
1	0.04	-2.829	-3.772	-0.943	41	1.64	1.886	-0.943	-1.886
2	0.08	-0.943	-3.772	-0.943	42	1.68	2.829	-0.943	-0.943
3	0.12	-0.943	-6.601	-1.886	43	1.72	0.943	-3.772	-3.772
4	0.16	2.829	5.658	3.772	44	1.76	0	-2.829	-3.772
5	0.20	1.886	2.829	2.829	45	1.80	3.772	1.886	0
6	0.24	0.943	0.943	0.943	46	1.84	3.772	0.943	1.886
7	0.28	-2.829	-6.601	-5.658	47	1.88	4.715	2.829	0.943
8	0.32	1.886	0	-1.886	48	1.92	3.772	1.886	0
9	0.36	0.943	0.943	-1.886	49	1.96	3.772	0.943	0
10	0.40	-0.943	-2.829	-3.772	50	2.00	2.829	-3.772	-0.943
11	0.44	-0.943	-4.715	-5.658	51	2.04	4.715	0.943	0
12	0.48	1.886	0	-0.943	52	2.08	1.886	0	-2.829
13	0.52	3.772	6.601	4.715	53	2.12	1.886	0.943	-1.886
14	0.56	2.829	4.715	1.886	54	2.16	0.943	-1.886	-2.829
15	0.60	0.943	0.943	-0.943	55	2.20	-0.943	-6.601	-4.715
16	0.64	0	-0.943	-2.829	56	2.24	1.886	0.943	0
17	0.68	0.943	-0.943	-2.829	57	2.28	0.943	2.829	-0.943
18	0.72	6.601	5.658	2.829	58	2.32	0	0	-1.886
19	0.76	3.772	1.886	-1.886	59	2.36	0.943	0	-0.943
20	0.80	0	-3.772	-6.601	60	2.40	2.829	1.886	0
21	0.84	-1.886	-10.373	-9.43	61	2.44	4.715	6.601	3.772
22	0.88	1.886	-2.829	-4.715	62	2.48	2.829	4.715	0.943
23	0.92	2.829	2.829	-0.943	63	2.52	1.886	1.886	0
24	0.96	3.772	4.715	0	64	2.56	-0.943	-5.658	-6.601
25	1.00	-2.829	-2.829	-4.715	65	2.60	0.943	-2.829	-3.772
26	1.04	0	-7.544	-5.658	66	2.64	0	-1.886	-4.715
27	1.08	3.772	0.943	1.886	67	2.68	4.715	9.43	1.886
28	1.12	3.772	0.943	0.943	68	2.72	0	-2.829	-5.658
29	1.16	4.715	5.658	5.658	69	2.76	-0.943	-8.487	-11.316
30	1.20	0	-4.715	-0.943	70	2.80	0.943	-1.886	-6.601
31	1.24	1.886	-2.829	1.886	71	2.84	1.886	0.943	-5.658
32	1.28	2.829	1.886	2.829	72	2.88	1.886	0.943	-4.715
33	1.32	5.658	3.772	1.886	73	2.92	0	-3.772	-7.544
34	1.36	5.658	0.943	0	74	2.96	0.943	-0.943	-4.715
35	1.40	0	0	-0.943	75	3.00	1.886	0	-2.829
36	1.44	0.943	-1.886	-1.886	76	3.04	4.715	8.487	3.772
37	1.48	1.886	-1.886	-2.829	77	3.08	0.943	-0.943	-0.943
38	1.52	3.772	1.886	0.943	78	3.12	0.943	-0.943	0
39	1.56	1.886	-2.829	-2.829	79	3.16	-1.886	-4.715	-5.658
40	1.60	5.658	2.829	1.886	80	3.20	0	-1.886	-2.829

APPENDIX A

Experimental Data Record No.

17 Aug 25mmdia 1052-26gate1

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)	Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
81	3.24	0.943	1.886	-1.886	134	5.36	1.886	0	1.886
82	3.28	0.943	-1.886	-1.886	135	5.40	1.886	-2.829	0.943
83	3.32	-3.772	-12.259	-9.43	136	5.44	-0.943	-8.487	-3.772
84	3.36	-0.943	-6.601	-7.544	137	5.48	2.829	-0.943	0
85	3.40	1.886	0.943	-4.715	138	5.52	3.772	0.943	0.943
86	3.44	0.943	-0.943	-4.715	139	5.56	3.772	1.886	0.943
87	3.48	0	-3.772	-6.601	140	5.60	0	-9.43	-4.715
88	3.52	-0.943	-8.487	-6.601	141	5.64	0.943	-3.772	-4.715
89	3.56	1.886	-0.943	-2.829	142	5.68	1.886	-2.829	-1.886
90	3.60	3.772	5.658	0.943	143	5.72	4.715	1.886	2.829
91	3.64	0.943	0.943	0	144	5.76	5.658	3.772	3.772
92	3.68	3.772	1.886	2.829	145	5.80	1.886	-6.601	-1.886
93	3.72	-1.886	-6.601	-6.601	146	5.84	1.886	-2.829	0
94	3.76	1.886	1.886	0.943	147	5.88	4.715	0.943	1.886
95	3.80	3.772	3.772	4.715	148	5.92	4.715	4.715	1.886
96	3.84	-0.943	-0.943	-0.943	149	5.96	0.943	-5.658	-2.829
97	3.88	-1.886	-3.772	-2.829	150	6.00	2.829	-3.772	0
98	3.92	-0.943	-3.772	-2.829	151	6.04	1.886	-3.772	0.943
99	3.96	0	-0.943	-2.829	152	6.08	3.772	0	3.772
100	4.00	0.943	0	0	153	6.12	4.715	3.772	4.715
101	4.04	-0.943	-0.943	-4.715	154	6.16	0.943	-3.772	-0.943
102	4.08	-4.715	-10.373	-8.487	155	6.20	2.829	-1.886	1.886
103	4.12	-1.886	-5.658	-5.658	156	6.24	1.886	-2.829	-0.943
104	4.16	-1.886	-3.772	-5.658	157	6.28	3.772	3.772	1.886
105	4.20	-1.886	-0.943	-3.772	158	6.32	1.886	1.886	-0.943
106	4.24	0	3.772	-0.943	159	6.36	2.829	1.886	0
107	4.28	-0.943	-2.829	-2.829	160	6.40	2.829	-1.886	-1.886
108	4.32	-1.886	-4.715	-3.772	161	6.44	2.829	1.886	0
109	4.36	-0.943	-1.886	0	162	6.48	2.829	3.772	0
110	4.40	1.886	3.772	4.715	163	6.52	0.943	0	-1.886
111	4.44	-1.886	-2.829	-0.943	164	6.56	-0.943	-4.715	-5.658
112	4.48	-0.943	0.943	2.829	165	6.60	-1.886	-5.658	-7.544
113	4.52	0.943	2.829	4.715	166	6.64	0.943	2.829	-0.943
114	4.56	0	0	4.715	167	6.68	4.715	6.601	3.772
115	4.60	-4.715	-8.487	-2.829	168	6.72	2.829	4.715	1.886
116	4.64	-1.886	-1.886	0.943	169	6.76	0	0	-0.943
117	4.68	0	2.829	4.715	170	6.80	0	-1.886	-0.943
118	4.72	0	0	4.715	171	6.84	1.886	3.772	1.886
119	4.76	-0.943	-1.886	1.886	172	6.88	2.829	2.829	2.829
120	4.80	-3.772	-8.487	-3.772	173	6.92	0	1.886	0.943
121	4.84	-2.829	-3.772	-1.886	174	6.96	0.943	-3.772	-0.943
122	4.88	-1.886	-1.886	-0.943	175	7.00	3.772	1.886	1.886
123	4.92	-2.829	-1.886	-0.943	176	7.04	3.772	3.772	0.943
124	4.96	-4.715	-3.772	-3.772	177	7.08	3.772	6.601	1.886
125	5.00	-3.772	-3.772	-2.829	178	7.12	0.943	0.943	-1.886
126	5.04	-1.886	-0.943	1.886	179	7.16	0	0	-2.829
127	5.08	-3.772	-6.601	-0.943	180	7.20	2.829	2.829	0
128	5.12	-0.943	0.943	2.829	181	7.24	3.772	3.772	-0.943
129	5.16	-1.886	0	1.886	182	7.28	2.829	2.829	-0.943
130	5.20	0	-0.943	1.886	183	7.32	-0.943	-2.829	-4.715
131	5.24	0	-4.715	0.943	184	7.36	0.943	0	-1.886
132	5.28	0	-4.715	1.886	185	7.40	0.943	-0.943	-1.886
133	5.32	1.886	0	2.829	186	7.44	1.886	0.943	0.943

Experimental Data Record No.
17 Aug 25mmdia 1052-26gate1

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)	Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
187	7.48	1.886	2.829	0.943	240	9.60	-1.886	-1.886	1.886
188	7.52	1.886	1.886	1.886	241	9.64	0.943	-3.772	0.943
189	7.56	0	-0.943	0	242	9.68	4.715	0	7.544
190	7.60	-0.943	-3.772	-1.886	243	9.72	3.772	1.886	3.772
191	7.64	0.943	1.886	1.886	244	9.76	2.829	0	1.886
192	7.68	1.886	4.715	2.829	245	9.80	-0.943	-4.715	-4.715
193	7.72	1.886	4.715	3.772	246	9.84	-1.886	-8.487	-4.715
194	7.76	0.943	1.886	0	247	9.88	2.829	0.943	1.886
195	7.80	0	0.943	0.943	248	9.92	0.943	0	-0.943
196	7.84	0	1.886	-0.943	249	9.96	1.886	0	0
197	7.88	2.829	3.772	3.772	250	10.00	-0.943	-2.829	-1.886
198	7.92	2.829	4.715	1.886	251	10.04	-1.886	-3.772	-2.829
199	7.96	0	0.943	-2.829	252	10.08	-0.943	-2.829	-2.829
200	8.00	0	0.943	-3.772	253	10.12	3.772	2.829	1.886
201	8.04	-0.943	-1.886	-3.772	254	10.16	2.829	0.943	0
202	8.08	0	0	-2.829	255	10.20	-1.886	-6.601	-4.715
203	8.12	0	0	-3.772	256	10.24	1.886	-3.772	-0.943
204	8.16	1.886	2.829	0.943	257	10.28	2.829	0	3.772
205	8.20	3.772	5.658	3.772	258	10.32	4.715	3.772	5.658
206	8.24	0	0	-0.943	259	10.36	1.886	-2.829	0.943
207	8.28	0.943	-0.943	-0.943	260	10.40	-1.886	-7.544	-1.886
208	8.32	-1.886	-4.715	-5.658	261	10.44	1.886	-3.772	0
209	8.36	3.772	4.715	0.943	262	10.48	2.829	2.829	1.886
210	8.40	4.715	7.544	0.943	263	10.52	5.658	4.715	3.772
211	8.44	1.886	2.829	-2.829	264	10.56	0.943	-2.829	-0.943
212	8.48	-0.943	-6.601	-9.43	265	10.60	0	-4.715	-4.715
213	8.52	0	-1.886	-9.43	266	10.64	1.886	-2.829	-0.943
214	8.56	2.829	2.829	-4.715	267	10.68	0.943	-2.829	-1.886
215	8.60	4.715	5.658	-1.886	268	10.72	1.886	-0.943	-2.829
216	8.64	0.943	-0.943	-6.601	269	10.76	1.886	-1.886	-0.943
217	8.68	-1.886	-5.658	-9.43	270	10.80	1.886	-2.829	-2.829
218	8.72	0.943	-0.943	-7.544	271	10.84	1.886	-0.943	0
219	8.76	2.829	3.772	-2.829	272	10.88	3.772	4.715	3.772
220	8.80	1.886	1.886	-4.715	273	10.92	3.772	2.829	2.829
221	8.84	0	-2.829	-6.601	274	10.96	2.829	0.943	3.772
222	8.88	-0.943	-3.772	-7.544	275	11.00	-1.886	-5.658	-3.772
223	8.92	1.886	-0.943	-4.715	276	11.04	3.772	3.772	3.772
224	8.96	4.715	8.487	5.658	277	11.08	2.829	0	2.829
225	9.00	4.715	4.715	2.829	278	11.12	2.829	-0.943	1.886
226	9.04	0	-3.772	-2.829	279	11.16	0.943	-3.772	-0.943
227	9.08	0	-6.601	-5.658	280	11.20	1.886	-2.829	0.943
228	9.12	1.886	-0.943	-1.886	281	11.24	2.829	0	2.829
229	9.16	7.544	9.43	4.715	282	11.28	1.886	-4.715	0
230	9.20	3.772	2.829	-1.886	283	11.32	0	-4.715	-0.943
231	9.24	2.829	-2.829	-5.658	284	11.36	1.886	-3.772	-0.943
232	9.28	1.886	-4.715	-5.658	285	11.40	4.715	1.886	3.772
233	9.32	2.829	-0.943	-4.715	286	11.44	4.715	2.829	2.829
234	9.36	4.715	3.772	0.943	287	11.48	1.886	-1.886	-0.943
235	9.40	2.829	1.886	-2.829	288	11.52	4.715	1.886	2.829
236	9.44	2.829	-2.829	-5.658	289	11.56	1.886	-4.715	-0.943
237	9.48	0	-5.658	-3.772	290	11.60	1.886	-3.772	-0.943
238	9.52	3.772	5.658	3.772	291	11.64	1.886	-2.829	-0.943
239	9.56	8.487	5.658	7.544	292	11.68	4.715	3.772	2.829

[illegible]

Experimental Data Record No.										
17 Aug 25mmdia 1052-26gate1										
Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)		Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
399	15.96	0.943	2.829	4.715		452	18.08	1.886	-1.886	3.772
400	16.00	0.943	2.829	6.601		453	18.12	4.715	1.886	6.601
401	16.04	-0.943	0.943	3.772		454	18.16	6.601	6.601	8.487
402	16.08	-0.943	0.943	2.829		455	18.20	1.886	0.943	3.772
403	16.12	-2.829	-2.829	-0.943		456	18.24	0	-2.829	-0.943
404	16.16	-5.658	-6.601	-3.772		457	18.28	-0.943	-4.715	-2.829
405	16.20	-0.943	0.943	0.943		458	18.32	0.943	-1.886	-1.886
406	16.24	-1.886	0.943	0		459	18.36	2.829	0.943	0.943
407	16.28	-0.943	2.829	0		460	18.40	0	-1.886	-2.829
408	16.32	-3.772	-1.886	-3.772		461	18.44	4.715	0	-1.886
409	16.36	-1.886	-0.943	-1.886		462	18.48	0.943	-2.829	-1.886
410	16.40	0.943	0.943	0.943		463	18.52	1.886	0.943	0
411	16.44	0.943	2.829	0		464	18.56	2.829	2.829	3.772
412	16.48	-0.943	-3.772	-2.829		465	18.60	0	2.829	2.829
413	16.52	-1.886	-5.658	-3.772		466	18.64	-0.943	-0.943	0.943
414	16.56	1.886	2.829	0.943		467	18.68	7.544	1.886	1.886
415	16.60	0.943	-0.943	0.943		468	18.72	0.943	5.658	3.772
416	16.64	0.943	0	0		469	18.76	3.772	3.772	6.601
417	16.68	0.943	0	2.829		470	18.80	2.829	-1.886	1.886
418	16.72	0.943	2.829	2.829		471	18.84	-4.715	-7.544	-2.829
419	16.76	0	0.943	3.772		472	18.88	4.715	0.943	2.829
420	16.80	2.829	3.772	6.601		473	18.92	0.943	-1.886	-1.886
421	16.84	0.943	1.886	3.772		474	18.96	4.715	0	0.943
422	16.88	1.886	3.772	5.658		475	19.00	-0.943	-5.658	-3.772
423	16.92	-0.943	-0.943	0.943		476	19.04	-1.886	-5.658	-4.715
424	16.96	0	0	0.943		477	19.08	4.715	1.886	1.886
425	17.00	0.943	3.772	2.829		478	19.12	4.715	2.829	0.943
426	17.04	-1.886	-1.886	-2.829		479	19.16	0	-1.886	-2.829
427	17.08	0	-0.943	-0.943		480	19.20	-0.943	-2.829	-1.886
428	17.12	0.943	-1.886	-0.943		481	19.24	3.772	3.772	1.886
429	17.16	1.886	1.886	0		482	19.28	1.886	-1.886	-1.886
430	17.20	1.886	0	-0.943		483	19.32	2.829	3.772	1.886
431	17.24	1.886	-1.886	-0.943		484	19.36	2.829	0.943	0
432	17.28	1.886	-1.886	0		485	19.40	-0.943	-5.658	-4.715
433	17.32	2.829	0	1.886		486	19.44	1.886	0	-1.886
434	17.36	4.715	3.772	6.601		487	19.48	0.943	-2.829	-2.829
435	17.40	2.829	0.943	5.658		488	19.52	1.886	0	-1.886
436	17.44	2.829	1.886	4.715		489	19.56	1.886	0.943	0
437	17.48	1.886	-1.886	2.829		490	19.60	2.829	1.886	-1.886
438	17.52	0.943	-2.829	0		491	19.64	-0.943	-3.772	-6.601
439	17.56	4.715	2.829	2.829		492	19.68	0	-2.829	-4.715
440	17.60	3.772	0.943	2.829		493	19.72	0	-3.772	-7.544
441	17.64	1.886	-1.886	-0.943		494	19.76	0.943	-2.829	-3.772
442	17.68	0	-8.487	-3.772		495	19.80	1.886	-2.829	-5.658
443	17.72	1.886	-2.829	-0.943		496	19.84	0.943	-3.772	-4.715
444	17.76	4.715	1.886	1.886		497	19.88	2.829	1.886	-0.943
445	17.80	5.658	5.658	2.829		498	19.92	2.829	3.772	-3.772
446	17.84	-0.943	-6.601	-4.715		499	19.96	1.886	-0.943	-3.772
447	17.88	0	-8.487	-4.715		500	20.00	0.943	-2.829	-5.658
448	17.92	0	-5.658	-3.772		501	20.04	2.829	1.886	-1.886
449	17.96	4.715	5.658	3.772		502	20.08	2.829	4.715	-0.943
450	18.00	4.715	5.658	5.658		503	20.12	0.943	0.943	-3.772
451	18.04	0.943	-0.943	1.886		504	20.16	-0.943	-4.715	-5.658

Experimental Data Record No.										
17 Aug 25mmdia 1052-26gate1										
Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)		Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
505	20.20	0	-2.829	-4.715		558	22.32	4.715	4.715	1.886
506	20.24	1.886	1.886	-0.943		559	22.36	2.829	3.772	0
507	20.28	0	-0.943	-2.829		560	22.40	4.715	8.487	3.772
508	20.32	-1.886	-4.715	-6.601		561	22.44	3.772	4.715	0.943
509	20.36	-2.829	-6.601	-7.544		562	22.48	2.829	2.829	-0.943
510	20.40	0	1.886	-2.829		563	22.52	0.943	0	-3.772
511	20.44	5.658	11.316	5.658		564	22.56	4.715	8.487	3.772
512	20.48	-0.943	-1.886	-3.772		565	22.60	1.886	3.772	0.943
513	20.52	-1.886	-6.601	-7.544		566	22.64	2.829	1.886	0.943
514	20.56	0	-3.772	-1.886		567	22.68	-0.943	-4.715	-5.658
515	20.60	3.772	2.829	1.886		568	22.72	0	0	-1.886
516	20.64	2.829	2.829	1.886		569	22.76	2.829	3.772	0.943
517	20.68	1.886	1.886	0.943		570	22.80	0	-0.943	-5.658
518	20.72	0	-0.943	-0.943		571	22.84	0	-0.943	-4.715
519	20.76	0.943	-0.943	0		572	22.88	0.943	-1.886	-4.715
520	20.80	-1.886	-2.829	-4.715		573	22.92	2.829	4.715	-1.886
521	20.84	0.943	3.772	0		574	22.96	1.886	5.658	-0.943
522	20.88	-0.943	1.886	-0.943		575	23.00	0	0	-2.829
523	20.92	-2.829	-3.772	-4.715		576	23.04	-1.886	-2.829	-5.658
524	20.96	0	0	-0.943		577	23.08	-1.886	-1.886	-3.772
525	21.00	0.943	0	0		578	23.12	0	3.772	1.886
526	21.04	0.943	1.886	1.886		579	23.16	0	1.886	0.943
527	21.08	-1.886	-3.772	-2.829		580	23.20	0	1.886	1.886
528	21.12	-3.772	-3.772	-4.715		581	23.24	0	-1.886	0
529	21.16	-2.829	-3.772	-3.772		582	23.28	-1.886	-1.886	-0.943
530	21.20	-0.943	-0.943	-2.829		583	23.32	0	1.886	3.772
531	21.24	0.943	1.886	0		584	23.36	0.943	2.829	2.829
532	21.28	-1.886	-0.943	-0.943		585	23.40	-0.943	-0.943	0.943
533	21.32	0	0	-0.943		586	23.44	-0.943	-3.772	-0.943
534	21.36	0	-0.943	-1.886		587	23.48	0.943	-0.943	-0.943
535	21.40	2.829	6.601	0		588	23.52	0	-1.886	-1.886
536	21.44	1.886	5.658	1.886		589	23.56	0.943	0	0
537	21.48	-0.943	-0.943	-2.829		590	23.60	-1.886	-3.772	-3.772
538	21.52	-2.829	-4.715	-6.601		591	23.64	0	-4.715	-2.829
539	21.56	0	-1.886	-3.772		592	23.68	0	0	-2.829
540	21.60	0.943	1.886	-2.829		593	23.72	2.829	4.715	2.829
541	21.64	0.943	1.886	0		594	23.76	0.943	2.829	-0.943
542	21.68	0.943	0	-1.886		595	23.80	0.943	0	-1.886
543	21.72	0.943	2.829	-0.943		596	23.84	1.886	1.886	0
544	21.76	1.886	2.829	1.886		597	23.88	0.943	0.943	-0.943
545	21.80	0	0	-0.943		598	23.92	2.829	0	1.886
546	21.84	0.943	0	0		599	23.96	-1.886	-8.487	-5.658
547	21.88	0	-1.886	-1.886		600	24.00	-0.943	-4.715	-2.829
548	21.92	1.886	4.715	3.772		601	24.04	0.943	0	0.943
549	21.96	3.772	4.715	5.658		602	24.08	0.943	0	2.829
550	22.00	-0.943	-3.772	-1.886		603	24.12	0.943	-0.943	0
551	22.04	1.886	2.829	0.943		604	24.16	-2.829	-5.658	-5.658
552	22.08	-0.943	-4.715	-5.658		605	24.20	0	0	-1.886
553	22.12	2.829	3.772	0		606	24.24	0.943	-0.943	-0.943
554	22.16	0	-1.886	-4.715		607	24.28	-0.943	-2.829	-3.772
555	22.20	2.829	5.658	0		608	24.32	0	2.829	-1.886
556	22.24	2.829	2.829	0		609	24.36	3.772	5.658	1.886
557	22.28	0.943	-1.886	-2.829		610	24.40	-0.943	-4.715	-5.658

