ANALYSIS OF BURST PRESSURE ON ELBOW AND T-SECTION IN THE PRESENCE OF DEFECT

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Report submitted in partial fulfillment of the requirements for the awards of Bachelor of Mechanical Engineering

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I certify that the project entitled “Analysis of Burst Pressure on Elbow and T-section In The Presence of Defect” is written by Adzmil Bin Abdul Aziz. I have examined the final copy of this report and in my opinion, it is fully adequate in terms of language standard, and report formatting requirement for the award of the degree of Bachelor of Engineering. I herewith recommend that it be accepted in partial fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering.

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STUDENT'S DECLARATION

I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted for award of other degree.

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ABSTRACT

This study focuses on the development of short hydrostatic burst model of PVC fittings and their analysis. The experiments of burst pressure for fittings are hardly can be seen to be carried out either by industry or by researchers and especially for PVC fittings. This situation exists because of many reasons. One of them is the difficulty of getting a superb; zero leaks for PVC material. As for example, in hydrostatic burst test that involves metal, the technique of welding and thread are widely available for them for the jointing procedures. As for PVC cement, the most practical jointing procedure is only by using PVC cement. However, this method has high probability of leakage even if any small mistake done during the jointing process. In addition, parallel to the low pressure application of PVC fittings, there is no requirement in industry to have data on the PVC fittings burst pressures. After a well reliable model design is achieved, and then the main focus is to observe and analyze the effect of defected PVC model on its burst pressure. This is the main objective in this analysis. In a circuit of PVC piping installation, the is small probability for the fittings to break due to internal pressure as the thinner and weaker straight pipe will breaks first. However, in the presence of defect on fittings, the piping break can occur on fittings. In the experimental analysis, both perfect and defected fitting are to be obtained their burst pressures. Analysis will be carried out on both data to see the pattern of effect of defected fittings and also able to predict its left strength using previous solution. The expected result produces from the experiment is the burst pressure of the PVC fittings will be getting lower as the depth of defect introduced increases. Defected fittings will be less resistant to internal pressure.

ABSTRAK

Kajian ini memberi tumpuan pada pembangunan model ujian hidrostatik jangka pendek untuk kelengkapan PVC dan beserta analisis ujikaji tersebut. Eksperimen untuk mendapatkan tekanan yang paling tinggi boleh dihadapi oleh kelengkapan PVC amat jarang dilakukan dijalankan sama ada oleh industri atau oleh penyelidik dan terutama untuk kelengkapan PVC. Keadaan ini wujud kerana banyak sebab. Salah satu sebabnya adalah kesukaran untuk mendapatkan teknik pemasangan yang tidak memiliki sebarang kebocoran untuk kelengkapan PVC. Sebagai contoh, dalam ujian hidrostatik yang melibatkan logam, teknik kimpalan dan benang boleh didapati secara meluas bagi mereka untuk prosedur penyambungan. Bagi PVC simen, prosedur penyambungan yang paling praktikal adalah hanya dengan menggunakan PVC simen. Walau bagaimanapun, kaedah ini mempunyai kebarangkalian yang tinggi untuk masalah kebocoran walaupun dengan kesilapan kecil yang dilakukan semasa proses penyambungan. Di samping itu, selari dengan applikasi yang melibatkan tekanan rendah untuk kelengkapan PVC, tidak ada keperluan dalam industry untuk mempunyai data mengenai tekana yang boleh dihadapi olehkelengkapan PVC. Selepas reka bentuk model yang baik dan dipercayai dicapai, fokus utama seterusnya adalah untuk melihat dan menganalisis kesan model PVC yang mempunyai kawasan yang dinipiskan pada tekanan pecah itu. Ini adalah objektif utama dalam analisis ini. Dalam litar pemasangan paip PVC, adalah kebarangkalian kecil untuk kelengkapan untuk pecahkan kerana tekanan dalaman paip nipis dan lemah lurus akan pecah terlebih dahulu. Walabagaimanapun, kehadiran kecacatan pada kelengkapan, Kepecahan boleh berlaku pada alat kelengkapan. Dalam analisis eksperimen, kedua-dua sempurna dan berpaling tadah sesuai perlu diperolehi tekanan pecah mereka. Analisis akan dijalankan ke atas kedua-dua data untuk melihat corak kesan kelengkapan berpaling tadah dan juga dapat meramalkan kekuatan kiri menggunakan penyelesaian sebelumnya.

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LIST OF SYMBOLS

°C	Temperature (Degree Celcius)
P	Pressure
σ_y	Yield Stress
t	Thickness
r	Radius
L	Length
D	Diameter
A	Area
J^p	Weakening Factor

LIST OF ABBREVIATIONS

PVC	Polyvinyl chloride
MS	Malaysian Standard
FYP	Final Year Project
ASTM	American Society for Testing and Materials
BS	British Standard
CPVC	Chlorinated Polyvinyl Chloride
ESC	Environmental stress cracking
MAOP	Maximum Operating Pressure
SMYS	Specified Minimum Yield
LTA	Local Thinned Area

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Previously, the effect of external defects was studied via a series of small-scale experiments and through a nonlinear numerical model based on the finite element method. After calibration was conducted, based on the experimental results, the model was used to determine the burst pressure as a function of material and geometric parameters of different pipes and defects. In this case, Polyvinyl chloride pipelines will be the model and specifically it will involve only Polyvinyl chloride fittings which are the long radius 90 degree elbow and tee. The effect of the defect that introduced to the fitting will be viewed on their burst pressure. Burst pressure is the maximum pressure which the Polyvinyl chloride fitting can endure before it will break.

Malaysian standard (MS) is a standard that developed in Malaysia. The Department of Standards Malaysia (DSM) is the national standardisation and accreditation body. Malaysian Standards are developed through consensus by committees which comprise of balanced representation of producers, users, consumers and others with relevant interests, as may be appropriate to the subject in hand. These standards where appropriate are adoption of international standards. Approval of a standard as a Malaysian Standard is governed by the Standards of Malaysia Act 1996 (Act 549).MS628 is the Malaysian standard for Polyvinyl chloride joints and fittings. ASTM International is the American Society for Testing and Materials (ASTM) are an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services. The ASTM standard for joints and fittings that is parallel to MS628 is ASTM D2665. British Standards are the standards produced by BSI Group which is incorporated under a Royal Charter The BSI Group produces British Standards under the authority of the Charter. The British standard for Polyvinyl chloride joints and fittings is BS4346.

1.2 IMPORTANCE OF RESEARCH

The consequences of a reduced operating pressure can be view economically such as loss of production due to downtime, repairs, or replacement which are can be severe and, in some cases, not affordable. Thus, there are several pipelines kept in operation even though signs of erosion are visible on their external surface. This only can be done if the burst pressures of the defected pipelines are known. Detail understanding on the effects that caused by the defects on the burst pressure will allow for the management of allowable defects on pipelines. The knowledge able us to define at which level the defect should be fixed or action need to be made on the pipelines, specifically to the fitting.

1.3 PROBLEM STATEMENT

In testing pipelines specifically the fittings, the connection must be perfectly strong enough to ensure that the burst of the fittings are only due to the defect introduced, not by any weakness or leakage in connection. In addition, leakage in connection will cause pressure leakage. Another problem involved is to get the best method to introduce the defect on fitting which will give the same criteria when a fitting has undergone thermoplastic failures such as erosion and cracking.

1.4 OBJECTIVES

The project is concentrate on:

1. To observe and analyse the effect of defected Polyvinyl chloride fittings on their collapse or burst pressure.
2. To compare the experimental data with theoretical data of collapse pressure.

1.5 SCOPES OF STUDY

The scope of study is to carry out experimentation procedures and analysis of burst pressure test on Polyvinyl chloride fittings. Burst pressure test is important for quality maintenance and prediction of remaining strength of a Polyvinyl chloride fitting.

1.5.1 Standard of Short Term Hydrostatic Burst Test

The test will be carried out based on the Malaysian standard of MS628. The apparatus specification of this standard is the apparatus shall consists of a temperature controlled water bath or air space maintained at 20 °C ± I °C and equipment that permits the joint or fitting to be subjected to an internal hydrostatic pressure to an accuracy of ± 2 %.The standard also requires The specimen shall be a complete joint or fitting. The open ends of the specimen shall be closed with suitable end caps, and these shall be provided with connections for the entry of water under controlled pressure. Joints and fittings not designed to withstand the end thrust due to internal pressure may have their open ends closed with male plugs which are retained in place by a jig or former. Joints and fittings designed to withstand the end thrust due to internal pressure. The method of closure of the open ends and the mounting of these joints and fittings in the apparatus shall be arranged so that the full end thrust is carried by the test specimen.

1.5.2 Method of Short Term Hydrostatic Burst Test

The short term hydrostatic burst test will be carried out on the MS628 standard of Polyvinyl chloride fittings which are normal 90° elbow and tee. The test will be carried out for both with defect and without defect being introduced. The enclosed fittings will be given an internal pressure until it burst. The burst pressure will be recorded.

1.5.3 Test of Difference Types of Defects

Difference types of defects will be introduced to the fittings. There will be several depths of defect of constant area of defect. In addition, difference location of defects also will be introduced on the fittings as the strength of fittings is not consistent throughout them.

1.5.4 Result and Conclusion

In data collection, the burst pressure of the fittings will be recorded and analysed for each case. The burst pressure obtained also will be compared to the actual designated burst pressure. As in the conclusion, the effect that defected fittings brought to the collapse pressure will be confirmed.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter will explain some crucial information about material that being tested and also the standard dimension of some related Polyvinylchloride fittings. Besides that, the discussion on previous modelling and testing of fittings in order to get their burst pressures are presented here. Previously, there are only several research be made on the burst failure of fittings and most of them involving metal fittings. There are still very lack of experiments done on the burst failure of PVC fittings. However, for PVC material the burst or crack criteria is well discussed here. All of the resources give the information needed to complete this project. There are many things need to be consider in designing the model for fitting testing and also the characteristics of the fitting involved also must be understand in detail. The burst pressure experiment is a vital step as the material related to this test is hardly available.

2.2 POLYVINYLCHLORIDE MATERIAL SPECIFICATION

Polyvinylchloride and Unplasticised polyvinylchloride are largely made of the same material. Polyvinylchloride is a polymer that can be heated and moulded to create very hard, strong compounds such as piping. Because of its rigid properties once it's formed, manufacturers frequently blend additional plasticizing polymers into Polyvinylchloride. These polymers make Polyvinylchloride pipe more bendable and, generally, easier to work with than if it remains unplasticized. Those plasticizing agents are left out when Unplasticised polyvinylchloride is manufactured. Unplasticised polyvinylchloride pipe is pipe that is specifically free of plasticizers and is 100% Polyvinylchloride. The name is short for unplasticized polyvinylchloride, which is nearly as rigid as cast iron pipe. The fittings standard used in whole experimental procedures and analysis will be of MS628.

Vinyl chloride (VC) was first discovered by Regnault in 1835, and the polymer was first observed in 1838. In 1872, Baumann reported the polymerization of a number of vinyl halides including VC using sunlight to afford the white powder product recognized as PVC. Since then, the technology for the polymerization of VC has progressed significantly mainly in Germany and USA. Commercial production of PVC first started in German, in the early 1930s using emulsion polymerization. The first breakthrough to overcome the processing and heat stability problems of PVC came in 1932 when Semon discovered plasticizers for PVC. The use of stabilizer was developed in the 1930s. PVC is now one of the world’s major polymers and a large amount of PVC is produced worldwide for its superior mechanical and physical properties. Fluid plasticity and thermal stability of PVC are, however, inferior to those of other commodity plastics such as polyethylene and polystyrene. PVC is mainly produced by radical polymerization.