Experimental Data Record No.
17 Aug 25mmdia 1052-26gate1

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
611	24.44	1.886	1.886	0.943
612	24.48	2.829	4.715	3.772
613	24.52	1.886	0.943	3.772
614	24.56	0.943	-3.772	0
615	24.60	0	-4.715	-2.829
616	24.64	1.886	1.886	0.943
617	24.68	2.829	4.715	2.829
618	24.72	2.829	3.772	2.829
619	24.76	0.943	-2.829	-2.829
620	24.80	-0.943	-5.658	-5.658
621	24.84	2.829	5.658	2.829
622	24.88	2.829	3.772	0.943
623	24.92	-1.886	-2.829	-3.772
624	24.96	-2.829	-7.544	-7.544
625	25.00	0	0	0
626	25.04	3.772	3.772	1.886
627	25.08	1.886	1.886	-0.943
628	25.12	-0.943	-5.658	-3.772
629	25.16	0.943	-0.943	0
630	25.20	2.829	3.772	4.715
631	25.24	7.544	5.658	4.715
632	25.28	5.658	1.886	-0.943
633	25.32	1.886	-1.886	0
634	25.36	2.829	0.943	0.943
635	25.40	0.943	0.943	-0.943
636	25.44	4.715	3.772	-0.943
637	25.48	0.943	-1.886	-2.829
638	25.52	0	-3.772	-2.829
639	25.56	0.943	-0.943	-1.886
640	25.60	6.601	7.544	4.715
641	25.64	5.658	6.601	2.829
642	25.68	-1.886	-2.829	-3.772
643	25.72	1.886	0	-0.943
644	25.76	4.715	0.943	-1.886
645	25.80	0.943	4.715	0.943
646	25.84	3.772	5.658	0.943
647	25.88	4.715	5.658	1.886
648	25.92	1.886	-1.886	-3.772
649	25.96	3.772	0.943	-2.829
650	26.00	2.829	2.829	-1.886
651	26.04	0	-2.829	-7.544
652	26.08	2.829	4.715	0
653	26.12	1.886	0	-2.829
654	26.16	0.943	0	-1.886
655	26.20	4.715	4.715	2.829
656	26.24	0.943	0	-0.943
657	26.28	1.886	0.943	-0.943
658	26.32	2.829	2.829	0
659	26.36	1.886	0.943	-1.886
660	26.40	0	-5.658	-7.544
661	26.44	1.886	0.943	-3.772
662	26.48	0.943	-2.829	-4.715
663	26.52	4.715	3.772	-0.943

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
664	26.56	3.772	3.772	-2.829
665	26.60	3.772	4.715	-2.829
666	26.64	3.772	2.829	-0.943
667	26.68	1.886	-1.886	-6.601
668	26.72	2.829	1.886	-3.772
669	26.76	0	-0.943	-5.658
670	26.80	2.829	3.772	-0.943
671	26.84	-0.943	-4.715	-5.658
672	26.88	-0.943	-5.658	-5.658
673	26.92	0	-2.829	-3.772
674	26.96	1.886	0.943	0
675	27.00	2.829	6.601	6.601
676	27.04	-1.886	-1.886	-1.886
677	27.08	1.886	0	2.829
678	27.12	3.772	4.715	5.658
679	27.16	2.829	8.487	5.658
680	27.20	0.943	1.886	0.943
681	27.24	-3.772	-5.658	-3.772
682	27.28	0	0.943	0
683	27.32	1.886	5.658	1.886
684	27.36	0	2.829	-1.886
685	27.40	-3.772	-3.772	-5.658
686	27.44	-1.886	-3.772	-3.772
687	27.48	-1.886	-2.829	-2.829
688	27.52	-1.886	0	-2.829
689	27.56	-1.886	0.943	-2.829
690	27.60	-1.886	-0.943	0.943
691	27.64	-4.715	-5.658	-4.715
692	27.68	-1.886	-0.943	-0.943
693	27.72	1.886	7.544	6.601
694	27.76	-0.943	2.829	3.772
695	27.80	-3.772	0	1.886
696	27.84	-5.658	-4.715	-2.829
697	27.88	-0.943	2.829	2.829
698	27.92	0.943	6.601	6.601
699	27.96	-3.772	0.943	0.943
700	28.00	-6.601	-6.601	-4.715
701	28.04	-4.715	-4.715	-3.772
702	28.08	-0.943	0.943	-0.943
703	28.12	-0.943	1.886	0
704	28.16	0	3.772	0.943
705	28.20	-3.772	-5.658	-5.658
706	28.24	0	0.943	-0.943
707	28.28	0.943	3.772	2.829
708	28.32	2.829	6.601	4.715
709	28.36	2.829	1.886	2.829
710	28.40	1.886	1.886	2.829
711	28.44	0.943	0.943	0.943
712	28.48	2.829	0.943	1.886
713	28.52	4.715	5.658	5.658
714	28.56	0	-3.772	-1.886
715	28.60	1.886	0	0.943
716	28.64	-0.943	-4.715	-1.886

Experimental Data Record No.														
17 Aug 25mmdia 1052-26gate1														
Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)		Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)				
717	28.68	3.772	2.829	2.829		770	30.80	0.943	2.829	0.943				
718	28.72	2.829	0.943	0.943		771	30.84	1.886	3.772	2.829				
719	28.76	0.943	-1.886	-2.829		772	30.88	-0.943	-1.886	-0.943				
720	28.80	4.715	4.715	3.772		773	30.92	0	2.829	1.886				
721	28.84	0.943	-1.886	-3.772		774	30.96	0	4.715	2.829				
722	28.88	1.886	1.886	-1.886		775	31.00	-1.886	0	0.943				
723	28.92	0	-3.772	-4.715		776	31.04	-1.886	0.943	0.943				
724	28.96	1.886	-0.943	-1.886		777	31.08	-3.772	-4.715	-0.943				
725	29.00	2.829	0	0		778	31.12	-0.943	1.886	2.829				
726	29.04	4.715	5.658	4.715		779	31.16	-0.943	0.943	0.943				
727	29.08	6.601	7.544	7.544		780	31.20	-0.943	3.772	2.829				
728	29.12	2.829	0.943	1.886		781	31.24	-5.658	-2.829	-2.829				
729	29.16	2.829	0	0.943		782	31.28	-1.886	0	-0.943				
730	29.20	2.829	-0.943	1.886		783	31.32	-0.943	0.943	-0.943				
731	29.24	4.715	5.658	6.601		784	31.36	0.943	4.715	1.886				
732	29.28	2.829	2.829	4.715		785	31.40	-0.943	0.943	-1.886				
733	29.32	0.943	0.943	1.886		786	31.44	-0.943	-1.886	-3.772				
734	29.36	-2.829	-7.544	-4.715		787	31.48	-1.886	-1.886	-3.772				
735	29.40	0	0	1.886		788	31.52	-0.943	0	-2.829				
736	29.44	0.943	2.829	3.772		789	31.56	0.943	2.829	-0.943				
737	29.48	-0.943	2.829	0.943		790	31.60	-0.943	-0.943	-2.829				
738	29.52	0.943	2.829	2.829		791	31.64	-1.886	-2.829	-4.715				
739	29.56	-2.829	-4.715	-0.943		792	31.68	3.772	4.715	0				
740	29.60	2.829	6.601	6.601		793	31.72	2.829	3.772	-0.943				
741	29.64	0	2.829	2.829		794	31.76	1.886	3.772	-1.886				
742	29.68	0.943	5.658	5.658		795	31.80	0	0	-3.772				
743	29.72	-1.886	-2.829	1.886		796	31.84	0.943	0	-5.658				
744	29.76	0.943	0.943	3.772		797	31.88	0	-1.886	-9.43				
745	29.80	1.886	3.772	3.772		798	31.92	-0.943	3.772	-5.658				
746	29.84	-0.943	0.943	-0.943		799	31.96	2.829	2.829	-4.715				
747	29.88	0	0.943	0		800	32.00	0.943	-2.829	-8.487				
748	29.92	-0.943	-2.829	-1.886		801	32.04	-1.886	-3.772	-8.487				
749	29.96	-0.943	-0.943	-0.943		802	32.08	0	0	-5.658				
750	30.00	0.943	1.886	1.886		803	32.12	1.886	1.886	-2.829				
751	30.04	1.886	3.772	1.886		804	32.16	1.886	0	0				
752	30.08	0	0.943	0		805	32.20	-1.886	-0.943	-1.886				
753	30.12	0	-0.943	-0.943		806	32.24	0.943	-1.886	-3.772				
754	30.16	0	-0.943	-1.886		807	32.28	2.829	4.715	3.772				
755	30.20	2.829	3.772	2.829		808	32.32	3.772	4.715	2.829				
756	30.24	1.886	2.829	0.943		809	32.36	0	-0.943	-1.886				
757	30.28	-0.943	-3.772	-2.829		810	32.40	-1.886	-3.772	-3.772				
758	30.32	0.943	-0.943	-0.943		811	32.44	-0.943	-0.943	-2.829				
759	30.36	0.943	0.943	0.943		812	32.48	4.715	4.715	1.886				
760	30.40	2.829	3.772	2.829		813	32.52	3.772	0	-2.829				
761	30.44	1.886	3.772	1.886		814	32.56	-0.943	-2.829	-6.601				
762	30.48	1.886	2.829	0.943		815	32.60	-1.886	-7.544	-5.658				
763	30.52	0.943	-0.943	0		816	32.64	-0.943	-3.772	-4.715				
764	30.56	0.943	0.943	-0.943		817	32.68	5.658	0	-1.886				
765	30.60	-0.943	-1.886	-2.829		818	32.72	1.886	0.943	-1.886				
766	30.64	-1.886	-0.943	-3.772		819	32.76	1.886	0.943	0				
767	30.68	0	0.943	-0.943		820	32.80	0.943	-5.658	-3.772				
768	30.72	-1.886	-2.829	-2.829		821	32.84	3.772	0.943	0				
769	30.76	2.829	5.658	2.829		822	32.88	5.658	2.829	4.715				

APPENDIX A

Experimental Data Record No.

17 Aug 25mmdia 1052-26gate1

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)	Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
823	32.92	2.829	1.886	4.715	876	35.04	0.943	-0.943	1.886
824	32.96	2.829	-1.886	2.829	877	35.08	-0.943	-2.829	-0.943
825	33.00	1.886	-1.886	0.943	878	35.12	-1.886	-5.658	-4.715
826	33.04	2.829	0	2.829	879	35.16	2.829	3.772	1.886
827	33.08	5.658	5.658	7.544	880	35.20	1.886	3.772	0.943
828	33.12	1.886	-2.829	0.943	881	35.24	-0.943	-0.943	-1.886
829	33.16	0.943	-3.772	0.943	882	35.28	-1.886	-3.772	-5.658
830	33.20	3.772	1.886	3.772	883	35.32	-0.943	-1.886	-3.772
831	33.24	2.829	0.943	3.772	884	35.36	1.886	3.772	0
832	33.28	0.943	-2.829	0	885	35.40	-0.943	0	-4.715
833	33.32	0	-2.829	-1.886	886	35.44	1.886	1.886	-0.943
834	33.36	0.943	0	0	887	35.48	-0.943	-3.772	-3.772
835	33.40	2.829	2.829	1.886	888	35.52	0	0	-1.886
836	33.44	0.943	-0.943	-0.943	889	35.56	1.886	0.943	0
837	33.48	0.943	-1.886	-1.886	890	35.60	0	0	-1.886
838	33.52	0	-2.829	-3.772	891	35.64	1.886	1.886	0
839	33.56	4.715	5.658	3.772	892	35.68	1.886	0	-0.943
840	33.60	0	-4.715	-1.886	893	35.72	2.829	3.772	1.886
841	33.64	5.658	5.658	4.715	894	35.76	0	-1.886	-1.886
842	33.68	5.658	6.601	5.658	895	35.80	-0.943	-2.829	-3.772
843	33.72	-0.943	-1.886	-3.772	896	35.84	0.943	-0.943	-1.886
844	33.76	0.943	-2.829	-2.829	897	35.88	0.943	-1.886	-1.886
845	33.80	0.943	0	0	898	35.92	0	-5.658	-4.715
846	33.84	3.772	4.715	1.886	899	35.96	0.943	-4.715	-2.829
847	33.88	1.886	3.772	0	900	36.00	2.829	0.943	-1.886
848	33.92	-0.943	-1.886	-3.772	901	36.04	2.829	-0.943	0
849	33.96	0.943	-4.715	-3.772	902	36.08	0.943	-1.886	-2.829
850	34.00	1.886	0	-2.829	903	36.12	0	-2.829	-3.772
851	34.04	0.943	0.943	-2.829	904	36.16	3.772	3.772	1.886
852	34.08	4.715	8.487	2.829	905	36.20	1.886	-0.943	-0.943
853	34.12	0	-0.943	-1.886	906	36.24	2.829	-0.943	0
854	34.16	-0.943	-2.829	-2.829	907	36.28	1.886	-2.829	-1.886
855	34.20	2.829	0.943	0	908	36.32	1.886	-1.886	-0.943
856	34.24	4.715	6.601	6.601	909	36.36	3.772	1.886	2.829
857	34.28	2.829	1.886	5.658	910	36.40	0.943	-3.772	-1.886
858	34.32	1.886	-0.943	2.829	911	36.44	0.943	-5.658	-0.943
859	34.36	0.943	0	1.886	912	36.48	-1.886	-8.487	-4.715
860	34.40	2.829	1.886	4.715	913	36.52	4.715	4.715	6.601
861	34.44	0.943	1.886	0.943	914	36.56	2.829	2.829	3.772
862	34.48	-0.943	-0.943	-4.715	915	36.60	-0.943	-5.658	-1.886
863	34.52	-1.886	-4.715	-5.658	916	36.64	0	-4.715	0
864	34.56	2.829	0.943	0	917	36.68	0.943	-2.829	1.886
865	34.60	1.886	0.943	0	918	36.72	1.886	-0.943	2.829
866	34.64	2.829	3.772	0.943	919	36.76	2.829	0	3.772
867	34.68	0.943	-0.943	-1.886	920	36.80	1.886	0	4.715
868	34.72	0	-2.829	-1.886	921	36.84	0.943	-5.658	2.829
869	34.76	2.829	0.943	2.829	922	36.88	0.943	-0.943	2.829
870	34.80	4.715	6.601	5.658	923	36.92	-0.943	-1.886	0.943
871	34.84	3.772	4.715	5.658	924	36.96	1.886	-0.943	2.829
872	34.88	-0.943	-2.829	-0.943	925	37.00	0	-4.715	0
873	34.92	0.943	-1.886	0	926	37.04	2.829	-2.829	1.886
874	34.96	0.943	-0.943	1.886	927	37.08	3.772	2.829	3.772
875	35.00	4.715	5.658	6.601	928	37.12	4.715	3.772	6.601

Experimental Data Record No.									
17 Aug 25mmdia 1052-26gate1									
Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)	Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
929	37.16	3.772	1.886	6.601	982	39.28	-0.943	-4.715	-0.943
930	37.20	0	-7.544	-0.943	983	39.32	4.715	0.943	3.772
931	37.24	1.886	-2.829	0.943	984	39.36	2.829	1.886	1.886
932	37.28	1.886	-0.943	1.886	985	39.40	6.601	8.487	9.43
933	37.32	2.829	1.886	3.772	986	39.44	3.772	1.886	3.772
934	37.36	-1.886	-5.658	-2.829	987	39.48	3.772	0	2.829
935	37.40	0	-2.829	-1.886	988	39.52	2.829	-0.943	1.886
936	37.44	3.772	0.943	3.772	989	39.56	2.829	-3.772	0
937	37.48	1.886	1.886	4.715	990	39.60	3.772	1.886	4.715
938	37.52	2.829	1.886	4.715	991	39.64	0.943	0	1.886
939	37.56	0	-3.772	0	992	39.68	0	-3.772	-1.886
940	37.60	0.943	-2.829	0	993	39.72	1.886	-4.715	-3.772
941	37.64	1.886	-0.943	1.886	994	39.76	-0.943	0.943	0.943
942	37.68	4.715	4.715	5.658	995	39.80	5.658	3.772	1.886
943	37.72	0.943	-1.886	1.886	996	39.84	-2.829	-0.943	-1.886
944	37.76	-0.943	-3.772	-0.943	997	39.88	0	-3.772	-2.829
945	37.80	0.943	-4.715	0	998	39.92	3.772	0.943	1.886
946	37.84	2.829	0	3.772	999	39.96	2.829	2.829	0.943
947	37.88	5.658	5.658	5.658	1000	40.00	3.772	3.772	1.886
948	37.92	3.772	2.829	3.772	1001	40.04	3.772	0	0.943
949	37.96	3.772	0	1.886	1002	40.08	0.943	-4.715	-0.943
950	38.00	0.943	-4.715	0	1003	40.12	5.658	2.829	2.829
951	38.04	3.772	4.715	3.772	1004	40.16	4.715	4.715	1.886
952	38.08	1.886	0.943	0.943	1005	40.20	1.886	0	-0.943
953	38.12	0.943	0	1.886	1006	40.24	-0.943	-5.658	-6.601
954	38.16	0.943	-0.943	0.943	1007	40.28	-0.943	-4.715	-4.715
955	38.20	1.886	0.943	1.886	1008	40.32	4.715	4.715	0.943
956	38.24	0.943	0	-0.943	1009	40.36	2.829	1.886	-2.829
957	38.28	0.943	0	-0.943	1010	40.40	1.886	0.943	-1.886
958	38.32	0.943	0	-0.943	1011	40.44	1.886	0	-2.829
959	38.36	-1.886	-2.829	-4.715	1012	40.48	0	-4.715	-5.658
960	38.40	0.943	2.829	0	1013	40.52	0.943	-1.886	-3.772
961	38.44	0.943	0.943	-0.943	1014	40.56	2.829	3.772	0
962	38.48	0	-2.829	-3.772	1015	40.60	3.772	3.772	1.886
963	38.52	0.943	0	-0.943	1016	40.64	0	-0.943	-1.886
964	38.56	0.943	-0.943	-2.829	1017	40.68	2.829	2.829	0.943
965	38.60	5.658	4.715	4.715	1018	40.72	0	-1.886	-1.886
966	38.64	-0.943	-4.715	-4.715	1019	40.76	1.886	1.886	0.943
967	38.68	2.829	1.886	0.943	1020	40.80	-0.943	0	0
968	38.72	0	-3.772	-2.829	1021	40.84	-0.943	0.943	0
969	38.76	2.829	-0.943	0	1022	40.88	-0.943	-1.886	0
970	38.80	5.658	3.772	7.544	1023	40.92	0	0.943	1.886
971	38.84	4.715	3.772	5.658	1024	40.96	-1.886	-2.829	0.943
972	38.88	1.886	-0.943	1.886	1025	41.00	-0.943	-0.943	1.886
973	38.92	1.886	-3.772	2.829	1026	41.04	-2.829	-5.658	0
974	38.96	2.829	0	4.715	1027	41.08	-3.772	-6.601	-1.886
975	39.00	3.772	0.943	4.715	1028	41.12	-0.943	2.829	2.829
976	39.04	4.715	3.772	5.658	1029	41.16	-2.829	0	-0.943
977	39.08	-0.943	-5.658	-0.943	1030	41.20	-4.715	-7.544	-4.715
978	39.12	1.886	-2.829	1.886	1031	41.24	-4.715	-6.601	-4.715
979	39.16	2.829	0.943	1.886	1032	41.28	-0.943	2.829	1.886
980	39.20	4.715	5.658	6.601	1033	41.32	0	3.772	3.772
981	39.24	0.943	-2.829	-0.943	1034	41.36	-1.886	0.943	1.886

[illegible]