The radical polymerization of VC, however, results in the formation of molecules with a number of isomeric forms and structural defects. These factors are of vital importance to the users of PVC, because they cause a colour problem, thermal stability of the polymer, its crystalline, processing behaviour, and the mechanical properties of the finished article. Studies of defects also give an insight into the nature of the side reactions occurring during polymerization. Much work on improvement of the inferior properties of PVC has been carried out besides the addition of additives such as plasticizers, heat stabilizers, lubricants, fillers and other polymers. Examples include copolymerization with other monomers and modification of the particle morphology to improve process ability. Graft copolymerization of PVC with acrylic monomers and vinyl acetate (VAc), and blends with MBS and ABS has been examined to improve the impact strength. Copolymerization of VC with imide monomers and chlorination of PVC was investigated to increase the heat resistance of PVC. Synthesis of high molecular weight polymers and partially cross linked PVC has been performed to increase the modulus. Synthesis of inner plasticized PVC is one solution to the problem of plasticizers like dioctyl phthalate (DOP) migrating from inner to the surface of materials. Thermal stability of PVC may be related to the presence of anomalous units in the chain, and it is thus of interest to be able to synthesize PVC consisting of an exclusively head-to-tail structure. Ionic polymerization of VC is an excellent way of preparing PVC consisting of only regular units due to the nature of ionic polymerization.

This is a fascination synthetic method from the viewpoint of thermally stable PVC. It is, however, difficult to obtain high molecular weight PVC using anionic catalysts, and believed to have its origin in the catalyst reacting with VC. Nevertheless, some work on the polymerization of VC with anionic catalysts has been carried out, and the structure of PVC obtained using these catalysts will be described in this article. The advance of transition metal alkyl catalysts has made it possible to prepare stereo regulated polymers of 1-olefins, dienes and some conjugated monomers. Recently, metallocene polymerization has seen remarkable progress, and many new polymers have been synthesized with metallocene catalysts. Stereo regular PVC has not been synthesized with a transition metal catalyst. Nevertheless, several attempts have been made to prepare PVC with metallocene catalysts. Some work on the polymerization of VC employing transition metal catalysts will be described.

2.2.1 Physical Properties

Thermoplastics Polyvinyl Chloride and Chlorinated Polyvinyl Chloride (CPVC) are light, flexible, and tough and provide exceptional corrosion resistance. Because of these and other properties of a high quality engineered thermoplastic, the savings that can be realized in initial installation and continuing maintenance costs are substantial. Polyvinyl Chloride can handle temperatures up to 140°F (60°C). Chlorinated Polyvinyl Chloride handles temperatures up to 210°F (99°C). Polyvinyl Chloride and Chlorinated Polyvinyl Chloride thermoplastics are highly resistant to acids, alkalis, alcohols and many other corrosive materials. Both materials are ideal for process piping installation and most service piping applications. PVC is used in construction because it is more effective than traditional materials such as copper, iron or wood in pipe and profile applications. It can be made softer and more flexible by the addition of plasticizers, the most widely used being phthalates. In this form, it is also used in clothing and upholstery, electrical cable insulation, inflatable products and many applications in which it replaces rubber.

Table 2.1: Mechanical Properties

Properties	**Unit**	**PVC**	**CPVC**	**Remarks**	**ASTM Test**
Tensile strength @ 73 °F	PSI	7,200	7,550	Same in circumferential direction	D-638
Modules of elasticity Tensile @73°F	PSI	430,000	375,000	Ratio of stress on bent sample at failure	D-638
Compressive Strength @ 73°F	PSI	9,500	10,100		
Flexural Strength @73°F	PSI	13,000	15,000	Tensile stress/strain on bent sample at failure	D-790
Izod Impact @ 73°F	Ft-Lbs/ln of notch	1.0	6.3	Impact resistance of a notched sample to a sharp blow	D-256

Relative hardness @ 73°F	Durometer “D”	80±3	80±3	Equivalent to aluminium	D-2240
	Rockwell “R”	110-120	119	-	D-785

Source: George Fischer (2004)

Polyvinyl chloride is a common thermoplastic and has uses in a variety of applications. Knowledge of its properties is important in understanding if Polyvinyl chloride has the strength for use in a specific application. Key mechanical properties include tensile, flex, compression and impact. Table 2.1 describes the mechanical properties of Polyvinyl Chloride and Chlorinated Polyvinyl Chloride thermoplastics while in Table 2.2, their thermodynamic properties are described. The heat stability of PVC is very poor, when the temperature reaches 140 °C PVC starts to decompose. Its melting temperature is 160 °C. The linear expansion coefficient of the PVC is small and has flame retardancy, the oxidation index is up to 45 or more. Therefore, the addition of a heat stabilizer during the process is necessary in order to ensure the product's properties.

Table 2.2 Thermodynamics Properties

Properties	**Unit**	**PVC**	**CPVC**	**Remarks**	**ASTM Test**
Coefficient of thermal linear expansion per °F	in/in/°F	2.8 x 10^{-5}	3.4 x 10^{-5}		D-696
Thermal Conductivity	BTU/hr/ft^{2}/F/in	1.3	0.95	Average specific heat	c-177

				of 0-100°c	
Specific Heat	CAL /g/°c	0.20-0.28		Ratio of thermal capacity to that of water at 15°c	
Maximum operating temperature	°F	140	210	Pressure rating is directly related to temperature	
Heat distortion temperature @ 264 PSI	°F	158	230	Thermal vibration and softening occurs	D-648

Source: George Fischer (2004)

A thermoplastic is a type of plastic made from polymer resins that becomes a homogenized liquid when heated and hard when cooled. When frozen, however, a thermoplastic becomes glass-like and subject to fracture. These characteristics, which lend the material its name, are reversible. That is, it can be reheated, reshaped, and frozen repeatedly. This quality also makes thermoplastics recyclable. There are dozens of kinds of thermoplastics, with each type varying in crystalline organization and density. Some types that are commonly produced today are polyurethane, polypropylene, polycarbonate, and acrylic.

2.3 Failures in Polyvinyl Chloride

Thermoplastic material failure can occur in four basic modes: softening, degradation, erosion, or cracking. These failures are consists of both the external and internal defects. Failure by softening is usually obvious from the appearance of the failure. The part will appear swollen and distorted and will usually have failed by ballooning and ductile rupture, or by distortion of the system. Softening of the material may be caused by simple exposure to temperatures in excess of the material's general capability given its heat distortion temperature, or it may be caused by a temperature/stress condition in excess of what is recommended for the material. (Michelle, 2002)

Failure by softening is usually obvious from the appearance of the failure. The part will appear swollen and distorted and will usually have failed by ballooning and ductile rupture, or by distortion of the system. Softening of the material may be caused by simple exposure to temperatures in excess of the material's general capability given its heat distortion temperature, or it may be caused by a temperature/stress condition in excess of what is recommended for the material, such as operating at a pressure in excess of the pipe's derated pressure rating for the operating temperature, or installing the piping with support spacing in excess of what is recommended for the operating temperature. An example of a ballooning failure caused by an operating pressure in excess of the derated pressure for the operating temperature is shown in Figure 2.1.

When failure by softening occurs due to over temperature and/or overpressure of the piping system, the failure analysis investigation naturally focuses on the system design and control. Softening of the material may also be caused by absorption of solvents or plasticizers, either from the process fluid itself, or from the external environment. When solvents are absorbed from the process fluid, it may be a simple case of having specified the wrong material for the known conditions. However, it may be a case of an unknown contaminant in the process fluid causing failure of the pipe where it would have been expected to be successful. Chemical contamination can arise from a variety of sources. Oils can leak from pumps or other mechanical devices; plasticizers can leach from gaskets, hoses, or tank linings; or the process fluids themselves may not be as clean or as well defined as had been thought. The effect of minor constituents in the process fluid may also be underestimated. Waste streams containing “only 50 ppm of toluene” may sound innocuous enough, however when contaminants are not water-soluble, they are floating along in the process stream as tiny bubbles of pure solvent. When these bubbles come in contact with the pipe wall, they will be immediately absorbed by it, eventually leading to softening and failure of the piping system. Solvents or plasticizers may also be absorbed from the environment external to the piping system.

Gasketing materials, caulks, or rubber padding or lining materials may all contain plasticizers which can migrate into the rigid vinyl over time leading to softening and eventual rupture under pressure. Figure 2.2 shows an example of a softening failure of CPVC potable water piping caused by absorption of plasticizers from a soft vinyl hanger padding. When a failure by softening occurs due to absorption of solvents or plasticizers, it is necessary to identify the chemical contamination and its source. An often useful course of action for rigid vinyl materials is to extract some of the contaminant with a solvent such as hexane or methanol, separate the contaminant from the solvent by evaporation or other separation techniques, and to identify the contaminant by simple analytical techniques such as infrared or mass spec analysis. It is advisable to run a blank sample of the material as well, as the solvents will often extract out some of the stabilizers or other compounding ingredients as well as the contamination. The results of a blank extraction can be subtracted out of the results of the contaminant analysis to avoid miss-identification of the contaminant.

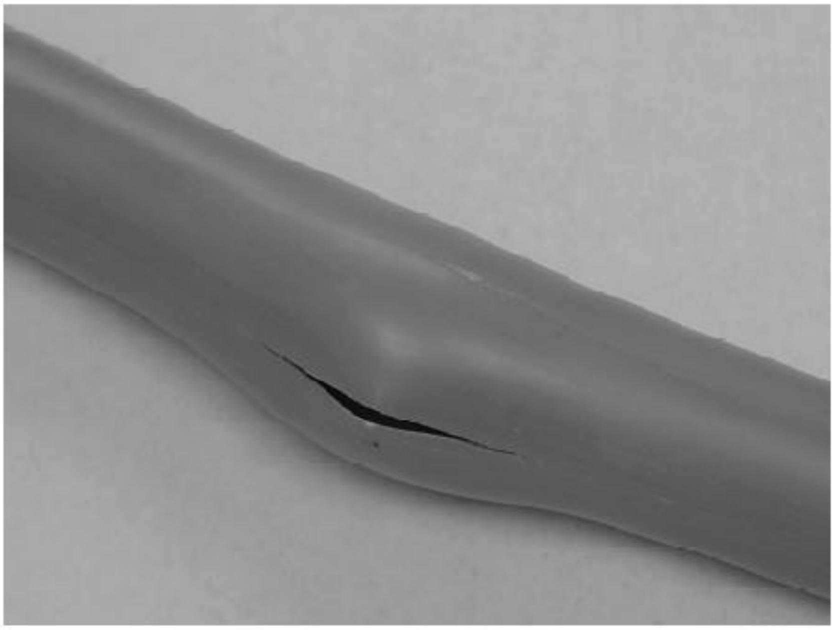

Figure 2.1 Ballooning failure of CPVC industrial pipe

Source: Michelle (2002)

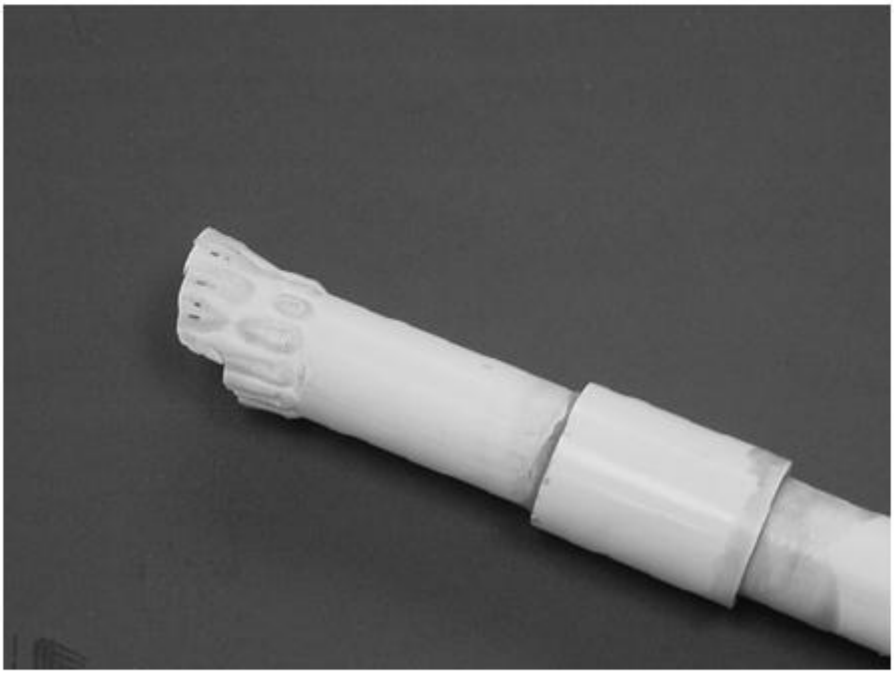

Figure 2.2 Softening failure of CPVC

Source: Michelle (2002)

Degradation of Polyvinyl Chloride piping materials occurs when the vinyl resin itself or other compounding ingredients in the material are attacked and altered or destroyed. Degradation can be caused by prolonged exposure to high heat or UV, or exposure to chemicals capable of reacting with and destroying the base polymer or the compounding additives. Polyvinyl Chloride has extremely good resistance to many strong acids and caustics, and this is the basis of their selection as the material of choice in a number of aggressive chemical environments such as industrial strength bleach applications or metal pickling and plating baths.

Degradation of PVC and CPVC materials can manifest itself in many ways. Hot concentrated sulphuric acid may cause blackening and blistering, while hot concentrated nitric acid generally causes whitening and surface etching. Figure 2.3 shows an example of the blackening and blistering of CPVC pipe caused by prolonged exposure to high concentrations of sulphuric acid at 82°C.One main area of difference between

PVC and CPVC chemical resistance is in the area of ammonia and amine chemistries. While PVC exhibits generally good resistance to ammonia and some amines, even at somewhat elevated temperatures, CPVC has extremely poor resistance to ammonia or ammonium hydroxide, and limited resistance to most amines, even at ambient temperatures. This is due to the extremely high reactivity of amines and chlorine, the higher availability of chlorine on the CPVC, and its lower bond strength on CPVC versus PVC. Even at fairly low concentrations and temperatures, ammonia and many amines are capable of rapid dehydrochlorination of CPVC.

Figure 2.4 shows an example of the blackening and blistering of CPVC pipe caused by prolonged exposure to high concentrations of sulphuric acid at 82°C.The originally gray industrial piping material has turned a dark chocolate brown penetrating nearly the thickness of the pipe, and deep networked surface cracking has appeared over the entire interior surface. Failure analysis of degraded samples involves determining how the material has degraded and what the source of the degradation was. Gel permeation chromatography can often be used to determine whether the molecular weight of the compounding ingredients or the base resin has been reduced. Infrared or mass spectrometry can be used to identify whether the ingredient's molecular structure has been altered, perhaps by addition or substitution reactions. Once the source of the degradation has been identified, the focus turns again to the system design itself.

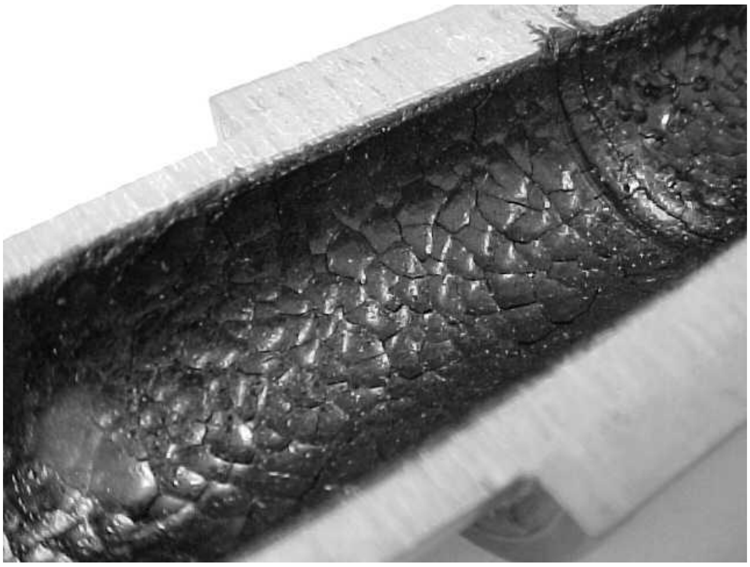

Figure 2.3 Degradation of CPVC pipe caused by prolonged exposure to hot concentrated sulphuric acid

Source: Michelle (2002)

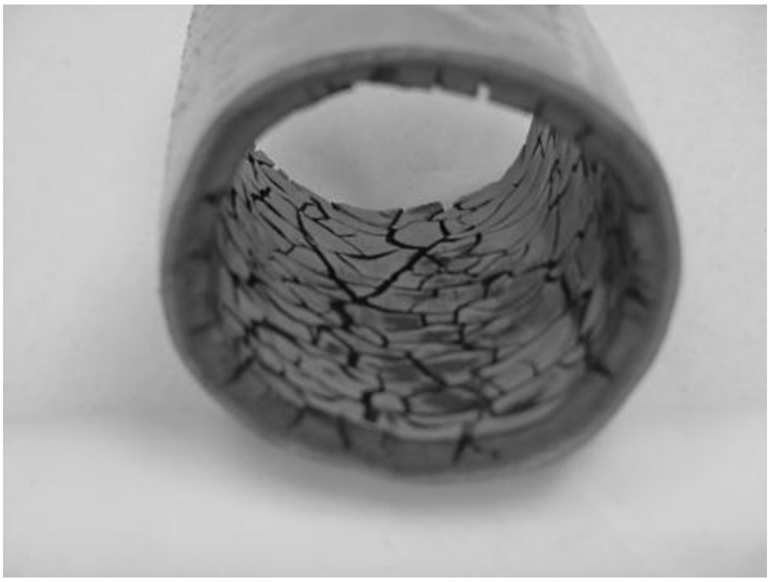

Figure 2.4 Example of CPVC pipe degraded by ammonium hydroxide

Source: Michelle (2002)

Erosion can be caused either by simple impingement of solid particles on the pipe wall, or by a combination of degradation and embrittlement of the pipe’s surface, allowing the fluid flow to erode the surface. While Polyvinyl Chloride is plastic in general, typically have better resistance to abrasion than most metals, they are still susceptible to erosion and wall thinning due to solids in the process streams. Standard engineering practices, such as using wide sweeps at changes in direction will be useful for Polyvinyl Chloride as well as other materials. In most cases where the process fluid is slurry, erosion of the piping cannot be completely eliminated, but it can be predicted by measuring wall thickness as a function of time in critical areas, and it can then be pre-empted with preventative maintenance to the system. Sometimes a degradation of the inside surface of the pipe can cause a surface embrittlement which will allow surface erosion by fluid streams containing no particles. Figure 2.5 shows an example of a segment of CPVC pipe which had been handling a solution containing bubbles of moist chlorine gas. The chlorine gas bubbles chlorinated the impact modifiers in the CPVC material, causing embrittlement. The embrittlement was sufficient to allow erosion of the surface by the fluid flow.

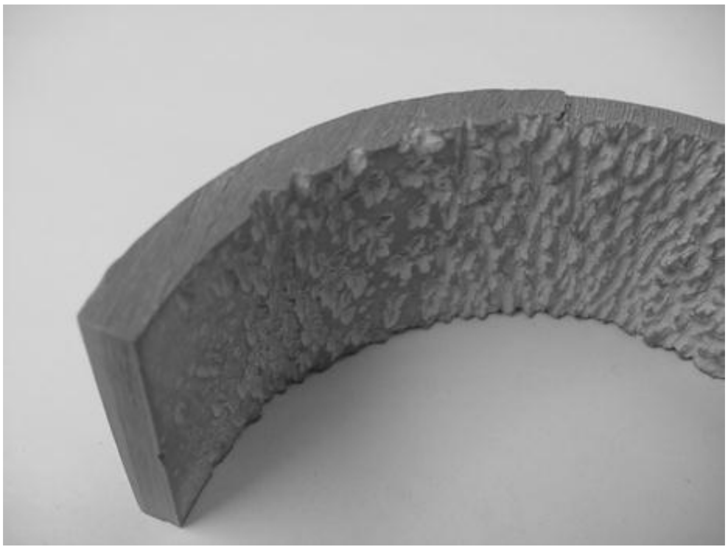

Figure 2.5 Erosion of CPVC pipe due to surface embrittlement by chlorine gas bubbles

Source: Michelle (2002)

There are three main possible forms of fracture for PVC and CPVC materials, and all are easily identified by their visual characteristics. Environmental stress cracking (ESC) is recognized by the smooth, glassy fracture surfaces associated with it. The fracture surfaces are very smooth and shiny enough to reflect light. When a fracture of this type is observed, it is always indicative of a chemical resistance issue. The fracture surfaces for brittle fracture are also typically smooth, but these surfaces are always dull, never glassy. Brittle fractures may indicate mechanical damage, such as impact, or they may indicate part quality problems as well. Ductile fractures have a rough, dull surface and may also exhibit stress whitening. Stress whitening at the fracture surface indicates that the material yielded before failing, usually indicating that the stresses at that site were extremely high. Figure 2.6 shows a cutaway of a fracture surface which exhibits all three forms of fracture in one single crack.