Experimental Data Record No.
17 Aug 25mmdia 1052-26gate1

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
1141	45.64	1.886	-0.943	-1.886
1142	45.68	0.943	0	-2.829
1143	45.72	0.943	0.943	-1.886
1144	45.76	2.829	2.829	1.886
1145	45.80	0.943	0.943	0.943
1146	45.84	-0.943	-2.829	-1.886
1147	45.88	2.829	4.715	4.715
1148	45.92	2.829	3.772	5.658
1149	45.96	2.829	2.829	3.772
1150	46.00	0.943	0.943	0.943
1151	46.04	-0.943	-0.943	-0.943
1152	46.08	2.829	3.772	2.829
1153	46.12	2.829	7.544	4.715
1154	46.16	-0.943	0	0
1155	46.20	-4.715	-8.487	-6.601
1156	46.24	1.886	2.829	3.772
1157	46.28	1.886	3.772	4.715
1158	46.32	1.886	3.772	4.715
1159	46.36	-1.886	-4.715	0.943
1160	46.40	-3.772	-6.601	-0.943
1161	46.44	-0.943	0.943	3.772
1162	46.48	0.943	4.715	5.658
1163	46.52	0	2.829	6.601
1164	46.56	-2.829	-6.601	0
1165	46.60	-0.943	-2.829	0.943
1166	46.64	1.886	5.658	5.658
1167	46.68	3.772	10.373	7.544
1168	46.72	-1.886	-2.829	-0.943
1169	46.76	-2.829	-6.601	-5.658
1170	46.80	0.943	-1.886	-2.829
1171	46.84	1.886	1.886	-1.886
1172	46.88	1.886	3.772	-0.943
1173	46.92	-0.943	-1.886	-4.715
1174	46.96	0.943	-0.943	-1.886
1175	47.00	2.829	-0.943	-0.943
1176	47.04	2.829	3.772	2.829
1177	47.08	3.772	2.829	3.772
1178	47.12	1.886	1.886	2.829
1179	47.16	1.886	-1.886	0.943
1180	47.20	1.886	2.829	2.829
1181	47.24	5.658	8.487	7.544
1182	47.28	0.943	5.658	4.715
1183	47.32	0	0	-0.943
1184	47.36	-1.886	-2.829	-2.829
1185	47.40	2.829	0.943	-0.943
1186	47.44	4.715	5.658	1.886
1187	47.48	0	0	-4.715
1188	47.52	-1.886	-4.715	-6.601
1189	47.56	-1.886	-3.772	-4.715
1190	47.60	0.943	1.886	0
1191	47.64	1.886	0.943	-0.943
1192	47.68	-0.943	-0.943	-2.829
1193	47.72	-4.715	-7.544	-4.715

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
1194	47.76	3.772	2.829	4.715
1195	47.80	1.886	0.943	0.943
1196	47.84	0	5.658	4.715
1197	47.88	4.715	5.658	4.715
1198	47.92	0.943	-1.886	0
1199	47.96	1.886	1.886	2.829
1200	48.00	4.715	5.658	4.715
1201	48.04	3.772	2.829	3.772
1202	48.08	-0.943	-0.943	-2.829
1203	48.12	0	-1.886	-3.772
1204	48.16	2.829	0.943	0
1205	48.20	1.886	0.943	-1.886
1206	48.24	0.943	0	-1.886
1207	48.28	-1.886	-3.772	-5.658
1208	48.32	0	-3.772	-1.886
1209	48.36	1.886	-1.886	0.943
1210	48.40	3.772	0.943	0.943
1211	48.44	0.943	-0.943	0
1212	48.48	0.943	-0.943	-0.943
1213	48.52	0.943	0.943	1.886
1214	48.56	0.943	0.943	0.943
1215	48.60	2.829	3.772	2.829
1216	48.64	-0.943	-5.658	-0.943
1217	48.68	0.943	-2.829	-0.943
1218	48.72	0	-2.829	-0.943
1219	48.76	3.772	1.886	0.943
1220	48.80	1.886	-0.943	-0.943
1221	48.84	0.943	-2.829	-2.829
1222	48.88	0	-2.829	-4.715
1223	48.92	2.829	1.886	0
1224	48.96	5.658	9.43	3.772
1225	49.00	1.886	1.886	-0.943
1226	49.04	0	-2.829	-3.772
1227	49.08	-1.886	-6.601	-5.658
1228	49.12	4.715	6.601	3.772
1229	49.16	5.658	11.316	7.544
1230	49.20	1.886	1.886	0
1231	49.24	0	-6.601	-3.772
1232	49.28	1.886	-1.886	-2.829
1233	49.32	4.715	5.658	0.943
1234	49.36	4.715	6.601	1.886
1235	49.40	1.886	0.943	-2.829
1236	49.44	0	-3.772	-4.715
1237	49.48	1.886	0	-3.772
1238	49.52	5.658	4.715	1.886
1239	49.56	4.715	3.772	-0.943
1240	49.60	1.886	0	-3.772
1241	49.64	1.886	-1.886	-2.829
1242	49.68	0.943	-1.886	-5.658
1243	49.72	4.715	4.715	0
1244	49.76	3.772	4.715	-0.943
1245	49.80	0.943	-0.943	-4.715
1246	49.84	2.829	0	-1.886

Experimental Data Record No.
17 Aug 25mmdia 1052-26gate1

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)	Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
1247	49.88	4.715	2.829	-0.943	1300	52.00	1.886	-1.886	-0.943
1248	49.92	2.829	2.829	-1.886	1301	52.04	1.886	0	0
1249	49.96	3.772	3.772	0	1302	52.08	1.886	0.943	0
1250	50.00	1.886	-1.886	-2.829	1303	52.12	-0.943	-6.601	-3.772
1251	50.04	0	-5.658	-6.601	1304	52.16	-0.943	-5.658	-4.715
1252	50.08	1.886	-0.943	-3.772	1305	52.20	0.943	1.886	0
1253	50.12	4.715	4.715	0	1306	52.24	3.772	4.715	3.772
1254	50.16	0.943	0	-4.715	1307	52.28	0.943	0	0
1255	50.20	0	-0.943	-4.715	1308	52.32	-1.886	-4.715	-2.829
1256	50.24	0.943	0	-3.772	1309	52.36	0.943	0.943	0.943
1257	50.28	1.886	3.772	-0.943	1310	52.40	1.886	5.658	3.772
1258	50.32	2.829	3.772	0.943	1311	52.44	0	5.658	3.772
1259	50.36	-1.886	0	-3.772	1312	52.48	-0.943	-0.943	0.943
1260	50.40	0	-1.886	-1.886	1313	52.52	-2.829	-3.772	-1.886
1261	50.44	0.943	-0.943	0	1314	52.56	0	2.829	1.886
1262	50.48	2.829	3.772	2.829	1315	52.60	1.886	7.544	5.658
1263	50.52	0.943	-0.943	0	1316	52.64	0.943	5.658	2.829
1264	50.56	0.943	0.943	0	1317	52.68	-4.715	-4.715	-5.658
1265	50.60	0.943	-1.886	-1.886	1318	52.72	-1.886	-1.886	-2.829
1266	50.64	1.886	0.943	-0.943	1319	52.76	0	0.943	0
1267	50.68	0	-1.886	-5.658	1320	52.80	-0.943	1.886	0.943
1268	50.72	1.886	1.886	-1.886	1321	52.84	-0.943	0.943	-0.943
1269	50.76	1.886	1.886	-0.943	1322	52.88	-3.772	-5.658	-1.886
1270	50.80	0	-4.715	-4.715	1323	52.92	-0.943	-0.943	1.886
1271	50.84	0.943	0.943	-3.772	1324	52.96	0	0.943	2.829
1272	50.88	0	0	-4.715	1325	53.00	1.886	5.658	6.601
1273	50.92	3.772	6.601	1.886	1326	53.04	-1.886	-0.943	1.886
1274	50.96	0	1.886	-1.886	1327	53.08	-0.943	-2.829	0.943
1275	51.00	0	3.772	-1.886	1328	53.12	-1.886	-2.829	-0.943
1276	51.04	0.943	1.886	-1.886	1329	53.16	1.886	5.658	4.715
1277	51.08	0	0	-2.829	1330	53.20	1.886	5.658	3.772
1278	51.12	1.886	0.943	-0.943	1331	53.24	-0.943	0	-0.943
1279	51.16	-0.943	-1.886	-3.772	1332	53.28	-1.886	-4.715	-3.772
1280	51.20	0	0	-2.829	1333	53.32	-0.943	-1.886	-1.886
1281	51.24	1.886	0.943	-0.943	1334	53.36	1.886	4.715	1.886
1282	51.28	0	-0.943	-1.886	1335	53.40	1.886	2.829	1.886
1283	51.32	-1.886	-3.772	-4.715	1336	53.44	-2.829	-3.772	-5.658
1284	51.36	-1.886	-0.943	-3.772	1337	53.48	-0.943	-7.544	-5.658
1285	51.40	-0.943	0.943	0	1338	53.52	2.829	0	0.943
1286	51.44	-0.943	0	-0.943	1339	53.56	0.943	0.943	0
1287	51.48	-3.772	-2.829	-4.715	1340	53.60	0	-0.943	-1.886
1288	51.52	-3.772	-5.658	-4.715	1341	53.64	1.886	0.943	0.943
1289	51.56	-0.943	0.943	0.943	1342	53.68	1.886	0	1.886
1290	51.60	-1.886	0	0.943	1343	53.72	2.829	2.829	3.772
1291	51.64	-1.886	0.943	0.943	1344	53.76	-0.943	-3.772	-2.829
1292	51.68	-1.886	0	1.886	1345	53.80	1.886	0.943	1.886
1293	51.72	-0.943	1.886	3.772	1346	53.84	1.886	0.943	0.943
1294	51.76	-1.886	-2.829	0	1347	53.88	2.829	2.829	2.829
1295	51.80	0	0	3.772	1348	53.92	0.943	-0.943	-0.943
1296	51.84	2.829	5.658	6.601	1349	53.96	0.943	-0.943	-1.886
1297	51.88	1.886	2.829	3.772	1350	54.00	0.943	-1.886	-2.829
1298	51.92	0	-0.943	0.943	1351	54.04	0	-2.829	-2.829
1299	51.96	-2.829	-7.544	-5.658	1352	54.08	1.886	-0.943	0

Experimental Data Record No.
17 Aug 25mmdia 1052-26gate1

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
1353	54.12	-0.943	-4.715	-4.715
1354	54.16	2.829	3.772	0.943
1355	54.20	2.829	1.886	0
1356	54.24	1.886	0.943	0
1357	54.28	0	-3.772	-2.829
1358	54.32	2.829	0.943	0.943
1359	54.36	2.829	2.829	2.829
1360	54.40	3.772	3.772	4.715
1361	54.44	1.886	1.886	0.943
1362	54.48	-0.943	-5.658	-4.715
1363	54.52	0	0	-2.829
1364	54.56	-1.886	-0.943	-4.715
1365	54.60	-1.886	-1.886	-4.715
1366	54.64	-0.943	-1.886	-4.715
1367	54.68	0.943	3.772	-0.943
1368	54.72	1.886	5.658	0.943
1369	54.76	-2.829	-1.886	-5.658
1370	54.80	-0.943	-0.943	-3.772
1371	54.84	-3.772	-2.829	-7.544
1372	54.88	1.886	5.658	0
1373	54.92	-2.829	-1.886	-6.601
1374	54.96	-1.886	0	-3.772
1375	55.00	-1.886	-1.886	-1.886
1376	55.04	1.886	3.772	0.943
1377	55.08	2.829	5.658	1.886
1378	55.12	0.943	0.943	-1.886
1379	55.16	-0.943	-1.886	-1.886
1380	55.20	0	-4.715	-6.601
1381	55.24	1.886	2.829	-1.886
1382	55.28	2.829	3.772	-0.943
1383	55.32	-1.886	1.886	-2.829
1384	55.36	0	-2.829	-3.772
1385	55.40	-1.886	-4.715	-5.658
1386	55.44	0	0	-2.829
1387	55.48	4.715	7.544	4.715
1388	55.52	0	0.943	1.886
1389	55.56	0	-1.886	0
1390	55.60	1.886	1.886	2.829
1391	55.64	3.772	4.715	5.658
1392	55.68	4.715	4.715	4.715
1393	55.72	-0.943	-0.943	0
1394	55.76	1.886	-6.601	-3.772
1395	55.80	2.829	0.943	1.886
1396	55.84	4.715	2.829	0.943
1397	55.88	3.772	3.772	0.943
1398	55.92	-3.772	-2.829	-5.658
1399	55.96	2.829	-1.886	-3.772
1400	56.00	1.886	-0.943	-2.829
1401	56.04	2.829	1.886	-2.829
1402	56.08	0.943	0.943	-0.943
1403	56.12	0.943	0	0
1404	56.16	0.943	-2.829	-3.772
1405	56.20	-1.886	-2.829	-3.772
1406	56.24	0.943	4.715	3.772
1407	56.28	2.829	2.829	4.715
1408	56.32	0	0.943	0.943
1409	56.36	0.943	-1.886	-0.943
1410	56.40	0.943	1.886	1.886
1411	56.44	2.829	6.601	4.715
1412	56.48	1.886	5.658	3.772
1413	56.52	-0.943	-1.886	-1.886
1414	56.56	-2.829	-2.829	-4.715
1415	56.60	-1.886	0.943	-0.943
1416	56.64	-0.943	0	-1.886
1417	56.68	-2.829	-2.829	-2.829
1418	56.72	-2.829	-2.829	-4.715
1419	56.76	-1.886	0.943	-1.886
1420	56.80	0.943	3.772	1.886
1421	56.84	-0.943	-0.943	-1.886
1422	56.88	0	-0.943	-0.943
1423	56.92	0	0.943	-0.943
1424	56.96	3.772	3.772	3.772
1425	57.00	1.886	1.886	0.943
1426	57.04	1.886	2.829	0
1427	57.08	0.943	-0.943	-2.829
1428	57.12	1.886	1.886	-0.943
1429	57.16	0.943	-0.943	-1.886
1430	57.20	0.943	0	-3.772
1431	57.24	1.886	0.943	-0.943
1432	57.28	0	-3.772	-3.772
1433	57.32	-1.886	-6.601	-8.487
1434	57.36	1.886	0.943	-2.829
1435	57.40	3.772	6.601	0.943
1436	57.44	-0.943	-1.886	-5.658
1437	57.48	-1.886	-2.829	-6.601
1438	57.52	0	-0.943	-3.772
1439	57.56	4.715	8.487	3.772
1440	57.60	2.829	5.658	1.886
1441	57.64	0	-0.943	-1.886
1442	57.68	-2.829	-4.715	-5.658
1443	57.72	1.886	2.829	1.886
1444	57.76	4.715	9.43	8.487
1445	57.80	-0.943	0.943	-1.886
1446	57.84	-2.829	-3.772	-4.715
1447	57.88	-0.943	-2.829	-2.829
1448	57.92	0.943	0.943	0.943
1449	57.96	2.829	2.829	0.943
1450	58.00	-1.886	-1.886	-3.772
1451	58.04	-2.829	-4.715	-6.601
1452	58.08	-0.943	-0.943	-3.772
1453	58.12	1.886	4.715	0
1454	58.16	0.943	3.772	-0.943
1455	58.20	0	3.772	0
1456	58.24	0.943	0.943	0
1457	58.28	0	0.943	-1.886
1458	58.32	0.943	4.715	-0.943

APPENDIX A

Experimental Data Record No.				
17 Aug 25mmdia 1052-26gate1				
Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
1459	58.36	0	3.772	-1.886
1460	58.40	-1.886	0	-4.715
1461	58.44	-3.772	-5.658	-6.601
1462	58.48	-2.829	-2.829	-7.544
1463	58.52	-0.943	-1.886	-3.772
1464	58.56	-0.943	0.943	-2.829
1465	58.60	-2.829	-2.829	-5.658
1466	58.64	-3.772	-7.544	-7.544
1467	58.68	0	-1.886	-2.829
1468	58.72	0	-0.943	-2.829
1469	58.76	0	0.943	-0.943
1470	58.80	0	-2.829	-1.886
1471	58.84	3.772	2.829	3.772
1472	58.88	3.772	2.829	4.715
1473	58.92	5.658	7.544	8.487
1474	58.96	2.829	2.829	4.715
1475	59.00	-1.886	-3.772	-1.886
1476	59.04	0	-4.715	-3.772
1477	59.08	0.943	0	-1.886
1478	59.12	2.829	2.829	0.943
1479	59.16	-1.886	-4.715	-5.658
1480	59.20	-1.886	-5.658	-4.715
1481	59.24	0.943	-3.772	-2.829
1482	59.28	2.829	3.772	1.886
1483	59.32	0.943	2.829	0
1484	59.36	0.943	0	-1.886
1485	59.40	4.715	4.715	2.829
1486	59.44	2.829	0	-0.943
1487	59.48	4.715	4.715	1.886
1488	59.52	2.829	0.943	0.943
1489	59.56	1.886	0	0
1490	59.60	0.943	0.943	-1.886
1491	59.64	2.829	1.886	0.943
1492	59.68	3.772	0.943	1.886
1493	59.72	0.943	1.886	-0.943
1494	59.76	0.943	2.829	-1.886
1495	59.80	-0.943	0.943	-4.715
1496	59.84	0	-0.943	-0.943
1497	59.88	-2.829	-5.658	-5.658
1498	59.92	-0.943	0.943	-0.943
1499	59.96	0	0.943	-0.943
1500	60.00	0	-0.943	-1.886

Figure A.1 Sample Results For Test Performed On 25mm Diameter Acrylic Pipe (With 3mm Neoprene Damping Thickness and 3mm Boundary Condition)

Figure A.2 Plot of Strain Versus Time For Three Channels

APPENDIX B
SAMPLE RESULTS FOR 40MM ACRYLIC PIPE

APPENDIX B

Experimental Data Record No.									
6 Aug 40mmdia 1177 length 28-g1									
Data Type : Dynamic									
File Comment :									
Record Word : 1500 word									
Sampling Cycle : 40 msec.									
Pretrigger Memory : 0 word									
No.		CH.001	CH.002	CH.003					
Mode		2.0Vrms	2.0Vrms	2.0Vrms					
L.P.F.		PASS	PASS	PASS					
Coeff.		9.43E-01	9.43E-01	9.43E-01					
Unit		μ	μ	μ					
MAX		7.544	16.974	7.544					
MIN		-8.487	-16.031	-7.544					
MEAN		0	-0.943	-0.943					

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)	Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
1	0.04	-3.772	-0.943	-1.886	41	1.64	3.772	8.487	3.772
2	0.08	-1.886	0.943	0.943	42	1.68	-1.886	-2.829	-1.886
3	0.12	-4.715	-2.829	-0.943	43	1.72	0.943	-2.829	0
4	0.16	-0.943	4.715	1.886	44	1.76	-2.829	-10.373	-5.658
5	0.20	-1.886	1.886	0	45	1.80	0	-5.658	-1.886
6	0.24	-2.829	0.943	-0.943	46	1.84	0	-3.772	-1.886
7	0.28	5.658	12.259	7.544	47	1.88	1.886	0.943	0
8	0.32	0.943	4.715	2.829	48	1.92	-0.943	-5.658	-1.886
9	0.36	-1.886	-2.829	-0.943	49	1.96	0	-7.544	-0.943
10	0.40	-0.943	0	-1.886	50	2.00	-0.943	-3.772	-2.829
11	0.44	-3.772	-6.601	-3.772	51	2.04	2.829	4.715	2.829
12	0.48	-5.658	-7.544	-4.715	52	2.08	2.829	5.658	2.829
13	0.52	-0.943	2.829	0.943	53	2.12	-0.943	-5.658	-2.829
14	0.56	-0.943	0	0.943	54	2.16	6.601	11.316	4.715
15	0.60	-0.943	-6.601	-2.829	55	2.20	2.829	5.658	2.829
16	0.64	-2.829	-3.772	-2.829	56	2.24	4.715	9.43	4.715
17	0.68	-3.772	-2.829	-2.829	57	2.28	2.829	2.829	1.886
18	0.72	-0.943	2.829	0.943	58	2.32	1.886	3.772	1.886
19	0.76	-0.943	2.829	0	59	2.36	3.772	4.715	3.772
20	0.80	-0.943	2.829	0	60	2.40	1.886	0.943	0.943
21	0.84	-1.886	2.829	-1.886	61	2.44	0.943	-0.943	0
22	0.88	3.772	4.715	4.715	62	2.48	-1.886	-5.658	-2.829
23	0.92	0.943	3.772	0.943	63	2.52	-1.886	-6.601	-3.772
24	0.96	2.829	12.259	2.829	64	2.56	4.715	1.886	1.886
25	1.00	0	-0.943	0	65	2.60	-0.943	-3.772	-2.829
26	1.04	2.829	3.772	2.829	66	2.64	0	-0.943	-0.943
27	1.08	3.772	6.601	3.772	67	2.68	1.886	-0.943	0.943
28	1.12	-3.772	-8.487	-4.715	68	2.72	0.943	-2.829	-0.943
29	1.16	-3.772	-10.373	-4.715	69	2.76	1.886	0	0
30	1.20	-0.943	-5.658	-0.943	70	2.80	0	-0.943	0
31	1.24	0.943	-1.886	0	71	2.84	2.829	2.829	1.886
32	1.28	0.943	0.943	0.943	72	2.88	4.715	6.601	4.715
33	1.32	-3.772	-3.772	-2.829	73	2.92	1.886	2.829	2.829
34	1.36	0	-6.601	-0.943	74	2.96	0	-3.772	-1.886
35	1.40	-0.943	0	-1.886	75	3.00	0.943	1.886	0
36	1.44	0.943	7.544	1.886	76	3.04	-0.943	-1.886	-0.943
37	1.48	-3.772	-2.829	-2.829	77	3.08	-1.886	-1.886	-2.829
38	1.52	0	3.772	0.943	78	3.12	0	-3.772	-1.886
39	1.56	-0.943	0	0	79	3.16	0	-3.772	-0.943
40	1.60	-0.943	-0.943	-1.886	80	3.20	0.943	1.886	1.886

APPENDIX B

Experimental Data Record No.