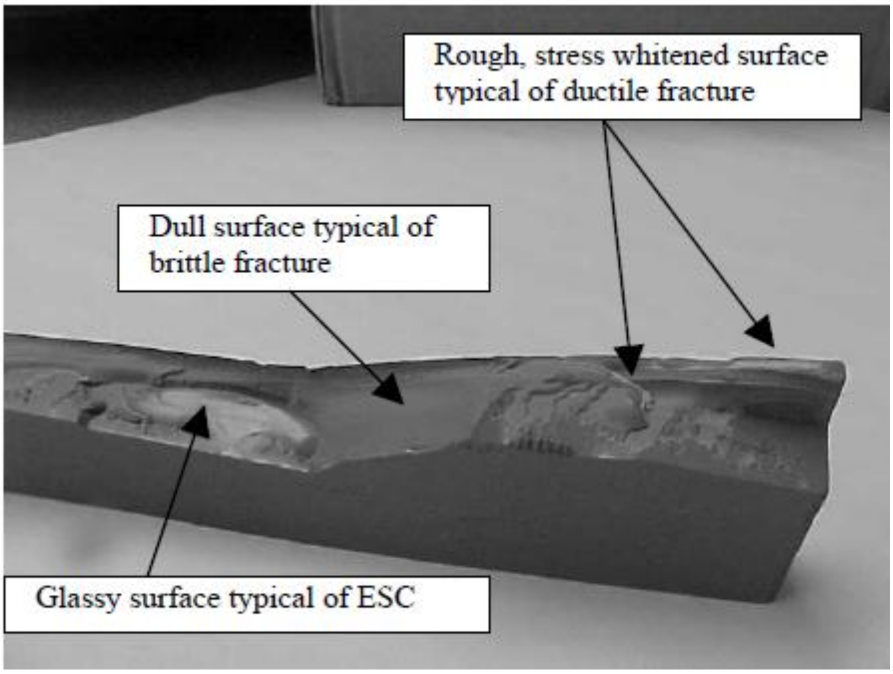

Figure 2.6 Examples of all three main forms of fracture

Source: Michelle (2002)

Environmental stress cracking of PVC and CPVC is a mechanism by which an organic chemicals which might be described as a weak solvent or even a non-solvent for the plastic achieves an extremely localized weakening of the material which permits propagation of a crack. To effectively understand how environmental stress cracking occurs in plastics one first has to consider the solvation process. Polymers are held together as a solid to a large extent by intermolecular forces or attractions. A good solvent has the ability to penetrate the plastic and overcome those forces to separate the molecules from each other and form a solution. A moderate solvent has the ability to penetrate the plastic and weaken those forces, spreading out the molecules somewhat, which is observed as swelling and softening. An environmental stress cracking agent has the ability to overcome or weaken those forces, but a poor ability to penetrate. It may be too large a molecule, such as a surfactant, to effectively move in among the polymer molecules; or it may have too much attraction for its own kind of molecules, as a hydrogen-bonded alcohol might, to be able to move away from them and into the polymer molecules. What an environmental stress cracking agent does have, however, is a good surface wetting ability, a low surface tension. It is able to have intimate contact with those molecules right on the surface of the plastic, but no deeper. Consider what happens then, when this chemical is put in contact with a plastic part under stress.

In the absence of the chemical the plastic part has the capability of bearing a certain amount of mechanical stress and performing its function. When the chemical is introduced, the plastic surface is wetted and the surface molecules are weakened by the chemical. If the plastic surface were perfectly smooth, the weakening of a few surface molecules against the vast bulk of unaffected material would not create any noticeable loss in properties or performance. Surfaces are rarely perfect however. There always exist small scratches, grooves, pores, or other surface imperfections. These are not necessarily anything one would consider a defect in the part, just normal manufacturing variations; however they act in two ways to promote environmental stress cracking of the material. They provide a foothold for the environmental stress cracking agent, and they amplify the part’s operating stresses at that site. In the absence of an environmental stress cracking agent, the amplification of the operating stresses at these minor surface notches does not affect the part’s long term performance.

However, when an environmental stress cracking agent is present, wetting the surface of the notch and weakening the intermolecular attractions at the tip of the notch, these amplified operating stresses may now be sufficient to initiate a crack at that site. Because the environmental stress cracking agent is an effective wetting agent, the newly exposed crack surface is wetted, the intermolecular forces at the crack tip are weakened, and the amplified operating stresses are able to propagate the crack further. This process continues until the part has cracked completely through. This is also the reason for the glassiness of the crack. With a brittle or ductile crack, the polymer molecules are forced or ripped apart, whereas with environmental stress cracking, the polymer molecules are eased apart with the aid of localized solvation. Figure 2.7 shows an example of a circumferential environmental stress crack on a piece of CPVC piping, illustrating the inherent glassiness of the crack. Failure analysis of environmental stress cracking issues involves first diagnosing the type of failure by the distinctive appearance of the fracture surfaces, and then identifying the chemical causing the cracking, and examining the system design and installation for any unusual sources of stress which may have exacerbated the situation. Often, enough of the chemical will remain clinging to the fracture surfaces and the inside surface of the pipe to be washed off with a solvent such as methanol or hexane and then identified via infrared spectroscopy or mass spectrometry. Once the chemical has been identified, it may be determined to be a known component of the process stream whose effect on the piping was not considered during the specification process, or it may be determined to be a contaminant in the system whose source must be identified.

Certain types of machine lubricants, or oils used in metal parts manufacturing may leach or wash into the process stream. Plasticizers may leach from rubber tank linings, hosing, or gasketing type materials. Or the process stream may not have been as clean or as well defined as expected. Installation stresses must also be considered in the failure analysis. Environmental stress cracking agents are only capable of a certain degree of weakening of the intermolecular attractions of the polymer, and some environmental stress cracking agents are more aggressive than others. The stress level at the tip of the imperfection acting as a foothold must then be high enough to overcome the material's residual strength and cause crack initiation. If the stresses are not that high, the part will perform adequately with no noticeable effect from the environmental stress cracking agent. In cases of very aggressive environmental stress cracking agents, very often the ordinary stresses which are ever-present in piping systems will be sufficient to initiate cracking. However, in the case of mild or moderate environmental stress cracking agents, very often unusually high localized stresses due to poor installation or design conditions will cause cracking, while a better designed and installed system will operate perfectly well in the presence of the same chemicals. Examples of sources of these types of avoidable stresses are overtight clamping, inadequate allowance for expansion and contraction, poor joint assembly technique, or pressure surges to the system. Often when these types of poor design and installation conditions are identified and corrected, PVC or CPVC will then perform well in handling the chemical service.

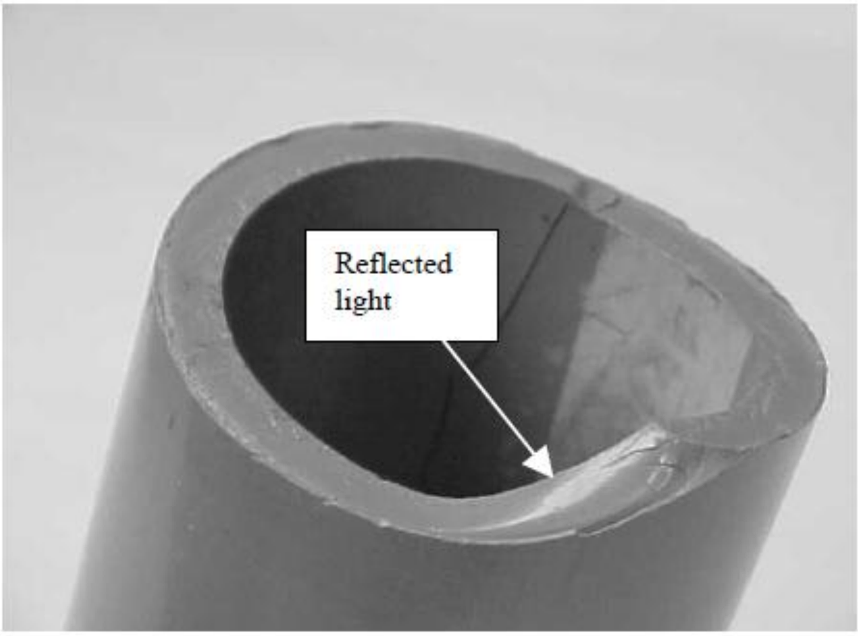

Figure 2.7 Example of environmental stress cracking of CPVC pipe

Source: Michelle (2002)

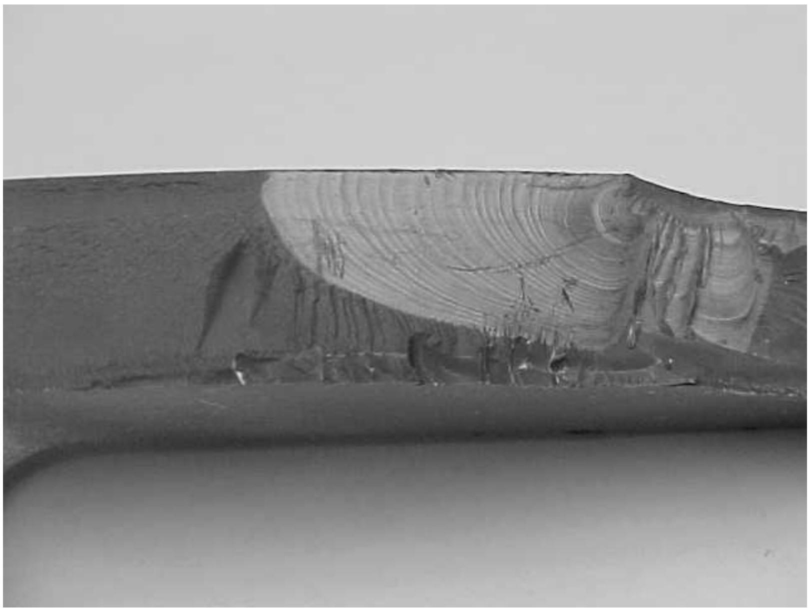

Figure 2.8 Example of fatigue failure of a PVC blind flange

Source: Michelle (2002)

Fatigue of PVC and CPVC materials is another mode of failure which is easily recognized by the distinctive appearance of its fracture surface. Fatigue cracks in vinyl materials have the typical brittle fracture surface (smooth and dull), but with a closely spaced pattern of propagation fronts, progressing either linearly, giving a striped appearance to the fracture, or radially, giving a rainbow effect to the fracture. Figure 2.8 shows a fatigue crack in a PVC blind flange with radial propagation fronts. Fatigue cracks may initiate at pre-existing damage (i.e., a small, non-catastrophic crack due to an impact may fatigue and give way over time due to expansion and contraction of the system as it heats and cools, or due to pressure surges in the system.

Fatigue cracks may also initiate at the normal corners and edges which are designed into the part. Failure analysis of fatigue cracking involves evaluation of the system design. If the part has fatigued at a damaged area, the system may then operate without further failure with just the simple repair of the damage. However, it the fatigue fracture has originated at a normal feature of the part, such as a corner or edge built into the part, then the engineer must consider whether the system is adequately designed and installed with regards to potential fatiguing stresses.

Impact fractures in PVC and CPVC due to impact can take a variety of forms, however in most cases, the fracture initiates on the inside surface and propagates outward. Impact fractures typically have a brittle (smooth, dull) fracture surface, or a combination of brittle and ductile. They may have the appearance of a star crack on the interior surface of the pipe or a simple straight or branching crack. One shape of crack which is common for impact fractures is a short crack, longitudinal on the pipe, which is curved both along the length of the pipe and through the wall thickness. Impact failure may sometimes occur as the result of an impact to an operating system, however most often the crack is caused during handling and installation.

Failure analysis of impact cracks generally involves simply looking for evidence of the event such as gouges or scuff marks on the exterior of the pipe at the location of crack initiation. Finding significant deposits and debris inside the crack from the process stream can also be an indicator that the crack was probably formed during handling or installation and then existed inside the system for some time, collecting deposits and debris from the fluid stream before finally propagating through and leaking.

Fractures of PVC or CPVC pipe caused by crushing will generally have the form of short, brittle, parallel longitudinal cracks which combine to create the major failure crack. When viewed end-on, (i.e., not the fracture surface, but the crack as it appears on the inside or outside surface of the pipe) the fracture may have an appearance like a sloppy dovetailed joint. These may initiate either on the inside surface or outside surface of the pipe, and there may be stress whitening of the pipe 90° removed from the crack circumferentially. These are typically caused by rough handling during transport or installation, however they may also occur in service due to overtight clamping and failure to allow for expansion. Failure analysis of crush cracks will likewise involve looking for evidence of the event such as scuffing or rub marks at the site of initiation.