6 Aug 40mmdia 1177 length 28-g1

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)	Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
81	3.24	0	-2.829	-0.943	134	5.36	1.886	1.886	0
82	3.28	-2.829	-8.487	-4.715	135	5.40	0.943	3.772	0.943
83	3.32	0.943	-1.886	0	136	5.44	1.886	2.829	0.943
84	3.36	4.715	6.601	4.715	137	5.48	1.886	2.829	0.943
85	3.40	1.886	1.886	1.886	138	5.52	0	0.943	-0.943
86	3.44	2.829	2.829	2.829	139	5.56	0	-1.886	-0.943
87	3.48	1.886	-2.829	0	140	5.60	2.829	5.658	1.886
88	3.52	4.715	4.715	4.715	141	5.64	0	-4.715	0
89	3.56	3.772	4.715	3.772	142	5.68	0	0	-1.886
90	3.60	0.943	0	0	143	5.72	-0.943	-5.658	-1.886
91	3.64	2.829	0	0.943	144	5.76	0.943	0	1.886
92	3.68	-0.943	-4.715	-2.829	145	5.80	1.886	1.886	0.943
93	3.72	1.886	0.943	0.943	146	5.84	2.829	3.772	1.886
94	3.76	2.829	2.829	1.886	147	5.88	0.943	0	0
95	3.80	3.772	0	0.943	148	5.92	-0.943	-2.829	-1.886
96	3.84	1.886	-4.715	-0.943	149	5.96	-0.943	-4.715	-1.886
97	3.88	1.886	-2.829	-0.943	150	6.00	-0.943	-0.943	-1.886
98	3.92	1.886	1.886	-0.943	151	6.04	4.715	11.316	4.715
99	3.96	6.601	7.544	4.715	152	6.08	0.943	3.772	1.886
100	4.00	1.886	-0.943	-0.943	153	6.12	0	-0.943	-0.943
101	4.04	3.772	-0.943	0	154	6.16	-1.886	-2.829	-2.829
102	4.08	1.886	-0.943	-1.886	155	6.20	-2.829	-4.715	-2.829
103	4.12	2.829	2.829	1.886	156	6.24	0.943	1.886	0.943
104	4.16	6.601	7.544	4.715	157	6.28	0.943	5.658	1.886
105	4.20	2.829	1.886	1.886	158	6.32	0.943	0	1.886
106	4.24	4.715	0.943	0.943	159	6.36	-2.829	-5.658	-2.829
107	4.28	1.886	-1.886	-1.886	160	6.40	-2.829	-3.772	-2.829
108	4.32	5.658	4.715	2.829	161	6.44	0.943	0	0
109	4.36	0	-4.715	-3.772	162	6.48	0.943	-1.886	0
110	4.40	0.943	-4.715	-1.886	163	6.52	-1.886	-5.658	-3.772
111	4.44	2.829	-2.829	0	164	6.56	1.886	0	0.943
112	4.48	0.943	-3.772	-1.886	165	6.60	1.886	4.715	0.943
113	4.52	6.601	7.544	4.715	166	6.64	0.943	4.715	0
114	4.56	3.772	0.943	0.943	167	6.68	0	0.943	0
115	4.60	0	-3.772	-3.772	168	6.72	0	0	-1.886
116	4.64	0.943	-4.715	-2.829	169	6.76	0.943	4.715	-0.943
117	4.68	7.544	10.373	4.715	170	6.80	3.772	8.487	1.886
118	4.72	2.829	1.886	-0.943	171	6.84	0.943	3.772	0
119	4.76	2.829	2.829	0	172	6.88	-0.943	-0.943	-1.886
120	4.80	0.943	-0.943	-1.886	173	6.92	-0.943	-4.715	-0.943
121	4.84	4.715	0.943	0.943	174	6.96	-2.829	-6.601	-4.715
122	4.88	1.886	-0.943	-0.943	175	7.00	0.943	-0.943	0
123	4.92	4.715	6.601	1.886	176	7.04	0	0.943	0
124	4.96	-2.829	-6.601	-3.772	177	7.08	-4.715	-9.43	-5.658
125	5.00	0.943	-4.715	-2.829	178	7.12	1.886	-1.886	-0.943
126	5.04	2.829	-0.943	0	179	7.16	-1.886	-0.943	-1.886
127	5.08	0.943	-2.829	-1.886	180	7.20	1.886	2.829	0
128	5.12	3.772	2.829	2.829	181	7.24	0.943	-3.772	-1.886
129	5.16	2.829	3.772	2.829	182	7.28	1.886	0	-0.943
130	5.20	0.943	-0.943	0	183	7.32	0	0	-1.886
131	5.24	0.943	-1.886	-0.943	184	7.36	3.772	6.601	1.886
132	5.28	2.829	0.943	0.943	185	7.40	7.544	10.373	5.658
133	5.32	0	0	-0.943	186	7.44	1.886	1.886	0.943

APPENDIX B

Experimental Data Record No.

6 Aug 40mmdia 1177 length 28-g1

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)	Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
187	7.48	-1.886	-4.715	-2.829	240	9.60	-3.772	-9.43	-4.715
188	7.52	-0.943	-6.601	-2.829	241	9.64	-1.886	-4.715	-1.886
189	7.56	0	0.943	-0.943	242	9.68	0.943	0	0.943
190	7.60	-0.943	0	-1.886	243	9.72	-0.943	0	0
191	7.64	-0.943	0	-0.943	244	9.76	-1.886	-3.772	-0.943
192	7.68	-3.772	-4.715	-3.772	245	9.80	-1.886	-6.601	-1.886
193	7.72	-3.772	-8.487	-3.772	246	9.84	-1.886	-2.829	-0.943
194	7.76	0	0.943	0	247	9.88	0	4.715	1.886
195	7.80	-0.943	0.943	-0.943	248	9.92	1.886	6.601	1.886
196	7.84	-1.886	0.943	0	249	9.96	-0.943	0	-0.943
197	7.88	0.943	5.658	1.886	250	10.00	0.943	1.886	1.886
198	7.92	0.943	5.658	0.943	251	10.04	1.886	1.886	0.943
199	7.96	-0.943	1.886	-0.943	252	10.08	-1.886	-1.886	-1.886
200	8.00	0.943	3.772	0.943	253	10.12	-0.943	-4.715	-0.943
201	8.04	2.829	6.601	3.772	254	10.16	0.943	2.829	1.886
202	8.08	0	0.943	0	255	10.20	-0.943	-4.715	-0.943
203	8.12	1.886	4.715	1.886	256	10.24	-1.886	-5.658	-1.886
204	8.16	-0.943	-0.943	-0.943	257	10.28	0.943	0	0.943
205	8.20	-1.886	-1.886	-1.886	258	10.32	-5.658	-11.316	-3.772
206	8.24	-3.772	-6.601	-4.715	259	10.36	-2.829	-4.715	-0.943
207	8.28	-1.886	-6.601	-2.829	260	10.40	-1.886	-0.943	0
208	8.32	0	1.886	1.886	261	10.44	0	2.829	1.886
209	8.36	0	3.772	1.886	262	10.48	0	2.829	1.886
210	8.40	-0.943	0	0	263	10.52	-3.772	-2.829	-1.886
211	8.44	-3.772	-4.715	-1.886	264	10.56	-2.829	-2.829	-0.943
212	8.48	-2.829	-5.658	-2.829	265	10.60	0	1.886	2.829
213	8.52	0	0.943	1.886	266	10.64	0	6.601	1.886
214	8.56	-0.943	0.943	0	267	10.68	-3.772	-0.943	-0.943
215	8.60	-1.886	0	-1.886	268	10.72	-1.886	0	0
216	8.64	1.886	6.601	3.772	269	10.76	-0.943	0	0
217	8.68	1.886	-1.886	2.829	270	10.80	0.943	2.829	2.829
218	8.72	2.829	8.487	3.772	271	10.84	-1.886	-1.886	-0.943
219	8.76	0	3.772	0.943	272	10.88	0	1.886	0.943
220	8.80	1.886	2.829	2.829	273	10.92	-1.886	-4.715	-0.943
221	8.84	-1.886	-3.772	-1.886	274	10.96	0	-2.829	0
222	8.88	-0.943	0	-0.943	275	11.00	0	-0.943	0
223	8.92	2.829	3.772	3.772	276	11.04	0.943	4.715	2.829
224	8.96	-4.715	-6.601	-3.772	277	11.08	0	0.943	0.943
225	9.00	-2.829	-7.544	-2.829	278	11.12	-2.829	-5.658	-3.772
226	9.04	-3.772	-7.544	-2.829	279	11.16	0.943	5.658	2.829
227	9.08	-0.943	0.943	0	280	11.20	1.886	7.544	3.772
228	9.12	0.943	2.829	1.886	281	11.24	-0.943	5.658	1.886
229	9.16	-0.943	0	0	282	11.28	-1.886	-0.943	-0.943
230	9.20	-1.886	-2.829	-1.886	283	11.32	-1.886	-1.886	-0.943
231	9.24	0.943	1.886	0	284	11.36	-4.715	-2.829	-2.829
232	9.28	3.772	8.487	3.772	285	11.40	1.886	8.487	3.772
233	9.32	2.829	6.601	2.829	286	11.44	-1.886	0	0
234	9.36	0.943	3.772	0.943	287	11.48	-2.829	-4.715	-0.943
235	9.40	0.943	0	0	288	11.52	-1.886	-1.886	0
236	9.44	-0.943	-0.943	-1.886	289	11.56	-1.886	-3.772	0
237	9.48	-0.943	1.886	0	290	11.60	0	1.886	1.886
238	9.52	0	0.943	0	291	11.64	0	3.772	1.886
239	9.56	-2.829	-5.658	-3.772	292	11.68	-2.829	-3.772	-1.886

Experimental Data Record No.														
6 Aug 40mmdia 1177 length 28-g1														
Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)		Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)				
293	11.72	-3.772	-1.886	-2.829		346	13.84	1.886	4.715	1.886				
294	11.76	2.829	8.487	4.715		347	13.88	0.943	1.886	0.943				
295	11.80	-0.943	2.829	0		348	13.92	0	3.772	0				
296	11.84	-1.886	0	-0.943		349	13.96	0	3.772	1.886				
297	11.88	0	2.829	1.886		350	14.00	-1.886	0	-0.943				
298	11.92	-2.829	-2.829	-1.886		351	14.04	-1.886	-2.829	-1.886				
299	11.96	-0.943	0	0.943		352	14.08	-2.829	-2.829	-2.829				
300	12.00	-0.943	0.943	0.943		353	14.12	-1.886	0.943	-0.943				
301	12.04	0	1.886	0.943		354	14.16	-3.772	-4.715	-3.772				
302	12.08	-0.943	0	0		355	14.20	-3.772	-7.544	-5.658				
303	12.12	-4.715	-6.601	-3.772		356	14.24	-2.829	-1.886	-1.886				
304	12.16	-0.943	0	0		357	14.28	0.943	6.601	1.886				
305	12.20	-1.886	-3.772	-0.943		358	14.32	0	2.829	0				
306	12.24	-0.943	-2.829	-1.886		359	14.36	-3.772	-16.031	-6.601				
307	12.28	0	-3.772	-1.886		360	14.40	1.886	7.544	0				
308	12.32	-6.601	-12.259	-7.544		361	14.44	5.658	10.373	2.829				
309	12.36	1.886	4.715	2.829		362	14.48	2.829	9.43	2.829				
310	12.40	-0.943	-2.829	-2.829		363	14.52	4.715	8.487	1.886				
311	12.44	-0.943	-4.715	-1.886		364	14.56	-0.943	-1.886	-1.886				
312	12.48	-3.772	-5.658	-2.829		365	14.60	0.943	1.886	-0.943				
313	12.52	3.772	7.544	4.715		366	14.64	3.772	6.601	2.829				
314	12.56	6.601	13.202	6.601		367	14.68	1.886	4.715	0.943				
315	12.60	-2.829	-7.544	-5.658		368	14.72	-4.715	-10.373	-5.658				
316	12.64	0	4.715	0.943		369	14.76	-3.772	-7.544	-3.772				
317	12.68	0	-4.715	-0.943		370	14.80	-0.943	-5.658	-0.943				
318	12.72	0	2.829	0.943		371	14.84	0.943	0.943	0.943				
319	12.76	1.886	3.772	1.886		372	14.88	-0.943	-0.943	0				
320	12.80	-0.943	-4.715	-1.886		373	14.92	-0.943	-3.772	-2.829				
321	12.84	-2.829	-9.43	-3.772		374	14.96	-0.943	-6.601	-2.829				
322	12.88	0.943	-4.715	0.943		375	15.00	0.943	0.943	-0.943				
323	12.92	0.943	-4.715	-0.943		376	15.04	3.772	8.487	3.772				
324	12.96	1.886	3.772	1.886		377	15.08	3.772	6.601	2.829				
325	13.00	0.943	4.715	2.829		378	15.12	1.886	0.943	0.943				
326	13.04	0	-4.715	-1.886		379	15.16	3.772	1.886	1.886				
327	13.08	2.829	0	0		380	15.20	0.943	1.886	0				
328	13.12	0.943	4.715	0.943		381	15.24	3.772	7.544	3.772				
329	13.16	3.772	7.544	3.772		382	15.28	1.886	4.715	1.886				
330	13.20	0.943	2.829	1.886		383	15.32	1.886	2.829	2.829				
331	13.24	0.943	0	0		384	15.36	-1.886	-2.829	-0.943				
332	13.28	0	-0.943	0		385	15.40	-0.943	0.943	0				
333	13.32	3.772	8.487	2.829		386	15.44	0.943	1.886	1.886				
334	13.36	0	1.886	-0.943		387	15.48	-0.943	-0.943	0				
335	13.40	-2.829	-7.544	-3.772		388	15.52	-1.886	-2.829	-0.943				
336	13.44	-2.829	-5.658	-2.829		389	15.56	-0.943	0	0				
337	13.48	0	1.886	0		390	15.60	0.943	4.715	1.886				
338	13.52	-0.943	0	0		391	15.64	1.886	2.829	1.886				
339	13.56	-1.886	-1.886	-1.886		392	15.68	0	3.772	0.943				
340	13.60	-1.886	-5.658	-2.829		393	15.72	-0.943	0	0				
341	13.64	0.943	0.943	0		394	15.76	4.715	9.43	6.601				
342	13.68	0.943	0	0		395	15.80	0.943	2.829	1.886				
343	13.72	-2.829	-3.772	-3.772		396	15.84	0.943	0.943	1.886				
344	13.76	0	0	0.943		397	15.88	-1.886	-2.829	-0.943				
345	13.80	0	0.943	0		398	15.92	0	-1.886	0.943				

APPENDIX B

Experimental Data Record No.

6 Aug 40mmdia 1177 length 28-g1

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)	Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
399	15.96	-1.886	-2.829	-0.943	452	18.08	-0.943	0	0
400	16.00	0	1.886	0.943	453	18.12	1.886	2.829	2.829
401	16.04	2.829	4.715	3.772	454	18.16	0	-3.772	-0.943
402	16.08	-1.886	-5.658	-0.943	455	18.20	-0.943	-1.886	-1.886
403	16.12	0	-1.886	0.943	456	18.24	-0.943	-4.715	-0.943
404	16.16	-0.943	-3.772	0	457	18.28	0.943	3.772	1.886
405	16.20	0	2.829	1.886	458	18.32	1.886	5.658	1.886
406	16.24	-0.943	1.886	0.943	459	18.36	1.886	5.658	1.886
407	16.28	-0.943	0	-0.943	460	18.40	0	-1.886	0
408	16.32	-0.943	-0.943	0	461	18.44	0	1.886	-0.943
409	16.36	0.943	5.658	1.886	462	18.48	0.943	7.544	2.829
410	16.40	0.943	6.601	2.829	463	18.52	0.943	-0.943	0.943
411	16.44	0.943	2.829	1.886	464	18.56	-1.886	-0.943	-1.886
412	16.48	0	0	0	465	18.60	-2.829	-12.259	-4.715
413	16.52	-0.943	-1.886	-0.943	466	18.64	0	-1.886	0.943
414	16.56	-0.943	0	-0.943	467	18.68	-1.886	0.943	0
415	16.60	-2.829	-2.829	-1.886	468	18.72	-0.943	-2.829	0
416	16.64	0	-2.829	0.943	469	18.76	-0.943	-2.829	-0.943
417	16.68	-0.943	-2.829	0	470	18.80	-0.943	-2.829	-1.886
418	16.72	0	-0.943	0.943	471	18.84	-1.886	-2.829	-1.886
419	16.76	1.886	2.829	2.829	472	18.88	0.943	3.772	0.943
420	16.80	0.943	1.886	0.943	473	18.92	-0.943	-1.886	-0.943
421	16.84	0.943	-1.886	0.943	474	18.96	-0.943	-0.943	-1.886
422	16.88	-0.943	-2.829	-1.886	475	19.00	1.886	7.544	2.829
423	16.92	0.943	1.886	0.943	476	19.04	0.943	1.886	0
424	16.96	1.886	5.658	2.829	477	19.08	-1.886	-1.886	-2.829
425	17.00	-1.886	0	-0.943	478	19.12	0.943	0.943	0
426	17.04	0	-0.943	-0.943	479	19.16	-1.886	-1.886	-3.772
427	17.08	0	0.943	0	480	19.20	0	-1.886	-0.943
428	17.12	0.943	1.886	1.886	481	19.24	-0.943	-2.829	-1.886
429	17.16	1.886	4.715	2.829	482	19.28	0.943	-0.943	-0.943
430	17.20	0	1.886	0	483	19.32	-1.886	-3.772	-2.829
431	17.24	0.943	2.829	0.943	484	19.36	-1.886	-5.658	-3.772
432	17.28	0.943	3.772	1.886	485	19.40	0	-1.886	-0.943
433	17.32	0.943	-1.886	0	486	19.44	-0.943	-1.886	-1.886
434	17.36	-1.886	-2.829	-2.829	487	19.48	-2.829	-3.772	-3.772
435	17.40	0.943	0	0.943	488	19.52	-0.943	3.772	-0.943
436	17.44	0	-1.886	0.943	489	19.56	-1.886	-10.373	-1.886
437	17.48	0	-0.943	0.943	490	19.60	0	3.772	-0.943
438	17.52	-0.943	-2.829	-0.943	491	19.64	4.715	10.373	3.772
439	17.56	-0.943	-0.943	0	492	19.68	0.943	2.829	0.943
440	17.60	-2.829	-4.715	-2.829	493	19.72	0.943	0.943	0
441	17.64	-1.886	-2.829	-1.886	494	19.76	-0.943	-1.886	-0.943
442	17.68	-0.943	0.943	-0.943	495	19.80	2.829	5.658	2.829
443	17.72	3.772	10.373	4.715	496	19.84	-0.943	1.886	0
444	17.76	0.943	5.658	1.886	497	19.88	0	-0.943	0
445	17.80	-0.943	-0.943	0	498	19.92	-2.829	-9.43	-4.715
446	17.84	-1.886	-1.886	-2.829	499	19.96	-3.772	-10.373	-4.715
447	17.88	2.829	8.487	3.772	500	20.00	1.886	-2.829	0
448	17.92	1.886	2.829	1.886	501	20.04	0	-2.829	-0.943
449	17.96	-4.715	-5.658	-3.772	502	20.08	-2.829	-8.487	-4.715
450	18.00	-4.715	-8.487	-2.829	503	20.12	-1.886	-7.544	-4.715
451	18.04	-0.943	-5.658	-0.943	504	20.16	1.886	0	0.943

Experimental Data Record No.														
6 Aug 40mmdia 1177 length 28-g1														
Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)		Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)				
505	20.20	1.886	0	0		558	22.32	-0.943	1.886	-0.943				
506	20.24	2.829	5.658	1.886		559	22.36	-0.943	-1.886	-2.829				
507	20.28	2.829	1.886	0.943		560	22.40	1.886	2.829	1.886				
508	20.32	0	-3.772	-1.886		561	22.44	0.943	1.886	0.943				
509	20.36	3.772	5.658	2.829		562	22.48	0.943	-0.943	-0.943				
510	20.40	4.715	7.544	4.715		563	22.52	1.886	0.943	0				
511	20.44	0	-1.886	0		564	22.56	-4.715	-9.43	-5.658				
512	20.48	-1.886	-4.715	-2.829		565	22.60	0	0	0				
513	20.52	0	0	0.943		566	22.64	-0.943	1.886	0.943				
514	20.56	-1.886	-3.772	-1.886		567	22.68	-1.886	-1.886	-1.886				
515	20.60	-0.943	-3.772	0		568	22.72	0.943	3.772	1.886				
516	20.64	-2.829	-7.544	-2.829		569	22.76	-1.886	-2.829	-0.943				
517	20.68	-2.829	-6.601	-1.886		570	22.80	-0.943	0	0				
518	20.72	2.829	4.715	2.829		571	22.84	-3.772	-4.715	-2.829				
519	20.76	-0.943	-4.715	-0.943		572	22.88	5.658	11.316	7.544				
520	20.80	0.943	0.943	1.886		573	22.92	0.943	5.658	1.886				
521	20.84	0	-2.829	-0.943		574	22.96	-0.943	0	0.943				
522	20.88	1.886	0.943	1.886		575	23.00	4.715	5.658	2.829				
523	20.92	0	-0.943	0		576	23.04	1.886	0.943	0				
524	20.96	0.943	0.943	0.943		577	23.08	4.715	7.544	3.772				
525	21.00	0	-0.943	1.886		578	23.12	1.886	3.772	1.886				
526	21.04	0.943	-1.886	1.886		579	23.16	-1.886	-5.658	-3.772				
527	21.08	-2.829	-6.601	-2.829		580	23.20	-2.829	-12.259	-6.601				
528	21.12	-1.886	-5.658	-1.886		581	23.24	1.886	0	0.943				
529	21.16	-0.943	1.886	1.886		582	23.28	3.772	2.829	2.829				
530	21.20	-1.886	-2.829	0.943		583	23.32	-0.943	-3.772	-2.829				
531	21.24	-3.772	-7.544	-3.772		584	23.36	-2.829	-5.658	-4.715				
532	21.28	-3.772	-7.544	-3.772		585	23.40	-0.943	-4.715	-2.829				
533	21.32	-0.943	-4.715	-0.943		586	23.44	0	1.886	0				
534	21.36	3.772	6.601	4.715		587	23.48	2.829	7.544	1.886				
535	21.40	0.943	-0.943	0.943		588	23.52	0	0.943	0				
536	21.44	-3.772	-8.487	-4.715		589	23.56	0.943	0	-0.943				
537	21.48	0.943	-0.943	0.943		590	23.60	3.772	1.886	1.886				
538	21.52	2.829	4.715	2.829		591	23.64	3.772	7.544	3.772				
539	21.56	-0.943	0	0		592	23.68	0.943	5.658	1.886				
540	21.60	0	0	0		593	23.72	-2.829	-5.658	-2.829				
541	21.64	-0.943	-1.886	0		594	23.76	-1.886	-8.487	-1.886				
542	21.68	-4.715	-9.43	-3.772		595	23.80	1.886	-2.829	0.943				
543	21.72	0	2.829	1.886		596	23.84	-0.943	-4.715	0				
544	21.76	-0.943	-0.943	-0.943		597	23.88	0	-2.829	0.943				
545	21.80	-6.601	-16.031	-4.715		598	23.92	-1.886	-6.601	0				
546	21.84	-3.772	-9.43	-4.715		599	23.96	0	-3.772	0				
547	21.88	0	-1.886	0		600	24.00	0	1.886	0				
548	21.92	1.886	0.943	1.886		601	24.04	0.943	0	0.943				
549	21.96	1.886	2.829	2.829		602	24.08	1.886	0.943	2.829				
550	22.00	0	-0.943	0.943		603	24.12	-1.886	-0.943	-1.886				
551	22.04	-2.829	-6.601	-2.829		604	24.16	-1.886	-8.487	-2.829				
552	22.08	-0.943	-1.886	-0.943		605	24.20	2.829	1.886	0.943				
553	22.12	2.829	5.658	2.829		606	24.24	2.829	3.772	2.829				
554	22.16	-0.943	-0.943	-0.943		607	24.28	3.772	4.715	3.772				
555	22.20	-1.886	-2.829	-2.829		608	24.32	0	-0.943	0				
556	22.24	-0.943	0	0		609	24.36	1.886	-1.886	0.943				
557	22.28	0	0.943	0		610	24.40	1.886	0.943	1.886				