Rapid brittle crack propagation is a failure mechanism with a very dramatic and distinctive appearance. It is characterized by acutely branching brittle cracks which may propagate the entire length of a run of pipe, straight through fittings. The fracture surfaces are extremely smooth and flat. They may have a slight herringbone pattern to the surface, pointing in the direction of crack propagation. This is very typically the form of failure when the pipe cracks due to freezing of the fluid inside the pipe. This can also be the form of failure taken when the piping system fails for some reason (impact, pre-existing damage) under moderate air pressure or high hydrostatic pressure. It is for this reason that PVC and CPVC are not recommended for compressed gas service.

2.3.1 Burst Failure of Polyvinyl Chloride

Burst failure in Polyvinyl Chloride pipe and fittings is usually rather dramatic. It may begin at a point of stress concentration or weakness and may continue by splitting through fittings and pipe for some distance. Burst failure usually occurs during hydraulic transient conditions that create large pressure variations in the system. These include rapid valve closure, pumps starting or stopping and rapidly escaping entrapped air. Burst failure will, sometimes occur in fitting that was damaged during installation or that is subject to external loads. In these cases the failure may occur at pressures well below the expected burst limit of the product.

Table 2.3 Burst Pressure of Polyvinyl Chloride fittings (MS628)

Nominal Size (mm)	Burst Pressure (MPa)	Working Pressure (MPa)
15	18	3
20	15	2
25	13	2.6
32	11	2.2
40	10	1.9
50	7	1.7
65	9	1.8
80	8	1.5

Source: (Bliesner, 1987)

The failure of a pipe or fitting from exceedingly high pressure over a short period, usually defined as less than a minute, would be classified as a burst or short term failure. The more common evidence for these failures is sharp edged cracks and fragments, similar to glass. If these fragments are not contained or entrapped during the failure they can be dangerous. This is the foremost reason that Polyvinyl Chloride fittings are not to be used to transport or to be tested with compressed air. A short term or brittle failure shows no visible, to the naked eye, material deformation, stretching, elongation or necking down close to the break.

2.4 Polyvinylchloride fittings dimension

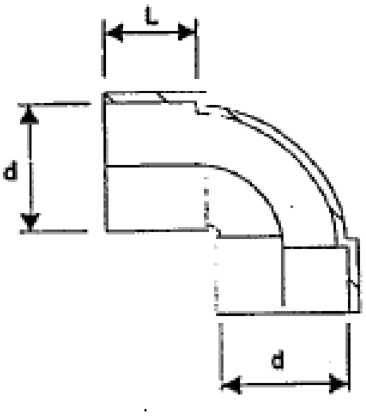

Figure 2.9 90° equal elbow

Source: Malaysian Standard, 1999

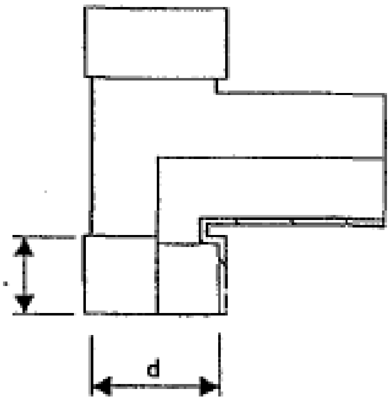

Figure 2.10: Reducing Tee

Source: Malaysian Standard, 1999

Table 2.4 Minimum socket depth and mean socket internal diameter

Nominal Size (mm)	Minimum socket depth (L) (mm)	Mean socket internal diameter at midpoint of socket depth (mm)
15	16.5	21.3
20	19.5	26.7
25	22.5	33.5
32	27.0	42.2
40	30.0	48.2
50	36.0	60.3
65	43.5	75.1
80	50.5	88.8

Source: Malaysian standard, 1999

2.5 Hydrostatic Burst Test

A hydrostatic test is a way in which pressure vessels such as pipelines, plumbing, gas cylinders, boilers and fuel tanks can be tested for strength and leaks. The test involves filling the vessel or pipe system with a liquid, usually water, which may be dyed to aid in visual leak detection, and pressurization of the vessel to the specified test pressure. Pressure tightness can be tested by shutting off the supply valve and observing whether there is a pressure loss. The location of a leak can be visually identified more easily if the water contains a colorant. Strength is usually tested by measuring permanent deformation of the container. Hydrostatic testing is the most common method employed for testing pipes and pressure vessels. Using this test helps maintain safety standards and durability of a vessel over time. Newly manufactured pieces are initially qualified using the hydrostatic test. They are then re-qualified at regular intervals using the proof pressure test which is also called the modified hydrostatic test.[citation needed] Testing of pressure vessels for transport and storage of gases is very important because such containers can explode if they fail under pressure. Hydrostatic tests are conducted under the constraints of either the industry's or the customer's specifications, or may be required by law. The vessel is filled with a nearly incompressible liquid - usually water or oil - and examined for leaks or permanent changes in shape.

The test pressure is always considerably higher than the operating pressure to give a margin for safety. This margin of safety is typically 166.66%, 143% or 150% of the designed pressure, depending on the regulations that apply. Water is commonly used because it is nearly incompressible, therefore requiring relatively little work to develop a high pressure, and is therefore also only able to release a small amount of energy in case of a failure - only a small volume will escape under high pressure if the container fails. If high pressure gas were used, then the gas would expand to $V= (nRT)/p$ with its compressed volume resulting in an explosion, with the attendant risk of damage or injury. This is the risk which the testing is intended to mitigate. Water is used mainly because it is cheap and easily available. Hydrotesting of pipes, pipelines and vessels is performed to expose defective materials that have missed prior detection, ensure that any remaining defects are insignificant enough to allow operation at design pressures, expose possible leaks and serve as a final validation of the integrity of the constructed system. ASME B31.3 requires this testing to ensure tightness and strength.

Buried high pressure oil and gas pipelines are tested for strength by pressurizing them to at least 125% of their maximum operating pressure (MAOP) at any point along their length. Since many long distance transmission pipelines are designed to have a steel hoop stress of 80% of specified minimum yield (SMYS) at MAOP, this means that the steel is stressed to SMYS and above during the testing, and test sections must be selected to ensure that excessive plastic deformation does not occur.

2.6 Solvent Welding PVC and CPVC Fittings

The solvent cemented connection in thermoplastic pipe and fittings is the last vital link in a plastic pipe installation. It can mean the success or failure of the system as a whole. Accordingly, it requires the same professional care and attention that are given to other components of the system. There are many solvent cementing techniques published covering step by step procedures on just how to make solvent cemented joints. However, we feel that if the basic principles involved are explained, known and understood, a better understanding would be gained, as to what techniques are necessary to suit particular applications, temperature conditions, and variations in sizes and fits of pipe and fittings.

To consistently make good joints the joining surfaces must be dissolved and made semi-fluid. There also must be sufficient cement applied to fill the gap between pipes and fitting. Assembly of pipe and fittings must be made while the surfaces are still wet and fluid. Joint strength develops as the cement dries. In the tight part of the joint the surfaces will tend to fuse together, in the loose part the cement w Penetration and dissolving can be achieved by a suitable primer, or by the use of both primer and cement. A suitable primer will penetrate and dissolve the plastic more quickly than cement alone. The use of a primer provides a safety factor for the installer for he can know, under various temperature conditions, when he has achieved sufficient softening.ill bond to both surfaces.

More than sufficient cement to fill the loose part of the joint must be applied. Besides filling the gap, adequate cement layers will penetrate the surface and also remain wet until the joint is assembled. Prove this for yourself. Apply on the top surface of a piece of pipe two separate layers of cement. First flow on a heavy layer of cement, then alongside it a thin brushed out layer. Test the layers every 15 seconds or so by a gentle tap with your finger. You will note that the thin layer becomes tacky and then dries quickly (probably within 15 seconds). The heavy layer will remain wet much longer. Now check for penetration a few minutes after applying these layers. Scrape them with a knife.

The thin layer will have achieved little or no penetration. The heavy one has much more penetration. If the cement coatings on the pipe and fittings are wet and fluid when assembly takes place, they will tend to flow together and become one cement layer. Also, if the cement is wet the surfaces beneath them will still be soft, and these softened surfaces in the tight part of the joint will tend to fuse together. As the solvent dissipates, the cement layer and the dissolved surfaces will harden with a corresponding increase in joint strength. A good joint will take the required working pressure long before the joint is fully dry and final strength will develop more quickly than in the looser (bonded) part of the joint.

2.7 Equations of Break Pressure

In order to have the theoretical data, the related solutions for break pressure of fittings are collected. Those solutions will give the predictions for the perfect and defected fittings. The theoretical data will be used to compare the value with the experimental results.

2.7.1 Goodall asymptotic solution

Previous research on the effect of internal pressure to fitting has developed series of solution or formula to predict collapse pressure of fitting whether perfect or defected. These solutions allow for the comparison between experimental data and theoretical data to be made. In perfect elbow case, Goodall gave the asymptotic solution, for Tresca and limited interaction yield criteria for the collapse load (P^*) of a pressurised elbow is as shown in equation **(2.1)**

Eq. (2.1)

$$P^* = \frac{\sigma_y t}{r} \frac{(1-\frac{r}{R})}{(1-\frac{r}{2R})} \tag{2.1}$$

The formula uses then yield stress $\boldsymbol{\sigma}_y$ value for plastic. The value of collapse load depends on the thickness of elbow. In a long radius elbow, the radius of curvature R is 1.5 times the nominal diameter while in standard elbow, the radius of curvature (R) is 1.0 times the nominal diameter of the fitting. When an elbow is subjected to internal pressure, the circumferential stress is different from a straight pipe with the same cross section. Recognizing that different parts of the elbow have different stress magnitude, it is expected that local thinned area position have an effect on the collapse load. From the research, it shows that local thinned area in the intrados of elbow has the most damaging effect on pressure-bearing capacity. Local thinned area located in the extrados has the least effect on its collapse load.

The collapse load of local thinned area elbow is different from the straight pipe. If the reduction criterion for a straight pipe is used to asses an elbow, it is unsafe for local thinned area in the intrados and over-conservative for the local thinned area in the extrados. Under internal pressure, the circumferential stress is the factor having the main effect. The difference between the collapse load of a straight pipe and an elbow relates to the different circumferential stress level. If the stress is larger in the elbow, the collapse load will be smaller. If the stress is equal for the two geometries, the collapse loads are also equal. So the collapse load of an elbow with intrados local thinned area is the lowest, with extrados local thinned area is the biggest and with crown local thinned area is equal to the straight pipe.

The effective area method was developed from a semi empirical fracture mechanics approach by Maxey and Kiefner. The remaining pressure-carrying of a pipe segment is calculated on the basis of the amount and distribution of metal lost to corrosion and the yield strength of the material. If the calculated-remaining pressure-carrying capacity exceeds maximum allowable operating pressure of the pipeline by a sufficient margin of safety, the corroded segment can remain in service. If not, it must be repaired, replaced or re-rated for reduced operating pressure. The resulting pipe wall hoop stress at failure at the flaws is given as in equation **(2.2)**.

Eq. (2.2)

$$\sigma_f = \sigma_0 \frac{A_o - A}{A_o - AM^{-1}} \qquad (2.1)$$

This equation was based upon a Dugdale plastic-zone- size model ,a ‘Folias’ bulging stress magnification factor M for an axial crack in pressurised cylinder and an empirical flaw depth to pipe thickness relationship that modifies the Folias M factor to asses a surface flaw .The expression was then enhanced to address corrosion flaws through replacement of the flaw depth with an expression for an effective cross sectional area . This is local collapse estimate. While empirical in nature; the effective area method was validated by a series of more than 80 experiments and field failures and has proven to provide conservative predictions of failures in almost all cases. Miller surveyed test results for this type of flaw and concluded that he best estimate for burst pressure was the above local collapse expression, in general. For elbow with local thinned area, the collapse load varies depend on the location of defect whether in intrados, extrados or crown. The circumferential stress is the factor having the main effect to the collapse load. Collapse load of thinned elbow:

In formula **(2.3)**, it gives the estimation formula of burst pressure formula when local thinned area is located on the intrados part of the elbow. While in formula **(2.4)**, Miller also gives the estimation for local thinned area on extrados and finally a solution for defected crown of elbow in formula **(2.5)**

Intrados

Eq. (2.3)

$$\frac{P_E}{p^*} = \frac{A_o - A}{A_o - AM^{-1}} \frac{(\frac{R}{r} - 1)}{(\frac{R}{r} - \frac{1}{2})}) \qquad (2.3)$$

Extrados:

Eq. (2.4)

$$\frac{P_E}{p^*}=\frac{A_o-A}{A_o-AM^{-1}}\,\frac{(\frac{R}{r}+1)}{(\frac{R}{r}+\frac{1}{2})} \tag{2.4}$$

Crown:

Eq (2.5)

$$\frac{P_E}{p^*}=\frac{A_o-A}{A_o-AM^{-1}} \tag{2.5}$$

Here P^* is the collapse load of defected free elbow and Folias factor,M must be calculated first. Formula **(2.6)** gives the equation developed by Folias for a correction factor.

Eq. (2.6)

$$M=[1+0.6275\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)-0.003375\left(\frac{L}{D}\right)^4\left(\frac{D}{t}\right)^2]^{\frac{1}{2}} \tag{2.6}$$

$$\text{For}\quad \left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)\leq 50$$

The 'Folias factor' is a geometrical correction factor in the failure criterion for a pressurized vessel with a crack, originally derived by E.S. Folias. Flow stress can be defined as the stress required sustaining plastic deformation at a particular strain. The flow stress is a function of plastic strain. Flow stresses occur when a mass of flowing fluid induces a dynamic pressure on a conduit wall. The force of the fluid striking the wall acts as the load. This type of stress may be applied in an unsteady fashion when flow rates fluctuate. Water hammer is an example of a transient flow stress.

2.7.2 Xuan limit load solution

When the internal pressure reaches the limit load, the stress components in fittings section should satisfy the plastic failure criteria which had been presented in a previous work (Xuan, 2003).Substituting the area of net section derived from Eq. (2.2) into Eqs. (2.3), (2.4)and (2.5) and taking the Poisson's ratio $\nu = 0.3$, normalizing these previous stresses by using flow stress and then substituting them into the plastic failure criterion (Eq. (2.7) in Ref. Xuan et al., 2003a).

Area of net section

Eq. (2.7)

$$A_c = \int_0^{\frac{\pi}{2}-\alpha} TD d\theta + \int_0^{\frac{\pi}{2}} TD d\theta + \int_0^{\frac{\pi}{2}-\alpha} \left(T-a\right) D d\theta \tag{2.7}$$

Eq. (2.8)

$$A_c = \pi TD(1-\frac{a}{T}\ \frac{\alpha}{\pi}) \tag{2.8}$$

Circumferential membrane stress

Eq. (2.9)

$$\sigma_{\omega p} = \frac{1}{A_c} \iint A_c \ dA = \frac{P_L D}{2T} [\left[1 + \frac{k\sigma_z \beta D T^2}{2A_c P_L}\right] x \ [2 - \frac{a}{T}(1 - \cos\alpha \\ + \frac{2\sigma_z T^2}{A_c P_L}(2- \frac{a}{T}\sin\alpha)] \tag{2.9}$$

The axial membrane stress

Eq. (2.10)

$$\sigma_{yp}=\frac{1}{A_c}\iint \sigma_y dA=\frac{P_L D}{4T} \tag{2.10}$$

The axial bending stress

Eq. (2.11)

$$\sigma_{ybp}=\frac{1}{A_c}\iint \sigma_{yb}\ dA=\frac{P_L D}{2T}[\left[1+\ \frac{2k\sigma_z T}{2A_c\beta P_L}\right] x\ [2-\frac{a}{T}(1-\cos\alpha)] \tag{2.11}$$

The circumferential bending stress

Eq. (2.12)

$$\sigma_{\omega bp}=\nu\ \sigma_{ybp} \tag{2.12}$$

Different solution will be for the case of tee. In the case of defected free tee, from the viewpoint of the effective loaded area and finite element (FE) analysis result, Xuan [developed an approximate solution for plastic limit pressure of equal diameter tees. The value of j^p is weakening factor of equal diameter tee under internal pressure.

Eq. (2.13)

$$P_L=\frac{\sigma_{fj}{}^{p}2T_m}{D} \tag{2.13}$$

The value of j^p is weakening factor of equal diameter tee under internal pressure

Eq. (2.14)

$$j^p=\frac{0.393\frac{T_m}{D}+2\sqrt{\frac{T_m}{D}}-0.215\frac{r}{D}}{0.215(\frac{r}{D})^2+0.25+0.5\frac{T_m}{D}+0.429\frac{rT_m}{D^2}-0.535(\frac{T_m}{D})^2+2\sqrt{\frac{T_m}{D}}-2\frac{T_m}{D}\sqrt{\frac{D}{T_m}}} \qquad (2.14)$$

In case of cracked tee, from the viewpoint of the effective wall thickness and the equivalent straight pipe concept, Xuan developed a semi-experiential solution for the limit load of the cracked tees under internal pressure. For the case of crack at the flank area the solution is

Eq. (2.15)

$$P_c=\frac{2\sigma_f T_m}{D}j^p\frac{1-\frac{a}{T_m}}{1-\frac{\frac{a}{T_m}}{[\frac{1+2.1c^2}{DT_m}]^{\frac{1}{2}}}} \qquad (2.15)$$

While for crack at the crotch corner, we have

Eq. (2.16)

$$P_c=\frac{2\sigma_f T_m}{D}j^p\frac{1-\frac{a}{T_m}}{1-\frac{\frac{a}{T_m}}{[\frac{1+2.1c^2}{DT_m}]^{\frac{1}{2}}}} \qquad (2.16)$$

The limit load definition requires that small deflections are assumed in any-analysis and elastic/perfectly elastic material is specified. For this limit load work a yield stress of 320 Mpa and a poisson ratio of 0.3 were used. For the equal-diameter piping branch junction, Xuan has brought into some conclusions.Firstly, the new approach for predicting the limit load of two-cylinder intersection structures with diameter ratio larger than 0.5 which has previously been developed for defect free cases subjected to various loadings can also be applied to cracked piping branch junctions. An approximitive limit load solution for equal diameter piping branch junctions with circumferential cracks is proposed. Secondly nonlinear finite element analyses of 36 cracked piping branch junctions have been performed and the results show a good agreement with those estimated from formulas proposed in this work. Lastly, the proposed formula has a high accuracy in calculating the limit load and simple form. So as its correctness and reasonableness are further validated by more experimental work and FE results, it could be utilized in the integrity assessment of pressurised pipeline

An alternative solution is used to compare the value with existing calculated solution. In this case Netto's solution is used. This solution usually used in plastic pipeline. This alternative approach allows us to see the whether the existing solution give significant difference in value compared to the Netto's solution.

Eq. (2.17)

$$\frac{P_{def}}{P} = \left[\frac{1-\frac{d}{t}}{1-\frac{d}{t}\left(1-\left(\frac{c}{\pi D}\right)^{0.4}\left(\frac{l}{10D}\right)^{0.4}\right)} \right]^{2.675} \tag{2.17}$$

2.8 Limit pressures of 90° elbows with circumferential surface cracks

Plastic limit analysis of pressurized pipes with circumferential cracks has been an important issue in the field of structural integrity assessment, due to its importance in design and assessment. For instance, plastic loads obtained from plastic limit analyses can be directly used to estimate maximum load-carrying capacities. As pressure loading is fundamental for pressurized piping, knowledge on plastic limit pressures of cracked piping components is essential. For cracked straight pipes, plastic limit pressure solutions are widely available typical pipe works include not only straight pipes but also elbows, and thus plastic limit analyses of circumferential cracked elbows need to be performed. Despite the importance of internal pressure on design and assessment of elbows, most of exiting works have been for plastic limit analyses of cracked elbows under bending. Some works investigated plastic limit loads for elbows under combined pressure and bending, but internal pressure was treated as a base load and thus the pure internal pressure case was not considered in details. For un-cracked elbows, Goodall presented an analytical limit pressure solution for an elbow. For circumferential cracked elbows under internal pressure, Yahiaoui performed finite element (FE) limit analysis but their cases were not sufficient to draw closed-form limit pressure solutions for cracked elbows. Another notable point is that all exiting works assume a circumferential crack in the centre of an elbow. It is natural, as the elastic stress analysis shows that the stress magnitude is the maximum in the centre of an elbow. On the other hand, elbows are typically butt-welded to straight pipes. Fig. 2.3 depicts a 90° elbow, considered in the present work. The mean radius and thickness of the pipe are denoted by r and t, respectively, and the bend radius by R, leading to non-dimensional variables, R/r and r/t.

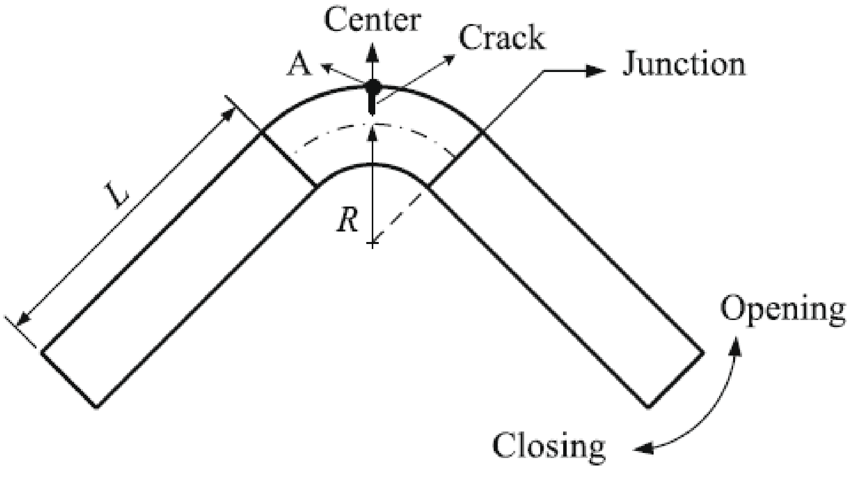

Figure 2.11 Designed model for 90° elbow

Source: Seok-Pyo (2009)

This paper provides approximate limit pressures for circumferential cracked elbows, resulting from small strain FE limit analyses using elastic–perfectly plastic materials. Circumferential through-wall and constant-depth surface cracks at both extrados and intrados are considered. The length of circumferential through-wall cracks is, however, limited to 50% of the circumference. Two locations along the longitudinal direction are considered; one in the centre of the elbow, and the other in the junction between the elbow and the attached straight pipe. Along the circumference, both extrados and intrados cracks are considered. One interesting finding is the effect of the crack location (in the longitudinal direction) on limit pressures. It is found that limit pressures for the case when a crack locates in the centre of an elbow are the same as those for the case when a crack locates in the junction between an elbow and attached straight pipe. Another interesting point is the effect of the circumferential crack size on limit pressures of elbows. When the depth of the circumferential crack is less than 60% of the pipe thickness, the presence of the crack does not affect the limit pressure and thus the limit pressure for the cracked elbow is the same as that for un-cracked elbow. Furthermore, even for the case of the through-wall crack, the presence of the crack does not affect the limit pressure, when its length is less than 20% of the circumference. This implies that limit pressures of elbows are affected by the presence of the circumferential surface crack, only when it is sufficiently deep and long.