Experimental Data Record No.										
6 Aug 40mmdia 1177 length 28-g1										
Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)		Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
611	24.44	0	-3.772	-0.943		664	26.56	0	-0.943	-0.943
612	24.48	-0.943	-3.772	-0.943		665	26.60	-2.829	-5.658	-3.772
613	24.52	0.943	-3.772	0		666	26.64	1.886	0.943	1.886
614	24.56	0	-6.601	0		667	26.68	1.886	3.772	2.829
615	24.60	-1.886	-2.829	-1.886		668	26.72	0.943	5.658	1.886
616	24.64	-1.886	-4.715	-1.886		669	26.76	1.886	5.658	1.886
617	24.68	0	-1.886	0		670	26.80	0	-0.943	-0.943
618	24.72	-1.886	-2.829	0		671	26.84	1.886	0.943	0.943
619	24.76	0.943	0	0.943		672	26.88	0	0.943	0.943
620	24.80	1.886	2.829	2.829		673	26.92	-0.943	0.943	-0.943
621	24.84	0.943	3.772	1.886		674	26.96	0	0.943	0
622	24.88	0.943	-0.943	0.943		675	27.00	0	0	0
623	24.92	-2.829	-8.487	-3.772		676	27.04	0	-2.829	-0.943
624	24.96	0	0	0.943		677	27.08	2.829	0.943	0
625	25.00	3.772	6.601	4.715		678	27.12	2.829	1.886	0
626	25.04	0.943	1.886	1.886		679	27.16	1.886	-1.886	0
627	25.08	-1.886	-5.658	-2.829		680	27.20	1.886	1.886	0
628	25.12	-2.829	-15.088	-3.772		681	27.24	0	-3.772	-1.886
629	25.16	-3.772	-6.601	-4.715		682	27.28	3.772	3.772	1.886
630	25.20	0.943	0.943	1.886		683	27.32	0	-0.943	-0.943
631	25.24	-1.886	-4.715	-0.943		684	27.36	2.829	3.772	0.943
632	25.28	-2.829	-9.43	-1.886		685	27.40	0	-0.943	-1.886
633	25.32	-1.886	-2.829	-1.886		686	27.44	0	0	-1.886
634	25.36	1.886	3.772	1.886		687	27.48	1.886	4.715	0.943
635	25.40	1.886	7.544	3.772		688	27.52	0	-0.943	-1.886
636	25.44	-1.886	-0.943	-0.943		689	27.56	0.943	-1.886	-1.886
637	25.48	1.886	0.943	0.943		690	27.60	-0.943	-3.772	-2.829
638	25.52	1.886	4.715	1.886		691	27.64	1.886	1.886	0
639	25.56	4.715	7.544	4.715		692	27.68	0.943	2.829	0
640	25.60	0	1.886	0		693	27.72	1.886	1.886	0.943
641	25.64	-0.943	-3.772	-1.886		694	27.76	1.886	-1.886	0
642	25.68	0	-3.772	-0.943		695	27.80	-1.886	-9.43	-4.715
643	25.72	-1.886	-3.772	-1.886		696	27.84	1.886	0	0
644	25.76	-0.943	0	0		697	27.88	0	-3.772	-1.886
645	25.80	-4.715	-6.601	-3.772		698	27.92	0.943	0.943	0.943
646	25.84	-2.829	-8.487	-4.715		699	27.96	0.943	-1.886	-0.943
647	25.88	0	-1.886	0		700	28.00	2.829	3.772	0.943
648	25.92	0	-2.829	-0.943		701	28.04	2.829	1.886	1.886
649	25.96	3.772	6.601	4.715		702	28.08	1.886	0.943	0
650	26.00	0	1.886	0		703	28.12	3.772	4.715	0.943
651	26.04	0	-0.943	0		704	28.16	0.943	-1.886	-0.943
652	26.08	-1.886	-2.829	-1.886		705	28.20	3.772	5.658	1.886
653	26.12	1.886	6.601	1.886		706	28.24	1.886	1.886	0.943
654	26.16	2.829	9.43	3.772		707	28.28	0.943	0	-2.829
655	26.20	0	5.658	0.943		708	28.32	1.886	0	0.943
656	26.24	0	3.772	1.886		709	28.36	3.772	4.715	2.829
657	26.28	0	0.943	0		710	28.40	-0.943	-5.658	-1.886
658	26.32	-1.886	-2.829	-1.886		711	28.44	1.886	0.943	0
659	26.36	0.943	0	0.943		712	28.48	0	-2.829	-0.943
660	26.40	-1.886	-1.886	-2.829		713	28.52	0	-5.658	-2.829
661	26.44	-2.829	-4.715	-4.715		714	28.56	1.886	-1.886	-0.943
662	26.48	-1.886	-2.829	-1.886		715	28.60	0	-4.715	-1.886
663	26.52	-0.943	-1.886	-1.886		716	28.64	5.658	8.487	4.715

Experimental Data Record No.														
6 Aug 40mmdia 1177 length 28-g1														
Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)		Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)				
717	28.68	-0.943	0	-0.943		770	30.80	0.943	0.943	0				
718	28.72	2.829	3.772	0.943		771	30.84	-0.943	-5.658	-2.829				
719	28.76	1.886	-3.772	-2.829		772	30.88	1.886	-1.886	-0.943				
720	28.80	4.715	9.43	4.715		773	30.92	0.943	-1.886	0				
721	28.84	3.772	3.772	2.829		774	30.96	-0.943	-2.829	-2.829				
722	28.88	0.943	-1.886	-0.943		775	31.00	-1.886	-6.601	-2.829				
723	28.92	0	-7.544	-3.772		776	31.04	0.943	-6.601	-1.886				
724	28.96	1.886	0	-0.943		777	31.08	-0.943	-4.715	-1.886				
725	29.00	0	2.829	0		778	31.12	3.772	4.715	1.886				
726	29.04	-1.886	-3.772	-1.886		779	31.16	1.886	0.943	0				
727	29.08	-1.886	-6.601	-3.772		780	31.20	1.886	-2.829	-1.886				
728	29.12	1.886	-1.886	-0.943		781	31.24	2.829	4.715	0				
729	29.16	-0.943	-6.601	-2.829		782	31.28	0.943	0	-0.943				
730	29.20	2.829	3.772	-0.943		783	31.32	0.943	0	-0.943				
731	29.24	7.544	9.43	6.601		784	31.36	0.943	0	-0.943				
732	29.28	0.943	0	-0.943		785	31.40	0	0.943	-0.943				
733	29.32	1.886	1.886	0		786	31.44	2.829	4.715	1.886				
734	29.36	5.658	9.43	2.829		787	31.48	2.829	3.772	1.886				
735	29.40	4.715	5.658	1.886		788	31.52	0.943	-0.943	0				
736	29.44	3.772	6.601	2.829		789	31.56	-1.886	-3.772	-3.772				
737	29.48	0.943	-0.943	-1.886		790	31.60	3.772	4.715	2.829				
738	29.52	1.886	0.943	0		791	31.64	0.943	-2.829	-0.943				
739	29.56	4.715	4.715	1.886		792	31.68	1.886	0.943	0				
740	29.60	2.829	2.829	0.943		793	31.72	0	0.943	-0.943				
741	29.64	0.943	-0.943	-0.943		794	31.76	-1.886	-5.658	-5.658				
742	29.68	-1.886	-8.487	-4.715		795	31.80	1.886	0.943	-1.886				
743	29.72	-0.943	-2.829	-0.943		796	31.84	-0.943	-1.886	-3.772				
744	29.76	-0.943	-2.829	-2.829		797	31.88	3.772	6.601	1.886				
745	29.80	-2.829	-3.772	-2.829		798	31.92	1.886	0.943	-1.886				
746	29.84	1.886	0.943	0		799	31.96	0.943	-1.886	-2.829				
747	29.88	0.943	0	-1.886		800	32.00	0.943	-2.829	-2.829				
748	29.92	0	-1.886	-1.886		801	32.04	1.886	0.943	-0.943				
749	29.96	3.772	3.772	0.943		802	32.08	4.715	7.544	0.943				
750	30.00	2.829	5.658	0.943		803	32.12	1.886	0	-0.943				
751	30.04	4.715	4.715	2.829		804	32.16	-0.943	-5.658	-4.715				
752	30.08	0	-2.829	-2.829		805	32.20	0.943	-1.886	-1.886				
753	30.12	3.772	1.886	0.943		806	32.24	0.943	0	-1.886				
754	30.16	3.772	9.43	3.772		807	32.28	1.886	-0.943	-0.943				
755	30.20	1.886	0.943	1.886		808	32.32	0.943	-0.943	-0.943				
756	30.24	0.943	-1.886	0		809	32.36	0	-5.658	-3.772				
757	30.28	-1.886	-11.316	-4.715		810	32.40	0.943	-3.772	-2.829				
758	30.32	0.943	1.886	-0.943		811	32.44	0.943	-0.943	-2.829				
759	30.36	4.715	2.829	4.715		812	32.48	0	-1.886	-1.886				
760	30.40	-2.829	-7.544	-4.715		813	32.52	2.829	1.886	0				
761	30.44	-2.829	-11.316	-4.715		814	32.56	-0.943	-4.715	-3.772				
762	30.48	0.943	-1.886	-0.943		815	32.60	2.829	1.886	0				
763	30.52	2.829	2.829	1.886		816	32.64	3.772	3.772	0.943				
764	30.56	3.772	4.715	1.886		817	32.68	3.772	0.943	-0.943				
765	30.60	-0.943	-1.886	-2.829		818	32.72	2.829	-0.943	-0.943				
766	30.64	3.772	1.886	0.943		819	32.76	-0.943	-5.658	-3.772				
767	30.68	2.829	3.772	0.943		820	32.80	3.772	2.829	0.943				
768	30.72	6.601	11.316	4.715		821	32.84	1.886	0.943	-0.943				
769	30.76	2.829	4.715	0.943		822	32.88	0	-2.829	-1.886				

Experimental Data Record No.
6 Aug 40mmdia 1177 length 28-g1

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
823	32.92	-2.829	-4.715	-3.772
824	32.96	-1.886	-2.829	-2.829
825	33.00	-2.829	-7.544	-4.715
826	33.04	-0.943	-2.829	-2.829
827	33.08	0.943	2.829	0
828	33.12	0	-4.715	-2.829
829	33.16	0.943	1.886	0
830	33.20	0	-0.943	-2.829
831	33.24	2.829	4.715	0.943
832	33.28	2.829	3.772	0.943
833	33.32	0	-3.772	-2.829
834	33.36	0.943	0	-0.943
835	33.40	0.943	4.715	1.886
836	33.44	2.829	5.658	1.886
837	33.48	-0.943	-4.715	-0.943
838	33.52	-2.829	-1.886	-1.886
839	33.56	-1.886	-4.715	-2.829
840	33.60	0.943	2.829	1.886
841	33.64	-2.829	0.943	-0.943
842	33.68	-2.829	-7.544	-2.829
843	33.72	-2.829	-8.487	-4.715
844	33.76	2.829	5.658	1.886
845	33.80	3.772	4.715	0.943
846	33.84	0	-0.943	-1.886
847	33.88	0.943	-1.886	-1.886
848	33.92	3.772	1.886	1.886
849	33.96	2.829	6.601	2.829
850	34.00	1.886	4.715	1.886
851	34.04	0	0	-1.886
852	34.08	0.943	-3.772	-1.886
853	34.12	-1.886	-5.658	-3.772
854	34.16	-1.886	-2.829	-2.829
855	34.20	-0.943	-2.829	-1.886
856	34.24	0	0	0
857	34.28	-3.772	-5.658	-2.829
858	34.32	-2.829	-4.715	-2.829
859	34.36	1.886	0.943	0.943
860	34.40	1.886	5.658	1.886
861	34.44	-0.943	-2.829	-1.886
862	34.48	2.829	5.658	1.886
863	34.52	1.886	3.772	0.943
864	34.56	1.886	1.886	0
865	34.60	2.829	4.715	1.886
866	34.64	-4.715	-7.544	-6.601
867	34.68	0	-1.886	-0.943
868	34.72	0.943	0	-0.943
869	34.76	2.829	4.715	1.886
870	34.80	0	-1.886	-0.943
871	34.84	-1.886	-3.772	-2.829
872	34.88	1.886	-3.772	0.943
873	34.92	-1.886	-5.658	-3.772
874	34.96	4.715	9.43	5.658
875	35.00	-1.886	-3.772	-1.886

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
876	35.04	-0.943	-2.829	-0.943
877	35.08	0.943	-3.772	-1.886
878	35.12	4.715	7.544	2.829
879	35.16	1.886	2.829	0.943
880	35.20	2.829	3.772	0.943
881	35.24	2.829	1.886	0.943
882	35.28	1.886	0.943	0.943
883	35.32	2.829	5.658	2.829
884	35.36	1.886	1.886	1.886
885	35.40	2.829	0	2.829
886	35.44	-1.886	-9.43	-3.772
887	35.48	0	-3.772	0
888	35.52	0	-4.715	-0.943
889	35.56	0	-5.658	-0.943
890	35.60	0	-7.544	-0.943
891	35.64	-1.886	-10.373	-2.829
892	35.68	-0.943	-2.829	-0.943
893	35.72	1.886	2.829	1.886
894	35.76	1.886	0.943	1.886
895	35.80	0	-1.886	-0.943
896	35.84	3.772	6.601	3.772
897	35.88	1.886	0.943	2.829
898	35.92	0	-2.829	-1.886
899	35.96	2.829	0.943	2.829
900	36.00	1.886	-0.943	0.943
901	36.04	0.943	-2.829	0.943
902	36.08	2.829	-0.943	1.886
903	36.12	0	-2.829	-0.943
904	36.16	0.943	-5.658	-0.943
905	36.20	2.829	-1.886	1.886
906	36.24	1.886	-4.715	0
907	36.28	1.886	0.943	1.886
908	36.32	0	-1.886	0
909	36.36	-1.886	-4.715	-1.886
910	36.40	-2.829	-9.43	-3.772
911	36.44	1.886	3.772	0.943
912	36.48	2.829	3.772	2.829
913	36.52	1.886	0	0
914	36.56	1.886	0	0.943
915	36.60	1.886	-2.829	-0.943
916	36.64	0.943	-0.943	0
917	36.68	4.715	4.715	3.772
918	36.72	0	-1.886	-1.886
919	36.76	0.943	-6.601	-1.886
920	36.80	0.943	-5.658	-1.886
921	36.84	3.772	2.829	1.886
922	36.88	3.772	0	0.943
923	36.92	0	-3.772	-1.886
924	36.96	0.943	-6.601	-0.943
925	37.00	0	-4.715	-1.886
926	37.04	1.886	1.886	1.886
927	37.08	-1.886	-1.886	-0.943
928	37.12	0	-1.886	-0.943

Experimental Data Record No.														
6 Aug 40mmdia 1177 length 28-g1														
Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)		Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)				
929	37.16	0	-2.829	-0.943		982	39.28	0	-1.886	-1.886				
930	37.20	0	0	0		983	39.32	0.943	2.829	0				
931	37.24	1.886	0	1.886		984	39.36	1.886	4.715	0.943				
932	37.28	3.772	3.772	3.772		985	39.40	-1.886	-4.715	-2.829				
933	37.32	0	-2.829	0		986	39.44	-0.943	-6.601	-3.772				
934	37.36	0	-6.601	-0.943		987	39.48	-1.886	-2.829	-4.715				
935	37.40	0	-3.772	-0.943		988	39.52	3.772	8.487	2.829				
936	37.44	-0.943	-5.658	-1.886		989	39.56	0.943	-5.658	-1.886				
937	37.48	-0.943	-4.715	-0.943		990	39.60	0.943	0	-0.943				
938	37.52	0.943	-1.886	0		991	39.64	2.829	0.943	-0.943				
939	37.56	1.886	-2.829	0.943		992	39.68	0.943	1.886	-1.886				
940	37.60	0.943	-0.943	0.943		993	39.72	4.715	9.43	3.772				
941	37.64	0.943	-1.886	0.943		994	39.76	3.772	9.43	2.829				
942	37.68	-0.943	-4.715	-1.886		995	39.80	-0.943	-2.829	-3.772				
943	37.72	-1.886	-7.544	-2.829		996	39.84	1.886	-1.886	-1.886				
944	37.76	0.943	-0.943	0		997	39.88	2.829	2.829	0				
945	37.80	2.829	5.658	2.829		998	39.92	0.943	1.886	-1.886				
946	37.84	3.772	7.544	4.715		999	39.96	0	-1.886	-2.829				
947	37.88	-2.829	-6.601	-3.772		1000	40.00	0	-5.658	-3.772				
948	37.92	-2.829	-9.43	-3.772		1001	40.04	0	-3.772	-2.829				
949	37.96	2.829	4.715	4.715		1002	40.08	3.772	-0.943	0				
950	38.00	0.943	-0.943	-0.943		1003	40.12	4.715	5.658	2.829				
951	38.04	-4.715	-7.544	-4.715		1004	40.16	0.943	-4.715	-1.886				
952	38.08	-0.943	-6.601	-1.886		1005	40.20	-0.943	-4.715	-3.772				
953	38.12	-1.886	-10.373	-2.829		1006	40.24	3.772	0.943	0				
954	38.16	1.886	-0.943	0.943		1007	40.28	1.886	0	0				
955	38.20	0.943	0	0.943		1008	40.32	1.886	0.943	-1.886				
956	38.24	-0.943	-5.658	-0.943		1009	40.36	2.829	4.715	-0.943				
957	38.28	1.886	3.772	0.943		1010	40.40	0.943	0	-1.886				
958	38.32	1.886	-2.829	0		1011	40.44	6.601	6.601	3.772				
959	38.36	3.772	4.715	2.829		1012	40.48	3.772	3.772	0.943				
960	38.40	0.943	4.715	0		1013	40.52	-1.886	-9.43	-6.601				
961	38.44	2.829	1.886	1.886		1014	40.56	0.943	0	-1.886				
962	38.48	-0.943	0	0		1015	40.60	0	-4.715	-1.886				
963	38.52	-0.943	2.829	0		1016	40.64	0.943	0.943	-0.943				
964	38.56	1.886	5.658	1.886		1017	40.68	1.886	-0.943	-0.943				
965	38.60	1.886	3.772	3.772		1018	40.72	1.886	-3.772	-1.886				
966	38.64	0	0.943	0.943		1019	40.76	1.886	-1.886	-0.943				
967	38.68	-4.715	-11.316	-5.658		1020	40.80	0	-6.601	-4.715				
968	38.72	-3.772	-4.715	-4.715		1021	40.84	2.829	-1.886	-0.943				
969	38.76	0.943	0.943	0.943		1022	40.88	4.715	6.601	1.886				
970	38.80	-1.886	-3.772	-1.886		1023	40.92	2.829	2.829	0.943				
971	38.84	-0.943	-3.772	-1.886		1024	40.96	-0.943	-3.772	-3.772				
972	38.88	-3.772	-4.715	-5.658		1025	41.00	0	-3.772	-1.886				
973	38.92	-1.886	-6.601	-3.772		1026	41.04	5.658	6.601	2.829				
974	38.96	0	-2.829	-1.886		1027	41.08	4.715	7.544	2.829				
975	39.00	-0.943	0	-2.829		1028	41.12	0.943	-0.943	0.943				
976	39.04	1.886	1.886	0		1029	41.16	1.886	-0.943	0				
977	39.08	3.772	6.601	2.829		1030	41.20	0	-5.658	-2.829				
978	39.12	2.829	5.658	1.886		1031	41.24	3.772	4.715	2.829				
979	39.16	-0.943	-1.886	-2.829		1032	41.28	0.943	-0.943	-0.943				
980	39.20	0.943	3.772	0		1033	41.32	-1.886	-7.544	-2.829				
981	39.24	2.829	3.772	0.943		1034	41.36	1.886	-2.829	0				