When pressures are affected by the presence of the crack, limit pressures for intrados circumferential surface cracked elbow decrease almost linearly with increasing a/t and h/p, and are almost independent on elbow geometries such as R/r and r/t. For extrados cracks, effects of h/p and r/t on limit pressures are slightly more complicated, although overall trends are quite similar to those for intrados cracks. Such simple functional dependence suggests closed-form approximations of limit pressure for circumferential cracked elbows, which in turn would be useful in crack assessment. As information on limit pressures for cracked components has its own merit in defect assessment, present results are believed to be valuable for defect assessment of circumferential elbows (Seok-Pyo Hong, 2009)

2.9 Related Academic paper

A comparison of the failure pressure with the results of existing models was made and showed that the existing models were excessively conservative in all cases and could not properly predict the dependence of failure pressure on the wall-thinning geometry. The failure pressure of wall-thinned elbows decreased and gradually saturated with increasing actual thinning length, and decreased linearly with increasing thinning depth. These dependences on thinning length and depth were similar to those observed for local wall-thinned straight pipe. The failure pressure decreased and saturated with increasing circumferential thinning angle, unlike the results of straight pipe. The experiments confirmed that an intrados wall-thinned elbow is weaker against bursting under internal pressure than an extrados wall-thinned elbow with the same actual wall thinning geometry. The extrados and intrados wall-thinned elbows fail by bulging, followed by axial cracking in the minimum wall thinned area. (Yong Park, 2009)

The wall thicknesses at different locations are not equivalent to normal wall thickness constantly; the average values of wall-thickness at run pipe, crotch and flank area are always larger than the nominal value; while for measured thickness of branch pipe, the average values are commonly less than nominal thickness, and the thinnest location is at the outlet of the branch pipe with value of 0.733T0. The radiuses at the transition of run and branch pipe are different, even for the tees with the same specification from different manufacturers. For the defect free ANSI B16.9 tees close to the collapse state, a significant characteristic observed in the test was bulging deformation in the lateral flank region and the bulging deformation became more obvious with increasing pressure.

The other notable characteristic, for all of the selected tees, was that the final failure was caused by leakage at the transition between the branch and run pipe. It is also noted that for the most plain carbon–manganese steel tees, the crevasse length was very short and distributed symmetrically at both sides of crotch. The value of radius of crotch corner will significantly influence on the limit load, that is, increasing the radius of crotch corner will reduce the loading capability of ABSI B16.9 tees. (Chen, 2005)

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, the method of experimentation and analysis will be discussed with the related parts and material involvement. This chapter is the overview to do the experiment short term hydrostatic burst pressure of PVC fittings which are 90° elbow and equal diameter tee. Flowchart system detailing the task need to be completed was drafted out. This flow chart shows the overall flow of project in step by step process. There must have a triangular in the flowchart, means that the result obtained from the experiment is to be changed if the result is invalid or unacceptable. Due to that, the experimental procedures need to be conducted again until the expected results are achieved.

The experiment is divided into two parts which is first experiment's objective is to develop the best PVC fittings model for short term hydrostatic burst test. This is including the type of joint used, the design of the model, the jointing material used and also the practicality of the model in getting the data required. For the second experiment's objective is to observe and analyse the effect of defected PVC fittings on the burst pressure. This second experiment requires the introduction local thinned area on the fittings.

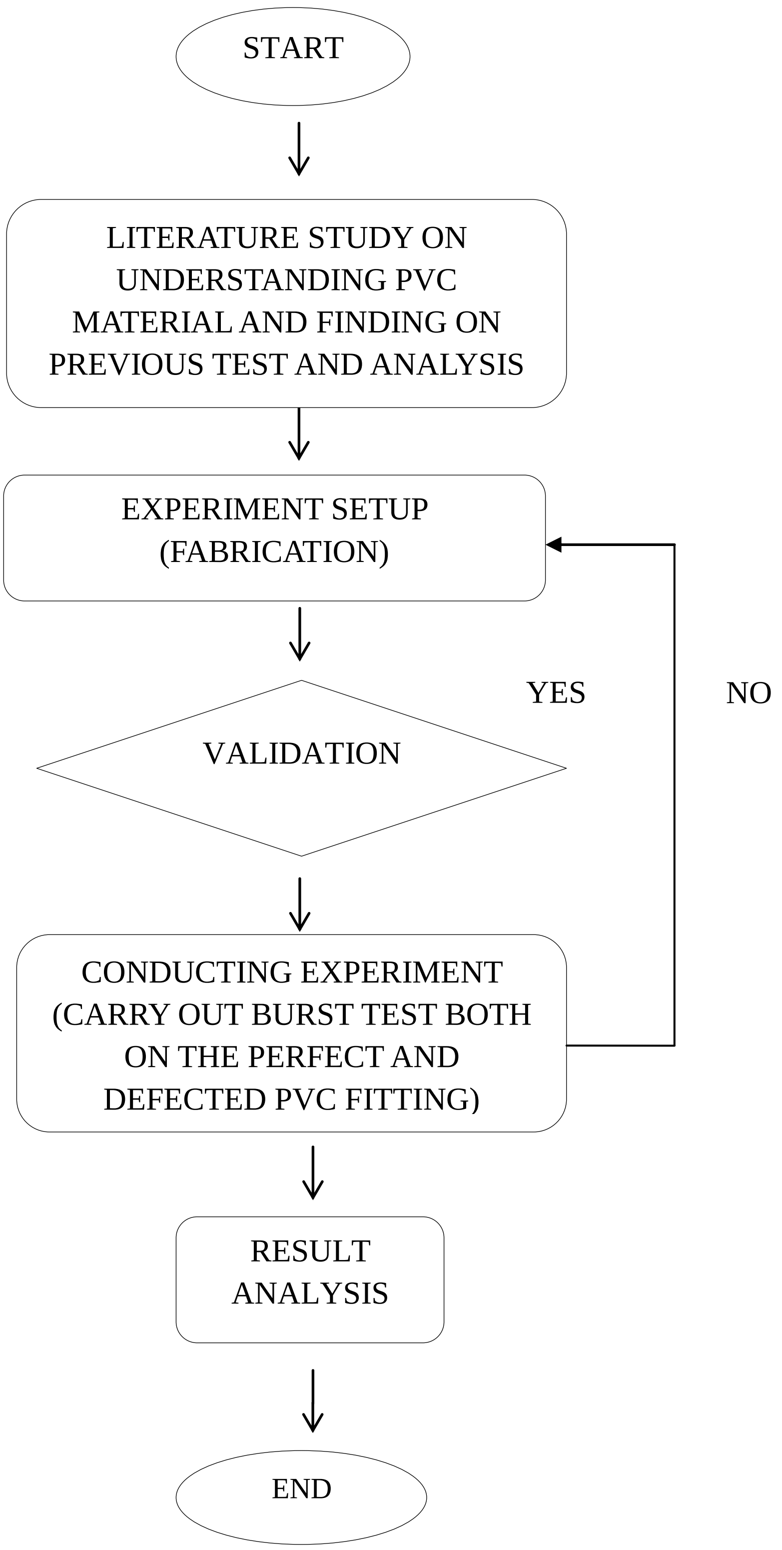

Figure 3.1: Flow chart for the production of the thesis

3.2 Design of Each Part

The design of experiment is the most of important part before proceeding to material and other aspects.

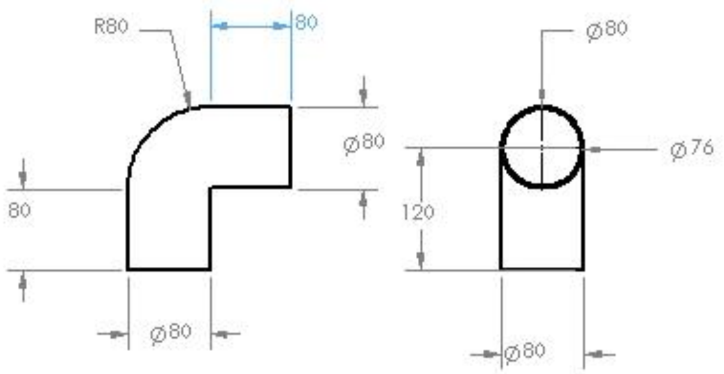

Figure 3.2: 90° Elbow

Figure 3.2 shows the technical drawing of 90° elbow fitting being used in this experiment. Three inch or 80mm diameter elbow is used for the testing as it will break in the range of (0-10)Mpa which is suitable with the hydraulic pump that is going to be used. The main factor of using large diameter elbow fitting is it has lower burst pressure than the smaller dimension of elbow fitting. As the elbow getting smaller in diameter, it has thicker wall. Thicker wall will cause the fitting to have larger burst pressure and much more difficult to collapse. 90° elbow is the connector that often being used in piping system.

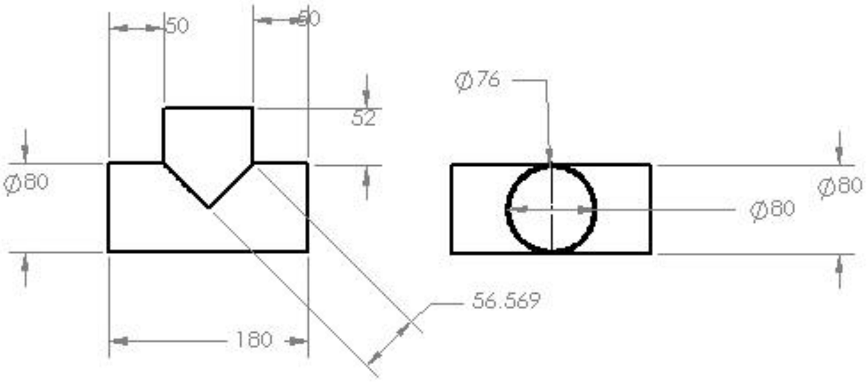

Figure 3.3: Equal diameter tee

Figure 3.3 shows the technical drawing of equal diameter tee with diameter of 80mm.The tee has wall with thickness of 4mm. Tee with diameter also has lower burst pressure than the tee with small diameter. Tee with small diameter will have thicker wall. Equal diameter tee used for connection of equal diameter pipes from all three holes.