Experimental Data Record No.										
6 Aug 40mmdia 1177 length 28-g1										
Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)		Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
1035	41.40	3.772	0	0.943		1088	43.52	-0.943	-2.829	-0.943
1036	41.44	5.658	3.772	3.772		1089	43.56	-1.886	-2.829	-2.829
1037	41.48	1.886	-2.829	-0.943		1090	43.60	3.772	5.658	2.829
1038	41.52	1.886	-2.829	-0.943		1091	43.64	1.886	1.886	0.943
1039	41.56	0	-6.601	-3.772		1092	43.68	0	-1.886	-0.943
1040	41.60	1.886	-0.943	-0.943		1093	43.72	-1.886	-4.715	-2.829
1041	41.64	3.772	2.829	1.886		1094	43.76	0.943	0.943	0.943
1042	41.68	2.829	4.715	0.943		1095	43.80	1.886	0.943	0.943
1043	41.72	2.829	0.943	0		1096	43.84	0.943	-0.943	0.943
1044	41.76	-0.943	-6.601	-4.715		1097	43.88	-3.772	-9.43	-4.715
1045	41.80	2.829	1.886	1.886		1098	43.92	0.943	-1.886	0.943
1046	41.84	6.601	7.544	5.658		1099	43.96	1.886	-0.943	1.886
1047	41.88	2.829	1.886	1.886		1100	44.00	-0.943	-6.601	-1.886
1048	41.92	0.943	-2.829	-1.886		1101	44.04	-2.829	-9.43	-4.715
1049	41.96	-0.943	-3.772	-1.886		1102	44.08	0	-2.829	-0.943
1050	42.00	0.943	-2.829	-0.943		1103	44.12	4.715	6.601	6.601
1051	42.04	0.943	-0.943	0		1104	44.16	-3.772	-9.43	-4.715
1052	42.08	0.943	0.943	0		1105	44.20	1.886	3.772	1.886
1053	42.12	3.772	0.943	1.886		1106	44.24	0	-3.772	-1.886
1054	42.16	-0.943	-2.829	-2.829		1107	44.28	0.943	0.943	0.943
1055	42.20	-0.943	-1.886	-0.943		1108	44.32	7.544	14.145	7.544
1056	42.24	0	-0.943	-0.943		1109	44.36	3.772	7.544	3.772
1057	42.28	-1.886	-4.715	-2.829		1110	44.40	0	-5.658	-0.943
1058	42.32	4.715	7.544	4.715		1111	44.44	-0.943	-5.658	-2.829
1059	42.36	2.829	5.658	2.829		1112	44.48	0.943	0	0.943
1060	42.40	1.886	0.943	0		1113	44.52	-2.829	-3.772	-2.829
1061	42.44	4.715	6.601	4.715		1114	44.56	-1.886	-5.658	-2.829
1062	42.48	-0.943	-6.601	-2.829		1115	44.60	0	-6.601	-1.886
1063	42.52	2.829	-1.886	-0.943		1116	44.64	-0.943	-9.43	-3.772
1064	42.56	1.886	0	0		1117	44.68	2.829	2.829	1.886
1065	42.60	0.943	0.943	0		1118	44.72	1.886	0	0
1066	42.64	-2.829	-6.601	-3.772		1119	44.76	-1.886	-5.658	-2.829
1067	42.68	-3.772	-8.487	-3.772		1120	44.80	-0.943	-8.487	-2.829
1068	42.72	-0.943	-7.544	-2.829		1121	44.84	1.886	3.772	0.943
1069	42.76	0	-4.715	-0.943		1122	44.88	0	0	-1.886
1070	42.80	0	2.829	0		1123	44.92	4.715	9.43	3.772
1071	42.84	1.886	4.715	1.886		1124	44.96	0.943	1.886	0.943
1072	42.88	-0.943	-3.772	-1.886		1125	45.00	3.772	0.943	0
1073	42.92	0	3.772	0		1126	45.04	-0.943	-3.772	-2.829
1074	42.96	4.715	11.316	4.715		1127	45.08	0.943	-1.886	-1.886
1075	43.00	4.715	12.259	5.658		1128	45.12	1.886	3.772	0
1076	43.04	-3.772	-6.601	-3.772		1129	45.16	-2.829	-7.544	-3.772
1077	43.08	0	0.943	0		1130	45.20	-0.943	-2.829	-1.886
1078	43.12	-1.886	-1.886	-1.886		1131	45.24	-1.886	-6.601	-4.715
1079	43.16	0.943	1.886	0		1132	45.28	0.943	-3.772	-1.886
1080	43.20	0	-0.943	0		1133	45.32	3.772	1.886	1.886
1081	43.24	-0.943	-7.544	-0.943		1134	45.36	0	-7.544	-2.829
1082	43.28	-4.715	-9.43	-3.772		1135	45.40	2.829	1.886	1.886
1083	43.32	-2.829	-10.373	-1.886		1136	45.44	2.829	1.886	0
1084	43.36	-1.886	-3.772	-0.943		1137	45.48	1.886	0	-0.943
1085	43.40	-0.943	-0.943	0		1138	45.52	0.943	-0.943	-0.943
1086	43.44	-0.943	0	-0.943		1139	45.56	0	-1.886	-2.829
1087	43.48	-1.886	-2.829	-0.943		1140	45.60	2.829	1.886	0

Experimental Data Record No.														
6 Aug 40mmdia 1177 length 28-g1														
Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)		Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)				
1141	45.64	0.943	0	-0.943		1194	47.76	0.943	-2.829	-1.886				
1142	45.68	3.772	5.658	1.886		1195	47.80	0.943	1.886	-1.886				
1143	45.72	1.886	1.886	0.943		1196	47.84	-1.886	-9.43	-5.658				
1144	45.76	0	-4.715	-1.886		1197	47.88	-0.943	-8.487	-4.715				
1145	45.80	0	-3.772	-1.886		1198	47.92	2.829	0.943	0.943				
1146	45.84	0.943	0.943	-0.943		1199	47.96	4.715	8.487	1.886				
1147	45.88	2.829	1.886	0.943		1200	48.00	0.943	1.886	-0.943				
1148	45.92	0	-6.601	-2.829		1201	48.04	1.886	2.829	0				
1149	45.96	1.886	-4.715	-1.886		1202	48.08	1.886	3.772	0				
1150	46.00	2.829	-3.772	-0.943		1203	48.12	1.886	4.715	-0.943				
1151	46.04	2.829	1.886	0		1204	48.16	2.829	4.715	0.943				
1152	46.08	0.943	0	0		1205	48.20	1.886	1.886	0				
1153	46.12	-2.829	-6.601	-4.715		1206	48.24	2.829	6.601	1.886				
1154	46.16	-2.829	-6.601	-5.658		1207	48.28	3.772	6.601	1.886				
1155	46.20	3.772	8.487	2.829		1208	48.32	-0.943	-0.943	-1.886				
1156	46.24	0.943	3.772	0		1209	48.36	0.943	0.943	0.943				
1157	46.28	0.943	2.829	0		1210	48.40	-3.772	-1.886	-4.715				
1158	46.32	-0.943	-0.943	-2.829		1211	48.44	-0.943	0	-1.886				
1159	46.36	0.943	0.943	-0.943		1212	48.48	0.943	-0.943	0				
1160	46.40	-0.943	-2.829	-2.829		1213	48.52	-1.886	-1.886	-2.829				
1161	46.44	1.886	2.829	0		1214	48.56	-0.943	-1.886	-2.829				
1162	46.48	0	-2.829	-0.943		1215	48.60	-0.943	-2.829	-2.829				
1163	46.52	-0.943	-6.601	-3.772		1216	48.64	-1.886	0	-2.829				
1164	46.56	0	-2.829	-1.886		1217	48.68	-0.943	-2.829	-2.829				
1165	46.60	0.943	-2.829	-1.886		1218	48.72	0.943	8.487	0.943				
1166	46.64	0.943	0	-0.943		1219	48.76	0.943	5.658	0.943				
1167	46.68	0.943	-0.943	-1.886		1220	48.80	-1.886	-0.943	-2.829				
1168	46.72	1.886	0	-0.943		1221	48.84	0	-0.943	-1.886				
1169	46.76	0.943	-0.943	-1.886		1222	48.88	0.943	1.886	-0.943				
1170	46.80	1.886	-1.886	-0.943		1223	48.92	3.772	16.974	2.829				
1171	46.84	0.943	-0.943	-0.943		1224	48.96	3.772	2.829	3.772				
1172	46.88	0.943	-0.943	-1.886		1225	49.00	-4.715	-3.772	-5.658				
1173	46.92	2.829	4.715	0.943		1226	49.04	-1.886	-1.886	-3.772				
1174	46.96	0.943	0	-1.886		1227	49.08	2.829	5.658	0.943				
1175	47.00	1.886	0.943	0		1228	49.12	-2.829	-2.829	-4.715				
1176	47.04	1.886	5.658	0.943		1229	49.16	-3.772	-5.658	-3.772				
1177	47.08	0	-6.601	-2.829		1230	49.20	-1.886	-1.886	-2.829				
1178	47.12	0.943	-2.829	-1.886		1231	49.24	-0.943	-1.886	-2.829				
1179	47.16	3.772	1.886	1.886		1232	49.28	0.943	4.715	0				
1180	47.20	3.772	2.829	0.943		1233	49.32	0	0	-0.943				
1181	47.24	0.943	-1.886	-0.943		1234	49.36	-1.886	-1.886	-3.772				
1182	47.28	2.829	0.943	0		1235	49.40	-1.886	-3.772	-3.772				
1183	47.32	0	0	-0.943		1236	49.44	3.772	9.43	2.829				
1184	47.36	-0.943	-3.772	-4.715		1237	49.48	3.772	10.373	2.829				
1185	47.40	0	-1.886	-1.886		1238	49.52	1.886	6.601	2.829				
1186	47.44	4.715	4.715	0.943		1239	49.56	0.943	4.715	0.943				
1187	47.48	-0.943	-1.886	-2.829		1240	49.60	-3.772	-6.601	-4.715				
1188	47.52	0.943	0.943	0		1241	49.64	-2.829	0	-1.886				
1189	47.56	4.715	7.544	2.829		1242	49.68	0.943	3.772	0.943				
1190	47.60	4.715	3.772	0.943		1243	49.72	-2.829	0.943	-0.943				
1191	47.64	0	-0.943	-1.886		1244	49.76	-6.601	-9.43	-5.658				
1192	47.68	1.886	-2.829	-0.943		1245	49.80	-4.715	-5.658	-3.772				
1193	47.72	1.886	0	-1.886		1246	49.84	-2.829	-0.943	-0.943				

Experimental Data Record No.

6 Aug 40mmdia 1177 length 28-g1

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)	Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
1247	49.88	-0.943	1.886	0	1300	52.00	0.943	7.544	2.829
1248	49.92	-2.829	-0.943	-1.886	1301	52.04	-4.715	0	-2.829
1249	49.96	-0.943	0.943	0	1302	52.08	-4.715	-1.886	-2.829
1250	50.00	0	1.886	-0.943	1303	52.12	0.943	4.715	1.886
1251	50.04	-0.943	0.943	-0.943	1304	52.16	1.886	14.145	3.772
1252	50.08	-0.943	3.772	0	1305	52.20	-3.772	1.886	-1.886
1253	50.12	-0.943	2.829	-0.943	1306	52.24	-3.772	-1.886	-1.886
1254	50.16	-0.943	2.829	0	1307	52.28	-5.658	-7.544	-3.772
1255	50.20	-0.943	3.772	0.943	1308	52.32	-2.829	0.943	-0.943
1256	50.24	-5.658	-4.715	-4.715	1309	52.36	-3.772	0.943	-0.943
1257	50.28	-4.715	-5.658	-3.772	1310	52.40	-5.658	-2.829	-3.772
1258	50.32	-0.943	1.886	0	1311	52.44	-1.886	-3.772	-0.943
1259	50.36	-2.829	-3.772	-1.886	1312	52.48	-3.772	-3.772	-3.772
1260	50.40	-3.772	-3.772	-3.772	1313	52.52	1.886	8.487	3.772
1261	50.44	0.943	5.658	1.886	1314	52.56	-1.886	0.943	-0.943
1262	50.48	-0.943	3.772	0.943	1315	52.60	-0.943	3.772	0
1263	50.52	-4.715	-2.829	-1.886	1316	52.64	-2.829	-1.886	-2.829
1264	50.56	-0.943	-0.943	-1.886	1317	52.68	-1.886	0	-0.943
1265	50.60	0.943	2.829	0	1318	52.72	3.772	7.544	4.715
1266	50.64	-1.886	0.943	-1.886	1319	52.76	4.715	10.373	5.658
1267	50.68	-1.886	0	-2.829	1320	52.80	-1.886	0	0
1268	50.72	0.943	2.829	0	1321	52.84	0	0	0
1269	50.76	0.943	0.943	-0.943	1322	52.88	-3.772	-7.544	-4.715
1270	50.80	0	1.886	-1.886	1323	52.92	0	1.886	0
1271	50.84	-1.886	1.886	-2.829	1324	52.96	0	4.715	0.943
1272	50.88	-0.943	1.886	0	1325	53.00	-4.715	-4.715	-4.715
1273	50.92	-1.886	-1.886	-2.829	1326	53.04	-0.943	-1.886	0
1274	50.96	-2.829	-5.658	-2.829	1327	53.08	-1.886	0	0
1275	51.00	-0.943	0	-0.943	1328	53.12	-1.886	-1.886	-2.829
1276	51.04	2.829	5.658	2.829	1329	53.16	-2.829	-0.943	-1.886
1277	51.08	-0.943	-2.829	-0.943	1330	53.20	0.943	3.772	1.886
1278	51.12	-1.886	-4.715	-2.829	1331	53.24	-1.886	-1.886	-0.943
1279	51.16	-3.772	-3.772	-3.772	1332	53.28	-1.886	1.886	-1.886
1280	51.20	0	3.772	0.943	1333	53.32	2.829	8.487	4.715
1281	51.24	-1.886	0.943	-0.943	1334	53.36	-0.943	2.829	0
1282	51.28	-5.658	-3.772	-4.715	1335	53.40	-0.943	0	-0.943
1283	51.32	-1.886	3.772	0	1336	53.44	0	4.715	0.943
1284	51.36	-0.943	2.829	0.943	1337	53.48	-0.943	-4.715	-0.943
1285	51.40	-2.829	1.886	-0.943	1338	53.52	-0.943	2.829	-1.886
1286	51.44	0	6.601	1.886	1339	53.56	0.943	0.943	1.886
1287	51.48	-3.772	-1.886	-1.886	1340	53.60	-2.829	-6.601	-2.829
1288	51.52	-0.943	1.886	0.943	1341	53.64	-1.886	-5.658	-2.829
1289	51.56	0.943	0.943	0.943	1342	53.68	-2.829	-1.886	-2.829
1290	51.60	-1.886	0.943	-0.943	1343	53.72	0	1.886	0.943
1291	51.64	-1.886	-1.886	-0.943	1344	53.76	-0.943	3.772	0.943
1292	51.68	-2.829	-2.829	-1.886	1345	53.80	-2.829	-2.829	-1.886
1293	51.72	-0.943	-0.943	-0.943	1346	53.84	-0.943	1.886	0
1294	51.76	-2.829	-4.715	-2.829	1347	53.88	-0.943	1.886	0
1295	51.80	-4.715	-3.772	-4.715	1348	53.92	1.886	7.544	2.829
1296	51.84	-1.886	0.943	0	1349	53.96	-2.829	0	-2.829
1297	51.88	-6.601	-5.658	-5.658	1350	54.00	-0.943	0	-0.943
1298	51.92	0	3.772	0.943	1351	54.04	0	2.829	0
1299	51.96	0	10.373	3.772	1352	54.08	2.829	9.43	2.829

Experimental Data Record No.
6 Aug 40mmdia 1177 length 28-g1

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
1353	54.12	-0.943	0.943	-0.943
1354	54.16	-3.772	-6.601	-2.829
1355	54.20	-0.943	-0.943	0
1356	54.24	-0.943	0.943	0
1357	54.28	0	2.829	0.943
1358	54.32	-0.943	0	0
1359	54.36	-4.715	-6.601	-3.772
1360	54.40	-4.715	-7.544	-4.715
1361	54.44	-1.886	0.943	-0.943
1362	54.48	-0.943	0	0
1363	54.52	0.943	2.829	0.943
1364	54.56	-1.886	-0.943	-1.886
1365	54.60	1.886	6.601	2.829
1366	54.64	0	2.829	0
1367	54.68	1.886	7.544	3.772
1368	54.72	-1.886	0.943	0
1369	54.76	-1.886	0	-0.943
1370	54.80	-0.943	-0.943	-0.943
1371	54.84	0.943	7.544	2.829
1372	54.88	-1.886	-0.943	-0.943
1373	54.92	-1.886	-2.829	-0.943
1374	54.96	-3.772	-7.544	-3.772
1375	55.00	-0.943	-2.829	-0.943
1376	55.04	-1.886	0	-0.943
1377	55.08	-1.886	0.943	0.943
1378	55.12	-2.829	-5.658	-2.829
1379	55.16	-2.829	-3.772	-2.829
1380	55.20	1.886	8.487	2.829
1381	55.24	0	5.658	0.943
1382	55.28	0.943	3.772	1.886
1383	55.32	0	-0.943	0
1384	55.36	-3.772	-2.829	-1.886
1385	55.40	-0.943	2.829	0.943
1386	55.44	-1.886	4.715	0
1387	55.48	-3.772	-2.829	-1.886
1388	55.52	-5.658	-6.601	-3.772
1389	55.56	-1.886	0.943	0
1390	55.60	0	0.943	1.886
1391	55.64	-0.943	0	0
1392	55.68	-3.772	-2.829	-2.829
1393	55.72	-2.829	-3.772	-0.943
1394	55.76	-0.943	2.829	0.943
1395	55.80	0	3.772	2.829
1396	55.84	-1.886	2.829	0
1397	55.88	-0.943	2.829	1.886
1398	55.92	0	3.772	1.886
1399	55.96	-1.886	0	-0.943
1400	56.00	-0.943	1.886	0.943
1401	56.04	-0.943	2.829	1.886
1402	56.08	-4.715	-5.658	-3.772
1403	56.12	-2.829	-0.943	-0.943
1404	56.16	-3.772	-3.772	-0.943
1405	56.20	2.829	12.259	5.658

Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
1406	56.24	-4.715	-5.658	-1.886
1407	56.28	-4.715	-9.43	-2.829
1408	56.32	-2.829	-7.544	-3.772
1409	56.36	0	1.886	0.943
1410	56.40	3.772	10.373	4.715
1411	56.44	-8.487	-11.316	-6.601
1412	56.48	0	-1.886	0.943
1413	56.52	-0.943	1.886	0.943
1414	56.56	1.886	9.43	1.886
1415	56.60	3.772	10.373	4.715
1416	56.64	-1.886	3.772	0.943
1417	56.68	0	1.886	1.886
1418	56.72	-3.772	-6.601	-2.829
1419	56.76	-0.943	1.886	0
1420	56.80	-2.829	-0.943	-0.943
1421	56.84	-4.715	-5.658	-3.772
1422	56.88	-7.544	-7.544	-4.715
1423	56.92	-2.829	-4.715	-1.886
1424	56.96	-2.829	0.943	-0.943
1425	57.00	-4.715	-6.601	-1.886
1426	57.04	-4.715	-3.772	-2.829
1427	57.08	0.943	0.943	0.943
1428	57.12	0.943	3.772	1.886
1429	57.16	-0.943	3.772	-0.943
1430	57.20	-2.829	1.886	-0.943
1431	57.24	-1.886	0.943	0
1432	57.28	0	1.886	0.943
1433	57.32	0	4.715	0.943
1434	57.36	-0.943	2.829	0
1435	57.40	-0.943	-0.943	-0.943
1436	57.44	-1.886	-1.886	-1.886
1437	57.48	-0.943	0	-1.886
1438	57.52	-1.886	0	-1.886
1439	57.56	-1.886	-2.829	-0.943
1440	57.60	-3.772	-6.601	-4.715
1441	57.64	-3.772	-5.658	-4.715
1442	57.68	1.886	5.658	1.886
1443	57.72	1.886	2.829	0
1444	57.76	-1.886	-0.943	-3.772
1445	57.80	0.943	4.715	0.943
1446	57.84	-2.829	-5.658	-5.658
1447	57.88	3.772	6.601	1.886
1448	57.92	1.886	6.601	0.943
1449	57.96	0.943	4.715	0
1450	58.00	-1.886	-3.772	-2.829
1451	58.04	-1.886	-0.943	-2.829
1452	58.08	-0.943	0.943	-0.943
1453	58.12	0	0.943	0
1454	58.16	-0.943	-1.886	-1.886
1455	58.20	-1.886	-6.601	-3.772
1456	58.24	-1.886	-3.772	-1.886
1457	58.28	0.943	2.829	1.886
1458	58.32	0	0	-0.943

APPENDIX B

Experimental Data Record No.				
6 Aug 40mmdia 1177 length 28-g1				
Data Point	Time (sec)	strain (μ)	strain (μ)	strain (μ)
1459	58.36	0.943	2.829	-0.943
1460	58.40	-1.886	-5.658	-2.829
1461	58.44	0.943	2.829	0
1462	58.48	1.886	4.715	1.886
1463	58.52	0	0	-0.943
1464	58.56	0	-2.829	-1.886
1465	58.60	-0.943	-3.772	-2.829
1466	58.64	0.943	1.886	0.943
1467	58.68	0	-0.943	-0.943
1468	58.72	0.943	2.829	0.943
1469	58.76	1.886	-0.943	1.886
1470	58.80	1.886	2.829	2.829
1471	58.84	-0.943	-2.829	-0.943
1472	58.88	-0.943	-1.886	-1.886
1473	58.92	0	0	0.943
1474	58.96	0.943	3.772	0
1475	59.00	0	1.886	0
1476	59.04	0	1.886	-0.943
1477	59.08	3.772	6.601	3.772
1478	59.12	-1.886	-0.943	-1.886
1479	59.16	-0.943	-1.886	-1.886
1480	59.20	0	0.943	0
1481	59.24	-0.943	0	-0.943
1482	59.28	0	3.772	0.943
1483	59.32	0	-1.886	0
1484	59.36	1.886	0	1.886
1485	59.40	0.943	0.943	0.943
1486	59.44	1.886	4.715	2.829
1487	59.48	0	-2.829	-0.943
1488	59.52	-0.943	-5.658	-1.886
1489	59.56	0.943	-1.886	-0.943
1490	59.60	-0.943	-3.772	-1.886
1491	59.64	0.943	2.829	0.943
1492	59.68	0.943	-1.886	0
1493	59.72	-2.829	-5.658	-3.772
1494	59.76	0	-1.886	-1.886
1495	59.80	3.772	0.943	1.886
1496	59.84	4.715	4.715	2.829
1497	59.88	2.829	1.886	1.886
1498	59.92	3.772	1.886	0.943
1499	59.96	3.772	0	0.943
1500	60.00	1.886	-0.943	-0.943

Figure B.1 Sample Results For Test Performed On 40mm Diameter Acrylic Pipe (With 3mm Neoprene Damping Thickness and 6mm Boundary Condition)

APPENDIX B

Figure B.2 Plot of Strain Versus Time For Three Channels

APPENDIX C
ALLOWABLE SPAN CALCULATIONS FOR 25MM ACRYLIC
PIPE AND 40MM ACRYLIC PIPE

APPENDIX C

PIPELINE ALLOWABLE SPAN CALCULATIONS BASED ON DNV 1981 CODE		
PARAMETER	UNIT	VALUE
Pipeline Outside Diameter	mm	25.00
Pipe Wall Thickness	mm	1.0
Corrosion Allowance	mm	0.000
Pipe Density	kg/m ³	1100.00
Concrete Coating Thickness	mm	0.0
Concrete Coating Density	kg/m ³	0.00
Concrete Water Absorbtion	%	0.00
Corrosion Coating Thickness	mm	0.0
Corrosion Coating Density	kg/m ³	0.0
Yield Stress of Pipe Material	N/mm ²	0.0
Young's Modulus of Elasticity	N/mm ²	1800.00
Poisson's Ratio		0.00
Density of Water	kg/m ³	1000.00
Kinematic Viscosity of Water	m ² /s	0.00000111
Density of Pipeline Content	kg/m ³	1000.00
Current Velocity	m/s	0.100
Reduced Pipe Wall Thickness	mm	1
Cross-sectional Area of Steel	mm ²	75.40
Cross-sectional Area of Concrete	mm ²	0.00
Cross-sectional Area of Corrosion Coating	mm ²	0.00
Density of Sea Water	kg/m ³	1000.0
Gravitational Acceleration	m/s ²	9.807
Pipe Steel Mass	kg/m	0.1
Concrete Coating Mass	kg/m	0.0
Corrosion Coating Mass	kg/m	0.0
Buoyancy	N/m	4.81
Content Mass	kg/m	0.42
PIPE WEIGHT		
Pipe Dry Weight	N/m	4.888
Pipe Submerged Weight	N/m	0.07
Pipe Specific Gravity in Seawater	-	1.0
Overall Pipe Diameter	mm	25.00
Pipe Moment of Inertia	mm ⁴	5438
Pipe Stiffness	N-m ²	9.78857439
Pipe Submerged Weight	N/m	0.07
Pipe Dry Weight	N/m	4.89
Pipe Displacement	N/m	4.81
A) DYNAMIC SPAN ANALYSIS - CROSS FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	0.99
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/sec	0.100
Stability Parameter	-	0.399
Reynold's Number	-	2252.25
Reduced Velocity	-	5.000
Pipeline Natural Frequency	Hz	0.800
Allowable Span Length	metres	3.10
B) DYNAMIC SPAN ANALYSIS - IN-LINE FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	0.99
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/s	0.100
Reynold's Number	-	2252.25
Stability Parameter	-	0.399
Reduced Velocity	-	1.45
Pipeline Natural Frequency	Hz	2.752
Allowable Span Length for fixed-fixed Condition	metres	2.02
Allowable Span Length for pin-fixed Condition	metres	1.67

Figure C.1 Detailed Calculations For Natural Frequencies and Span Lengths For 25mm Diameter Acrylic Pipe With 1mm Wall Thickness Under Pinned-Fixed and Fixed-Fixed Conditions (Current Velocity = 0.1m/s)

APPENDIX C

PIPELINE ALLOWABLE SPAN CALCULATIONS BASED ON DNV 1981 CODE		
PARAMETER	UNIT	VALUE
Pipeline Outside Diameter	mm	25.00
Pipe Wall Thickness	mm	1.0
Corrosion Allowance	mm	0.000
Pipe Density	kg/m ³	1100.00
Concrete Coating Thickness	mm	0.0
Concrete Coating Density	kg/m ³	0.00
Concrete Water Absorbtion	%	0.00
Corrosion Coating Thickness	mm	0.0
Corrosion Coating Density	kg/m ³	0.0
Yield Stress of Pipe Material	N/mm ²	0.0
Young's Modulus of Elasticity	N/mm ²	1800.00
Poisson's Ratio		0.00
Density of Water	kg/m ³	1000.00
Kinematic Viscosity of Water	m ² /s	0.00000111
Density of Pipeline Content	kg/m ³	1000.00
Current Velocity	m/s	0.200
Reduced Pipe Wall Thickness	mm	1
Cross-sectional Area of Steel	mm ²	75.40
Cross-sectional Area of Concrete	mm ²	0.00
Cross-sectional Area of Corrosion Coating	mm ²	0.00
Density of Sea Water	kg/m ³	1000.0
Gravitational Acceleration	m/s ²	9.807
Pipe Steel Mass	kg/m	0.1
Concrete Coating Mass	kg/m	0.0
Corrosion Coating Mass	kg/m	0.0
Buoyancy	N/m	4.81
Content Mass	kg/m	0.42
PIPE WEIGHT		
Pipe Dry Weight	N/m	4.888
Pipe Submerged Weight	N/m	0.07
Pipe Specific Gravity in Seawater	-	1.0
Overall Pipe Diameter	mm	25.00
Pipe Moment of Inertia	mm ⁴	5438
Pipe Stiffness	N-m ²	9.78857439
Pipe Submerged Weight	N/m	0.07
Pipe Dry Weight	N/m	4.89
Pipe Displacement	N/m	4.81
A) DYNAMIC SPAN ANALYSIS - CROSS FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	0.99
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/sec	0.200
Stability Parameter	-	0.399
Reynold's Number	-	4504.50
Reduced Velocity	-	5.000
Pipeline Natural Frequency	Hz	1.600
Allowable Span Length	metres	2.20
B) DYNAMIC SPAN ANALYSIS - IN-LINE FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	0.99
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/s	0.200
Reynold's Number	-	4504.50
Stability Parameter	-	0.399
Reduced Velocity	-	1.45
Pipeline Natural Frequency	Hz	5.505
Allowable Span Length for fixed-fixed Condition	metres	1.43
Allowable Span Length for pin-fixed Condition	metres	1.18

Figure C.2 Detailed Calculations For Natural Frequencies and Span Lengths For 25mm Diameter Acrylic Pipe With 1mm Wall Thickness Under Pinned-Fixed and Fixed-Fixed Conditions (Current Velocity = 0.2m/s)

APPENDIX C

PIPELINE ALLOWABLE SPAN CALCULATIONS BASED ON DNV 1981 CODE		
PARAMETER	UNIT	VALUE
Pipeline Outside Diameter	mm	25.00
Pipe Wall Thickness	mm	1.0
Corrosion Allowance	mm	0.000
Pipe Density	kg/m ³	1100.00
Concrete Coating Thickness	mm	0.0
Concrete Coating Density	kg/m ³	0.00
Concrete Water Absorbtion	%	0.00
Corrosion Coating Thickness	mm	0.0
Corrosion Coating Density	kg/m ³	0.0
Yield Stress of Pipe Material	N/mm ²	0.0
Young's Modulus of Elasticity	N/mm ²	1800.00
Poisson's Ratio		0.00
Density of Water	kg/m ³	1000.00
Kinematic Viscosity of Water	m ² /s	0.00000111
Density of Pipeline Content	kg/m ³	1000.00
Current Velocity	m/s	0.300
Reduced Pipe Wall Thickness	mm	1
Cross-sectional Area of Steel	mm ²	75.40
Cross-sectional Area of Concrete	mm ²	0.00
Cross-sectional Area of Corrosion Coating	mm ²	0.00
Density of Sea Water	kg/m ³	1000.0
Gravitational Acceleration	m/s ²	9.807
Pipe Steel Mass	kg/m	0.1
Concrete Coating Mass	kg/m	0.0
Corrosion Coating Mass	kg/m	0.0
Buoyancy	N/m	4.81
Content Mass	kg/m	0.42
PIPE WEIGHT		
Pipe Dry Weight	N/m	4.888
Pipe Submerged Weight	N/m	0.07
Pipe Specific Gravity in Seawater	-	1.0
Overall Pipe Diameter	mm	25.00
Pipe Moment of Inertia	mm ⁴	5438
Pipe Stiffness	N-m ²	9.78857439
Pipe Submerged Weight	N/m	0.07
Pipe Dry Weight	N/m	4.89
Pipe Displacement	N/m	4.81
A) DYNAMIC SPAN ANALYSIS - CROSS FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	0.99
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/sec	0.300
Stability Parameter	-	0.399
Reynold's Number	-	6756.76
Reduced Velocity	-	5.000
Pipeline Natural Frequency	Hz	2.400
Allowable Span Length	metres	1.79
B) DYNAMIC SPAN ANALYSIS - IN-LINE FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	0.99
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/s	0.300
Reynold's Number	-	6756.76
Stability Parameter	-	0.399
Reduced Velocity	-	1.45
Pipeline Natural Frequency	Hz	8.257
Allowable Span Length for fixed-fixed Condition	metres	1.16
Allowable Span Length for pin-fixed Condition	metres	0.97

Figure C.3 Detailed Calculations For Natural Frequencies and Span Lengths For 25mm Diameter Acrylic Pipe With 1mm Wall Thickness Under Pinned-Fixed and Fixed-Fixed Conditions (Current Velocity = 0.3m/s)

APPENDIX C

PIPELINE ALLOWABLE SPAN CALCULATIONS BASED ON DNV 1981 CODE		
PARAMETER	UNIT	VALUE
Pipeline Outside Diameter	mm	25.00
Pipe Wall Thickness	mm	1.0
Corrosion Allowance	mm	0.000
Pipe Density	kg/m ³	1100.00
Concrete Coating Thickness	mm	0.0
Concrete Coating Density	kg/m ³	0.00
Concrete Water Absorbtion	%	0.00
Corrosion Coating Thickness	mm	0.0
Corrosion Coating Density	kg/m ³	0.0
Yield Stress of Pipe Material	N/mm ²	0.0
Young's Modulus of Elasticity	N/mm ²	1800.00
Poisson's Ratio		0.00
Density of Water	kg/m ³	1000.00
Kinematic Viscosity of Water	m ² /s	0.00000111
Density of Pipeline Content	kg/m ³	1000.00
Current Velocity	m/s	0.400
Reduced Pipe Wall Thickness	mm	1
Cross-sectional Area of Steel	mm ²	75.40
Cross-sectional Area of Concrete	mm ²	0.00
Cross-sectional Area of Corrosion Coating	mm ²	0.00
Density of Sea Water	kg/m ³	1000.0
Gravitational Acceleration	m/s ²	9.807
Pipe Steel Mass	kg/m	0.1
Concrete Coating Mass	kg/m	0.0
Corrosion Coating Mass	kg/m	0.0
Buoyancy	N/m	4.81
Content Mass	kg/m	0.42
PIPE WEIGHT		
Pipe Dry Weight	N/m	4.888
Pipe Submerged Weight	N/m	0.07
Pipe Specific Gravity in Seawater	-	1.0
Overall Pipe Diameter	mm	25.00
Pipe Moment of Inertia	mm ⁴	5438
Pipe Stiffness	N-m ²	9.78857439
Pipe Submerged Weight	N/m	0.07
Pipe Dry Weight	N/m	4.89
Pipe Displacement	N/m	4.81
A) DYNAMIC SPAN ANALYSIS - CROSS FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	0.99
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/sec	0.400
Stability Parameter	-	0.399
Reynold's Number	-	9009.01
Reduced Velocity	-	5.000
Pipeline Natural Frequency	Hz	3.200
Allowable Span Length	metres	1.55
B) DYNAMIC SPAN ANALYSIS - IN-LINE FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	0.99
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/s	0.400
Reynold's Number	-	9009.01
Stability Parameter	-	0.399
Reduced Velocity	-	1.45
Pipeline Natural Frequency	Hz	11.009
Allowable Span Length for fixed-fixed Condition	metres	1.01
Allowable Span Length for pin-fixed Condition	metres	0.84

Figure C.4 Detailed Calculations For Natural Frequencies and Span Lengths For 25mm Diameter Acrylic Pipe With 1mm Wall Thickness Under Pinned-Fixed and Fixed-Fixed Conditions (Current Velocity = 0.4m/s)

APPENDIX C

PIPELINE ALLOWABLE SPAN CALCULATIONS BASED ON DNV 1981 CODE		
PARAMETER	UNIT	VALUE
Pipeline Outside Diameter	mm	40.00
Pipe Wall Thickness	mm	1.0
Corrosion Allowance	mm	0.000
Pipe Density	kg/m ³	1100.00
Concrete Coating Thickness	mm	0.0
Concrete Coating Density	kg/m ³	0.00
Concrete Water Absorbtion	%	0.00
Corrosion Coating Thickness	mm	0.0
Corrosion Coating Density	kg/m ³	0.0
Yield Stress of Pipe Material	N/mm ²	0.0
Young's Modulus of Elasticity	N/mm ²	1800.00
Poisson's Ratio		0.00
Density of Water	kg/m ³	1000.00
Kinematic Viscosity of Water	m ² /s	0.00000111
Density of Pipeline Content	kg/m ³	1000.00
Current Velocity	m/s	0.500
Reduced Pipe Wall Thickness	mm	1
Cross-sectional Area of Steel	mm ²	122.52
Cross-sectional Area of Concrete	mm ²	0.00
Cross-sectional Area of Corrosion Coating	mm ²	0.00
Density of Sea Water	kg/m ³	1000.0
Gravitational Acceleration	m/s ²	9.807
Pipe Steel Mass	kg/m	0.1
Concrete Coating Mass	kg/m	0.0
Corrosion Coating Mass	kg/m	0.0
Buoyancy	N/m	12.32
Content Mass	kg/m	1.13
PIPE WEIGHT		
Pipe Dry Weight	N/m	12.444
Pipe Submerged Weight	N/m	0.12
Pipe Specific Gravity in Seawater	-	1.0
Overall Pipe Diameter	mm	40.00
Pipe Moment of Inertia	mm ⁴	23310
Pipe Stiffness	N-m ²	41.95769776
Pipe Submerged Weight	N/m	0.12
Pipe Dry Weight	N/m	12.44
Pipe Displacement	N/m	12.32
A) DYNAMIC SPAN ANALYSIS - CROSS FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	2.53
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/sec	0.500
Stability Parameter	-	0.398
Reynold's Number	-	18018.02
Reduced Velocity	-	5.000
Pipeline Natural Frequency	Hz	2.500
Allowable Span Length	metres	2.00
B) DYNAMIC SPAN ANALYSIS - IN-LINE FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	2.53
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/s	0.500
Reynold's Number	-	18018.02
Stability Parameter	-	0.398
Reduced Velocity	-	1.45
Pipeline Natural Frequency	Hz	8.601
Allowable Span Length for fixed-fixed Condition	metres	1.30
Allowable Span Length for pin-fixed Condition	metres	1.08

Figure C.5 Detailed Calculations For Natural Frequencies and Span Lengths For 40mm Diameter Acrylic Pipe With 1mm Wall Thickness Under Pinned-Fixed and Fixed-Fixed Conditions (Current Velocity = 0.5m/s)

APPENDIX C

PIPELINE ALLOWABLE SPAN CALCULATIONS BASED ON DNV 1981 CODE		
PARAMETER	UNIT	VALUE
Pipeline Outside Diameter	mm	40.00
Pipe Wall Thickness	mm	1.0
Corrosion Allowance	mm	0.000
Pipe Density	kg/m ³	1100.00
Concrete Coating Thickness	mm	0.0
Concrete Coating Density	kg/m ³	0.00
Concrete Water Absorbtion	%	0.00
Corrosion Coating Thickness	mm	0.0
Corrosion Coating Density	kg/m ³	0.0
Yield Stress of Pipe Material	N/mm ²	0.0
Young's Modulus of Elasticity	N/mm ²	1800.00
Poisson's Ratio		0.00
Density of Water	kg/m ³	1000.00
Kinematic Viscosity of Water	m ² /s	0.00000111
Density of Pipeline Content	kg/m ³	1000.00
Current Velocity	m/s	0.700
Reduced Pipe Wall Thickness	mm	1
Cross-sectional Area of Steel	mm ²	122.52
Cross-sectional Area of Concrete	mm ²	0.00
Cross-sectional Area of Corrosion Coating	mm ²	0.00
Density of Sea Water	kg/m ³	1000.0
Gravitational Acceleration	m/s ²	9.807
Pipe Steel Mass	kg/m	0.1
Concrete Coating Mass	kg/m	0.0
Corrosion Coating Mass	kg/m	0.0
Buoyancy	N/m	12.32
Content Mass	kg/m	1.13
PIPE WEIGHT		
Pipe Dry Weight	N/m	12.444
Pipe Submerged Weight	N/m	0.12
Pipe Specific Gravity in Seawater	-	1.0
Overall Pipe Diameter	mm	40.00
Pipe Moment of Inertia	mm ⁴	23310
Pipe Stiffness	N-m ²	41.95769776
Pipe Submerged Weight	N/m	0.12
Pipe Dry Weight	N/m	12.44
Pipe Displacement	N/m	12.32
A) DYNAMIC SPAN ANALYSIS - CROSS FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	2.53
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/sec	0.700
Stability Parameter	-	0.398
Reynold's Number	-	25225.23
Reduced Velocity	-	5.000
Pipeline Natural Frequency	Hz	3.500
Allowable Span Length	metres	1.69
B) DYNAMIC SPAN ANALYSIS - IN-LINE FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	2.53
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/s	0.700
Reynold's Number	-	25225.23
Stability Parameter	-	0.398
Reduced Velocity	-	1.45
Pipeline Natural Frequency	Hz	12.041
Allowable Span Length for fixed-fixed Condition	metres	1.10
Allowable Span Length for pin-fixed Condition	metres	0.91

Figure C.6 Detailed Calculations For Natural Frequencies and Span Lengths For 40mm Diameter Acrylic Pipe With 1mm Wall Thickness Under Pinned-Fixed and Fixed-Fixed Conditions (Current Velocity = 0.7m/s)

APPENDIX C

PIPELINE ALLOWABLE SPAN CALCULATIONS BASED ON DNV 1981 CODE		
PARAMETER	UNIT	VALUE
Pipeline Outside Diameter	mm	40.00
Pipe Wall Thickness	mm	1.0
Corrosion Allowance	mm	0.000
Pipe Density	kg/m ³	1100.00
Concrete Coating Thickness	mm	0.0
Concrete Coating Density	kg/m ³	0.00
Concrete Water Absorbtion	%	0.00
Corrosion Coating Thickness	mm	0.0
Corrosion Coating Density	kg/m ³	0.0
Yield Stress of Pipe Material	N/mm ²	0.0
Young's Modulus of Elasticity	N/mm ²	1800.00
Poisson's Ratio		0.00
Density of Water	kg/m ³	1000.00
Kinematic Viscosity of Water	m ² /s	0.00000111
Density of Pipeline Content	kg/m ³	1000.00
Current Velocity	m/s	0.900
Reduced Pipe Wall Thickness	mm	1
Cross-sectional Area of Steel	mm ²	122.52
Cross-sectional Area of Concrete	mm ²	0.00
Cross-sectional Area of Corrosion Coating	mm ²	0.00
Density of Sea Water	kg/m ³	1000.0
Gravitational Acceleration	m/s ²	9.807
Pipe Steel Mass	kg/m	0.1
Concrete Coating Mass	kg/m	0.0
Corrosion Coating Mass	kg/m	0.0
Buoyancy	N/m	12.32
Content Mass	kg/m	1.13
PIPE WEIGHT		
Pipe Dry Weight	N/m	12.444
Pipe Submerged Weight	N/m	0.12
Pipe Specific Gravity in Seawater	-	1.0
Overall Pipe Diameter	mm	40.00
Pipe Moment of Inertia	mm ⁴	23310
Pipe Stiffness	N-m ²	41.95769776
Pipe Submerged Weight	N/m	0.12
Pipe Dry Weight	N/m	12.44
Pipe Displacement	N/m	12.32
A) DYNAMIC SPAN ANALYSIS - CROSS FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	2.53
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/sec	0.900
Stability Parameter	-	0.398
Reynold's Number	-	32432.43
Reduced Velocity	-	5.000
Pipeline Natural Frequency	Hz	4.500
Allowable Span Length	metres	1.49
B) DYNAMIC SPAN ANALYSIS - IN-LINE FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	2.53
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/s	0.900
Reynold's Number	-	32432.43
Stability Parameter	-	0.398
Reduced Velocity	-	1.45
Pipeline Natural Frequency	Hz	15.482
Allowable Span Length for fixed-fixed Condition	metres	0.97
Allowable Span Length for pin-fixed Condition	metres	0.80

Figure C.7 Detailed Calculations For Natural Frequencies and Span Lengths For 40mm Diameter Acrylic Pipe With 1mm Wall Thickness Under Pinned-Fixed and Fixed-Fixed Conditions (Current Velocity = 0.9m/s)

APPENDIX C

PIPELINE ALLOWABLE SPAN CALCULATIONS BASED ON DNV 1981 CODE		
PARAMETER	UNIT	VALUE
Pipeline Outside Diameter	mm	40.00
Pipe Wall Thickness	mm	1.0
Corrosion Allowance	mm	0.000
Pipe Density	kg/m ³	1100.00
Concrete Coating Thickness	mm	0.0
Concrete Coating Density	kg/m ³	0.00
Concrete Water Absorbtion	%	0.00
Corrosion Coating Thickness	mm	0.0
Corrosion Coating Density	kg/m ³	0.0
Yield Stress of Pipe Material	N/mm ²	0.0
Young's Modulus of Elasticity	N/mm ²	1800.00
Poisson's Ratio		0.00
Density of Water	kg/m ³	1000.00
Kinematic Viscosity of Water	m ² /s	0.00000111
Density of Pipeline Content	kg/m ³	1000.00
Current Velocity	m/s	1.100
Reduced Pipe Wall Thickness	mm	1
Cross-sectional Area of Steel	mm ²	122.52
Cross-sectional Area of Concrete	mm ²	0.00
Cross-sectional Area of Corrosion Coating	mm ²	0.00
Density of Sea Water	kg/m ³	1000.0
Gravitational Acceleration	m/s ²	9.807
Pipe Steel Mass	kg/m	0.1
Concrete Coating Mass	kg/m	0.0
Corrosion Coating Mass	kg/m	0.0
Buoyancy	N/m	12.32
Content Mass	kg/m	1.13
PIPE WEIGHT		
Pipe Dry Weight	N/m	12.444
Pipe Submerged Weight	N/m	0.12
Pipe Specific Gravity in Seawater	-	1.0
Overall Pipe Diameter	mm	40.00
Pipe Moment of Inertia	mm ⁴	23310
Pipe Stiffness	N-m ²	41.95769776
Pipe Submerged Weight	N/m	0.12
Pipe Dry Weight	N/m	12.44
Pipe Displacement	N/m	12.32
A) DYNAMIC SPAN ANALYSIS - CROSS FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	2.53
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/sec	1.100
Stability Parameter	-	0.398
Reynold's Number	-	39639.64
Reduced Velocity	-	5.000
Pipeline Natural Frequency	Hz	5.500
Allowable Span Length	metres	1.35
B) DYNAMIC SPAN ANALYSIS - IN-LINE FLOW MOTION		
Logarithmic Decrement	-	0.126
Effective Mass	kg/m	2.53
Design Steady Current + Wave Velocity (At Top of Pipeline)	m/s	1.100
Reynold's Number	-	39639.64
Stability Parameter	-	0.398
Reduced Velocity	-	1.45
Pipeline Natural Frequency	Hz	18.922
Allowable Span Length for fixed-fixed Condition	metres	0.88
Allowable Span Length for pin-fixed Condition	metres	0.73

Figure C.8 Detailed Calculations For Natural Frequencies and Span Lengths For 40mm Diameter Acrylic Pipe With 1mm Wall Thickness Under Pinned-Fixed and Fixed-Fixed Conditions (Current Velocity = 1.1m/s)

APPENDIX C

MAXIMUM ALLOWABLE SPAN LENGTHS TO PREVENT VORTEX INDUCED INLINE VIBRATIONS

BASED ON DNV-RP-F105

PIPE INPUT DATA

Pipe OD	25.00 mm
Pipe WT	1.00 mm
Pipe External Diameter	25.00 mm
Pipe density	1100.00 kg/m ³
External Corrosion Coating Thickness	0.00 mm
Corrosion Coating Density	0.00 kg/m ³
Marine Growth Thickness	0.00 mm
Marine Growth Density	0.00 kg/m ³
Internal contents Density	1000.00 kg/m ³
Concrete Weight Coating Thickness	0.00 mm
Concrete Density	- kg/m ³
Water density	1000.00 kg/m ³

CALCULATED DATA

Mass in air (empty)	0.08 kg/m
Mass of displ water	0.49 kg/m
Mass of contents	0.42 kg/m
Added Mass Coefficient, a	1.000
Effective mass, Me	0.99 kg/m
Specific Gavity (Specific Mass Ratio), S _g	1.02
2nd moment of area of Steel, I _{steel}	5.44E+03 mm ⁴
2nd moment of area of Concrete, I _{conc}	N.A. mm ⁴
Vertical Dynamic Soil Stiffness K _v (N.A.)	191.68 kPa
Lateral Dynamic Soil Stiffness K _L (N.A.)	127.79 kPa
Stability Parameters, K _s	0.099
Factored Stability Parameters, K _{sd}	0.077
Onset Inline Reduced Velocity, V _R ^{IL} _{onset}	0.909
Stiffening Effect of Concrete, CSF	0.000

Correction factor for seabed proximity, $\Psi_{proxonset}$	1.00 (NA)
Correction factor for specific mass, $\Psi_{massonset}$	0.84 (NA)
Correction factor for current wave ratio $\Psi_{\alpha onset}$	1.17 (NA)

Correction factor for Trench Effect $\Psi_{trenchonset}$	1.00 (NA)
Onset CrossFlow Reduce Velocity V _R ^{CF} _{onset}	2.67 (NA)

NA : Not Applicable

SOIL INPUT PROPERTIES (NA)

Soil Type	very soft clay
Coefficient for Vertical Stiffness, C _v	1200.00 kNm ^{-2.5}
Coefficient Ffor Lateral Stiffness, C _L	800.00 kNm ^{-2.5}

STRUCTURAL INPUT PARAMETERS

Logarithmic decrement of structural damping	0.031
Total modal damping ratio, δ_T	0.005

OTHERS PARAMETERS

Modulus of Elasticity Acrylic, E _s	1800.00 N/mm ²
Modulus of Elasticity Concrete, E _{conc}	N.A. N/mm ²
Water Depth (H)	2.00 m
Effective Axial Force, S _{eff}	0.00 kN
Slippage Constant, K _c	N.A.
Drag Coefficient, C _D	0.70
Trench Depth from Mean Seabed	0.00 mm

BOUNDARY CONDITION COEFFICIENT, TABLE 6-1, DNV-RP-F105

C1	3.560	1.57	2.45	3.56
C2	0.250	1	0.5	0.25
C3	0.000	0	0	0
C4	9.245 (NA)			
C5	0.100 (NA)			
C6	0.008			

SAFETY FACTOR FOR SCREENING CRITERIA
TABLE 2-1, DNV-RP-105

γ_{in}	1.15
γ_{CF}	1.30

SAFETY FACTORS FOR FATIGUE, TABLE 2-2, DNV-RP-105

η	0.25 (NA)
γ_s	1.05 (NA)
γ_f	1.15
γ_k	1.30
γ_{on}	1.10

APPENDIX C

FORMULAE AND VARIABLES USED

Stability Parameter, K_s	$K_s = (4 * \pi * M_e * \xi_T) / (\rho * D^2)$
Onset Reduced Velocity, $V_{R\text{onset}}$	$V_{R\text{onset}}^{\text{IL}} = f_n(K_s) \quad V_{R\text{onset}}^{\text{CR}} = (3 * \psi_{\text{proxinonset}} * \psi_{\text{massonset}} * \psi_{\alpha\text{onset}} * \psi_{\text{trenchonset}}) / \gamma_{\text{on}}$
Inline Natural Frequency	$f_{\text{IN}} = (U_{c,100\text{Year}} / V_{R,\text{onset}}) * \{1 - [L / (D * 250)]\} * (\gamma_{\text{IL}} / \alpha * \gamma_f)$
Cross Flow Natural Frequency	$f_{\text{CR}} = ((U_{c,100\text{Year}} + U_{w,1\text{Year}}) / (V_{R,\text{onset}} * D)) * \gamma_{\text{cf}} * \gamma_f$
Fundamental natural frequency (In-Line)	$f_{\text{oIL}} = C1 * \sqrt{(1 + \text{CSF}) * \sqrt{(EI / Me / L_{\text{eff}}^2) * [1 + (C2 * S_{\text{eff}} / PE) + (C3 * (\delta_{\text{in}} / D)^2)]}}$
Fundamental natural frequency (Cross Flow)	$f_{\text{oCR}} = C1 * \sqrt{(1 + \text{CSF}) * \sqrt{(EI / Me / L_{\text{eff}}^2) * [1 + (C2 * S_{\text{eff}} / PE) + (C3 * (\delta_{\text{cf}} / D)^2)]}}$

Inline Check					Cross Flow Check				
Drag Force	Inline Static Deflection	Natural frequency of Span	In-line Natural Frequency	In-line Condition	Submerged Weight	Cross Flow Static Deflection	Natural frequency of Span	Crossflow Natural Frequency	CrossFlow Condition
q_{in} (N/m)	δ_{in} (m)	f_{oIL}	f_{IN}	$f_{\text{oIL}} > f_{\text{IN}}$	q_{cf} (N/m)	δ_{cf} (m)	f_{oCF}	f_{CR}	$f_{\text{oCR}} > f_{\text{CR}}$
0.09	0.0005	4.32	4.32	OK	0.07	0.001	2.24	2.241	OK
0.35	0.0004	9.63	9.63	OK	0.07	0.000	4.48	4.482	OK
0.79	0.0003	15.05	15.05	OK	0.07	0.000	6.72	6.723	OK
1.40	0.0003	20.53	20.53	OK	0.07	0.000	8.96	8.964	OK

INPUT HYDRODYNAMIC DATA				CROSS FLOW SPAN RESULT				
Mid Span Elevation (m)	Current Velocity U_{c1} (m/s)	Wave Induced Velocity U_{w1} (m/s)	Current Flow Ratio	Euler Load P_E , N (N)	β	Effective Span $\text{Effect}_{\text{span}}$ (m)	$\frac{\text{Span}}{\text{Effect}_{\text{span}}}$	Click HERE to solve for Cross-Flow Span (m)
-	0.10	0.00	1.000	1.93E+01	5.51	2.24	1.00	2.24
-	0.20	0.00	1.000	3.87E+01	4.91	1.58	1.00	1.58
-	0.30	0.00	1.000	5.80E+01	4.56	1.29	1.00	1.29
-	0.40	0.00	1.000	7.73E+01	4.31	1.12	1.00	1.12

INLINE SPAN RESULT					Click HERE to solve for In-line Span (m)
Euler Load P_E , N (N)	β	Effective Span $\text{Effect}_{\text{span}}$ (m)	$\frac{\text{Span}}{\text{Effect}_{\text{span}}}$		
3.73E+01	4.94	1.61	1.00		1.61
8.31E+01	4.94	1.08	1.00		1.08
1.30E+02	4.94	0.86	1.00		0.86
1.77E+02	4.94	0.74	1.00		0.74

Figure C.9 Detailed Calculations For Natural Frequencies and Span Lengths For 25mm Diameter Acrylic Pipe With 1mm Wall Thickness Under Pinned-Fixed and Fixed-Fixed Conditions (Current Velocity = 0.1m/s, 0.2m/s, 0.3m/s, and 0.4m/s)

APPENDIX C

MAXIMUM ALLOWABLE SPAN LENGTHS TO PREVENT VORTEX INDUCED INLINE VIBRATIONS

BASED ON DNV-RP-F105

PIPE INPUT DATA

Pipe OD	40.00 mm
Pipe WT	1.00 mm
Pipe External Diameter	40.00 mm
Pipe density	1100.00 kg/m ³
External Corrosion Coating Thickness	0.00 mm
Corrosion Coating Density	0.00 kg/m ³
Marine Growth Thickness	0.00 mm
Marine Growth Density	0.00 kg/m ³
Internal contents Density	1000.00 kg/m ³
Concrete Weight Coating Thickness	0.00 mm
Concrete Density	- kg/m ³
Water density	1000.00 kg/m ³

CALCULATED DATA

Mass in air (empty)	0.13 kg/m
Mass of displ water	1.26 kg/m
Mass of contents	1.13 kg/m
Added Mass Coefficient, a	1.000
Effective mass, Me	2.53 kg/m
Specific Gavity (Specific Mass Ratio), S _g	1.01
2nd moment of area of Steel, I _{steel}	2.33E+04 mm ⁴
2nd moment of area of Concrete, I _{conc}	N.A. mm ⁴
Vertical Dynamic Soil Stiffness K _v (N.A.)	241.56 kPa
Lateral Dynamic Soil Stiffness K _L (N.A.)	161.04 kPa
Stability Parameters , K _s	0.099
Factored Stability Parameters , K _{sd}	0.076
Onset Inline Reduced Velocity, V _R ^{IL} _{onset}	0.909
Stiffening Effect of Concrete, CSF	0.000

Correction factor for seabed proximity, $\Psi_{proxionset}$	1.00 (NA)
Correction factor for specific mass, $\Psi_{massonset}$	0.84 (NA)
Correction factor for current wave ratio $\Psi_{\alpha onset}$	1.17 (NA)

Correction factor for Trench Effect $\Psi_{trenchonset}$	1.00 (NA)
Onset CrossFlow Reduce Velocity V _R ^{CF} _{onset}	2.66 (NA)

NA : Not Applicable

SOIL INPUT PROPERTIES (NA)

Soil Type	very soft clay
Coefficient for Vertical Stiffness, C _v	1200.00 kNm ^{-2.5}
Coefficient Ffor Lateral Stiffness, C _L	800.00 kNm ^{-2.5}

STRUCTURAL INPUT PARAMETERS

Logarithmic decrement of structural damping	0.031
Total modal damping ratio , δ_T	0.005

OTHERS PARAMETERS

Modulus of Elasticity Acrylic, E _s	1800.00 N/mm ²
Modulus of Elasticity Concrete, E _{conc}	N.A. N/mm ²
Water Depth (H)	2.00 m
Effective Axial Force, S _{eff}	0.00 kN
Slippage Constant , K _c	N.A.
Drag Coefficient, C _D	0.70
Trench Depth from Mean Seabed	0.00 mm

BOUNDARY CONDITION COEFFICIENT, TABLE 6-1, DNV-RP-F105

C1	3.560	1.57	2.45	3.56
C2	0.250	1	0.5	0.25
C3	0.000	0	0	0
C4	9.245 (NA)			
C5	0.100 (NA)			
C6	0.008			

SAFETY FACTOR FOR SCREENING CRITERIA
TABLE 2-1, DNV-RP-105

γ_{in}	1.15
γ_{CF}	1.30

SAFETY FACTORS FOR FATIGUE, TABLE 2-2, DNV-RP-105

η	0.25 (NA)
γ_s	1.05 (NA)
γ_f	1.15
γ_k	1.30
γ_{on}	1.10

APPENDIX C

FORMULAE AND VARIABLES USED

Stability Parameter, K_s	$K_s = (4 * \pi * Me * \xi_T) / (\rho * D^2)$
Onset Reduced Velocity, $V_{R\text{onset}}$	$V_{R\text{onset}}^{IL} = fn(K_s) \quad V_{R\text{onset}}^{CR} = (3 * \psi_{\text{proxonset}} * \psi_{\text{massonset}} * \psi_{\alpha\text{onset}} * \psi_{\text{trenchonset}}) / \eta_{\text{on}}$
Inline Natural Frequency	$f_{IN} = (U_{c,100\text{Year}} / V_{R\text{onset}}) * \{1 - [L / (D * 250)]\} * (V_{IL} / \alpha * Y_f)$
Cross Flow Natural Frequency	$f_{CR} = ((U_{c,100\text{Year}} * U_{W,1\text{Year}}) / (V_{R\text{onset}} * D)) * Y_{cf} * Y_f$
Fundamental natural frequency (In-Line)	$f_{oIL} = C1 * \text{sqrt}(1 + CSF) * \text{sqrt}((EI / Me / L_{\text{eff}}^2) * [1 + (C2 * S_{\text{eff}} / PE) + (C3 * (\delta_{in} / D)^2)])$
Fundamental natural frequency (Cross Flow)	$f_{oCR} = C1 * \text{sqrt}(1 + CSF) * \text{sqrt}((EI / Me / L_{\text{eff}}^2) * [1 + (C2 * S_{\text{eff}} / PE) + (C3 * (\delta_{cr} / D)^2)])$

Inline Check					Cross Flow Check				
Drag Force	Inline Static Deflection	Natural frequency of Span	In-line Natural Frequency	In-line Condition	Submerged Weight	Cross Flow Static Deflection	Natural frequency of Span	Crossflow Natural Frequency	CrossFlow Condition
q_{in} (N/m)	δ_{in} (m)	f_{oIL}	f_{IN}	$f_{oIL} > f_{IN}$	q_{cf} (N/m)	δ_{cr} (m)	f_{ocr}	f_{cR}	$f_{oCR} > f_{cR}$
3.50	0.0005	16.48	16.48	OK	0.12	0.000	7.02	7.018	OK
6.86	0.0005	23.46	23.46	OK	0.12	0.000	9.83	9.826	OK
11.34	0.0005	30.47	30.47	OK	0.12	0.000	12.63	12.633	OK
16.94	0.0005	37.52	37.52	OK	0.12	0.000	15.44	15.441	OK

INPUT HYDRODYNAMIC DATA				CROSS FLOW SPAN RESULT				
Mid Span Elevation (m)	Current Velocity U_{c1} (m/s)	Wave Induced Velocity U_{W1} (m/s)	Current Flow Ratio	Euler Load P_E , N (N)	β	Effective Span $Effect_{span}$ (m)	Span $Effect_{span}$	Click HERE to solve for Cross-Flow Span (m)
-	0.50	0.00	1.000	2.00E+02	4.21	1.44	1.00	1.44
-	0.70	0.00	1.000	2.80E+02	3.92	1.22	1.00	1.22
-	0.90	0.00	1.000	3.61E+02	3.70	1.07	1.00	1.07
-	1.10	0.00	1.000	4.41E+02	3.53	0.97	1.00	0.97

INLINE SPAN RESULT					Click HERE to solve for In-line Span (m)
Euler Load P_E , N (N)	β	Effective Span $Effect_{span}$ (m)	Span $Effect_{span}$		
4.70E+02	3.47	0.94	1.00	0.94	
6.69E+02	3.47	0.79	1.00	0.79	
8.70E+02	3.47	0.69	1.00	0.69	
1.07E+03	3.47	0.62	1.00	0.62	

Figure C.10 Detailed Calculations For Natural Frequencies and Span Lengths For 40mm Diameter Acrylic Pipe With 1mm Wall Thickness Under Pinned-Fixed and Fixed-Fixed Conditions (Current Velocity = 0.5m/s, 0.7m/s, 0.9m/s, and 1.1m/s)

APPENDIX D
PIPE SPAN SAMPLE CALCULATIONS FOR NORMALIZED
DEFLECTION AND REDUCED VELOCITY

APPENDIX D

Calculations for Deflection at Center of Acrylic Pipe		
Description	Value	Unit
Root Mean Square Strain Gauge Value (ϵ) for Center Strain Gauge	4.505790441	ϵ
Length of Pipe Span, L	1.052	m
Measured Diameter of Acrylic Pipe, D	0.0246	m
Half Diameter of Acrylic Pipe, y	0.0123	m
Calculated Deflection	4.22305E-05	m
Calculated Deflection	0.04223049	mm
Normalised Deflection	0.001716687	-

Calculations for Reduced Velocity for Acrylic Pipe Span		
Description	Value	Unit
Measured thickness of Acrylic Pipe, t	0.00095	m
Modulus of Elasticity of Acrylic Material	3000000000	Pa
L_2	1.106704	m^2
Average Current Velocity, U	0.1246	m/s
Added Mass, M_e	0.96655424	kg/m
Boundary Coefficient for Pinned-Pinned Conditions	1.57	-
Moment of Inertia, I	4.94285E-09	m^4
Lowest Natural Frequency of Oscillation, N	5.55653745	-
Reduced Velocity, V_r	0.91154621	-

Figure D.1 Calculations For Deflection at Center of Diameter 25mm Acrylic Pipe and Reduced Velocity for Acrylic Pipe Span

APPENDIX D

Calculations for Deflection at Center of Acrylic Pipe		
Description	Value	Unit
Root Mean Square Strain Gauge Value (ε) for Center Strain Gauge	4.089402975	ε
Length of Pipe Span, L	1.145	m
Measured Diameter of Acrylic Pipe, D	0.0392	m
Half Diameter of Acrylic Pipe, y	0.0196	m
Calculated Deflection	2.84934E-05	m
Calculated Deflection	0.028493354	mm
Normalised Deflection	0.001453743	-

Calculations for Reduced Velocity for Acrylic Pipe Span		
Description	Value	Unit
Measured thickness of Acrylic Pipe, t	0.00091	m
Modulus of Elasticity of Acrylic Material	3000000000	Pa
L_2	1.311025	m^2
Average Current Velocity, U	0.2453	m/s
Added Mass, M_e	2.445094132	kg/m
Boundary Coefficient for Pinned-Pinned Conditions	1.57	-
Moment of Inertia, I	2.00726E-08	m^4
Lowest Natural Frequency of Oscillation, N	5.942960152	-
Reduced Velocity, V_r	1.052952216	-

Figure D.2 Calculations For Deflection at Center of Diameter 40mm Acrylic Pipe and Reduced Velocity for Acrylic Pipe Span