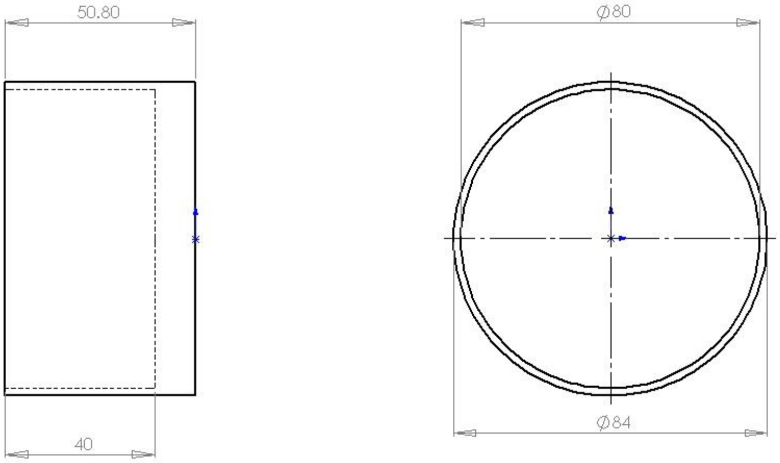

Figure 3.4: End cap

Figure 3.4 shows the technical drawing for PVC cap of 80mm diameter. Based on the SIRIM guidelines, there must be a suitable enclosure for the fitting being tested. 80mm diameter PVC cap is suitable as it has thicker wall than the elbow and tee. There is no possibility for the cap to collapse when being tested. While in figure 3.5, it shows the PVC that has been introduce a hole on the top surface of the cap. The hole is made to allow a socket connector to be put on the cap as a connector between the hose of hydraulic pump and the tested fitting

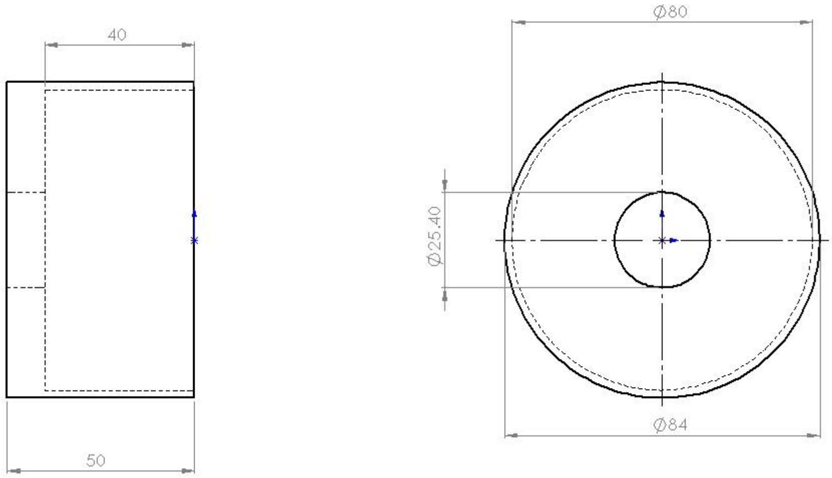

Figure 3.5: End cap with holes

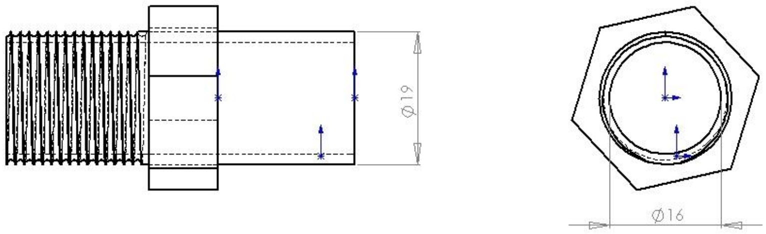

Figure 3.6: PVC socket connector

In figure 3.6, it shows the technical drawing for PVC socket connector. There is a thread inside the socket which allows connecting with threaded hose hydraulic pump. This threaded connection will ensure tight connection and zero leaking between the connections. The threaded part will be inside the cap and the top part of the socket will be jointed to the top of the cap and act as the connection door for the assembly.

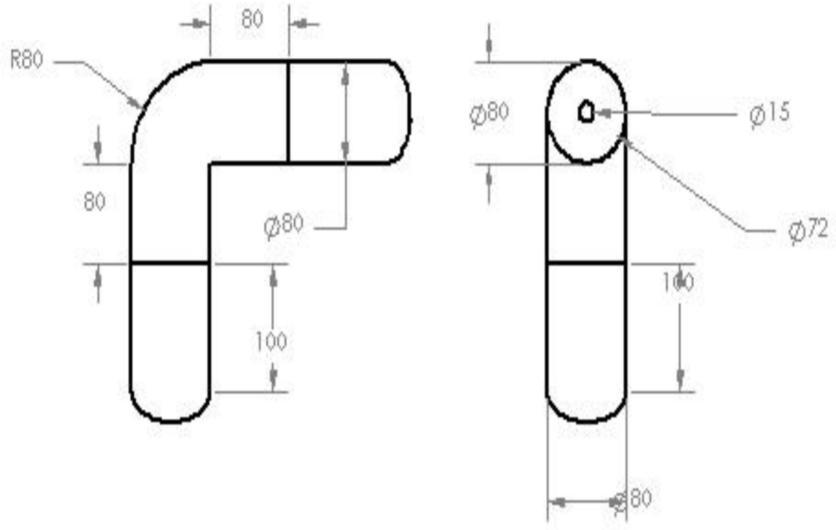

Figure 3.7: The assembly for elbow

In figure 3.7, it shows the assembly between the cap, elbow and also the socket. One cap will be a normal without hole and another with socket for the connection during testing. This design will be used for testing of both perfect and defected elbows. The design is the final design that being used after several improvements on the old design. This design leads to strong connection and reduce the possibilities of leaking on the jointed components.

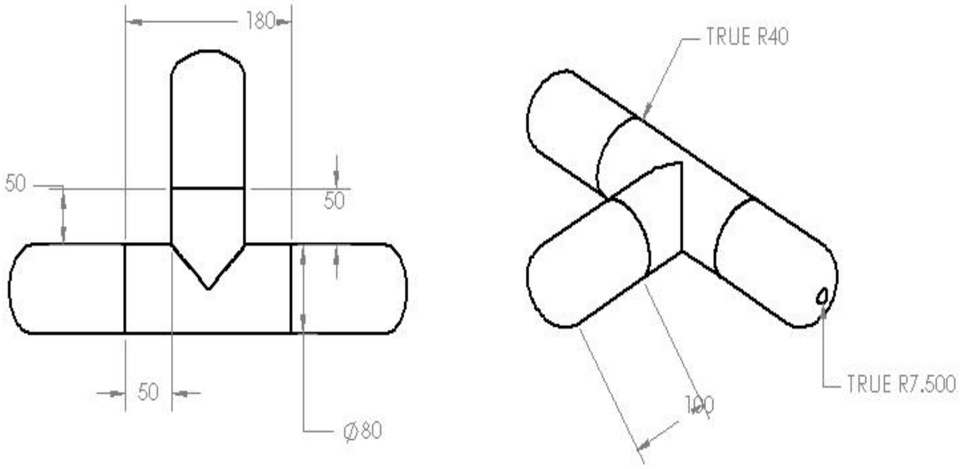

Figure 3.8: The assembly for tee

In figure 3.7, it shows the technical drawing for equal diameter tee assembly between the tee, cap and also the socket. It involves three caps, and only one of them will be inserted a socket for connection during the testing. This design will also be used for the testing of both perfect and defected tee. This design is the improved design after several designs have being tested their connection whether strong or not. The improved design also leads to small possibility of leaking during testing.

3.3 DESIGN OF EXPERIMENT

The experiment to determine the burst pressure of the PVC pipes is designed as below using SolidWork 2012. The complete testing design consists of the complete assembly of the tested fittings, the threaded hose, the hydraulic pump and also the water tank. This design is an example of simple short term hydrostatic test model. It does not require any additional complex parts. The tank is used to store the testing fluid such as water or oil. The manual hydraulic pump is used as it will not require any electricity involvement and this way is the safest way of doing test that involve fluid. The manual hydraulic pump is also easy to control its pressure, easy to handle and mobile.

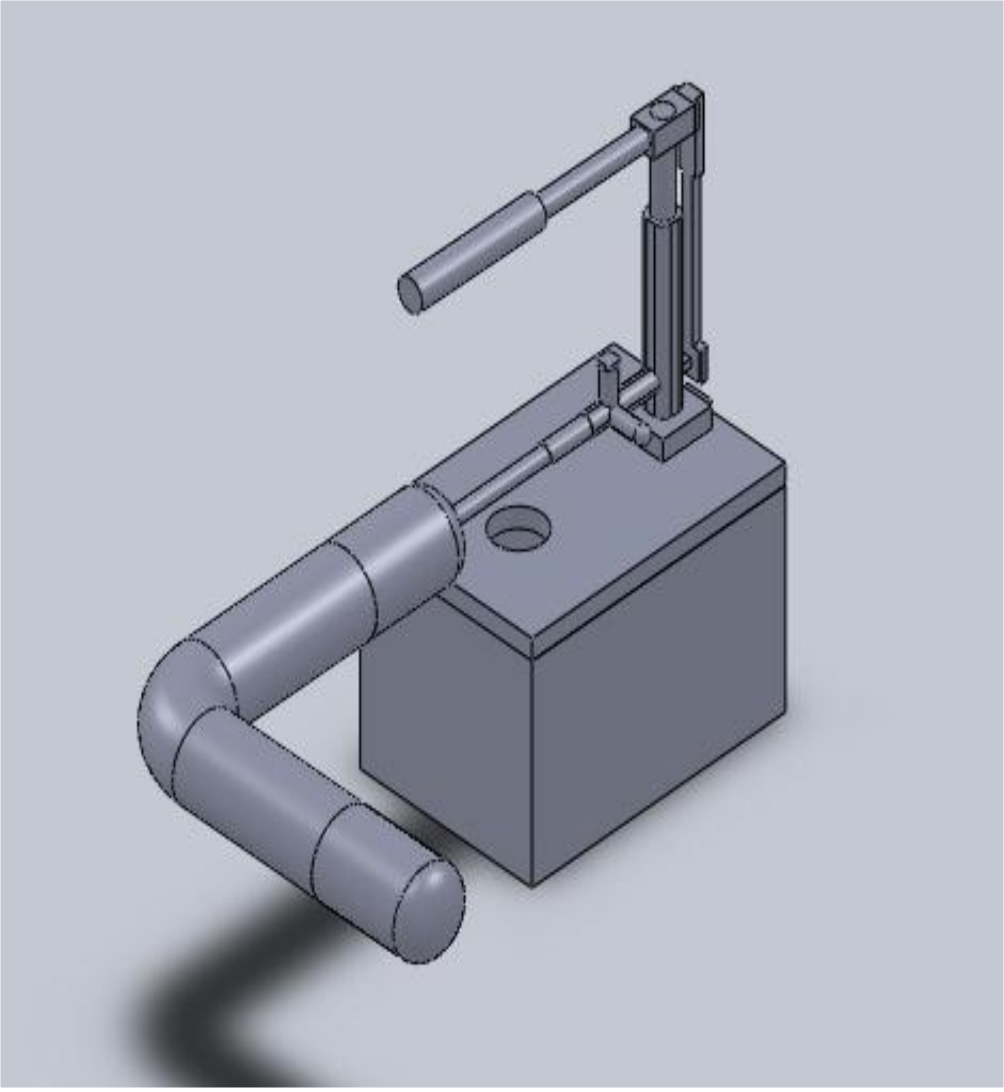

Figure 3.8: Design of experiment

In figure 3.8, it shows the complete design of short term hydrostatic burst pressure used in this experiment. Each fitting will be enclosed with PVC cap. One of the caps is attached with socket connector to connect the pump's hose to the fitting. The hydraulic pump will supply water into the fitting giving internal pressure to the tested fittings. The gauge at the side of the pump will be used to record the reading of the internal pressure being supplied as the tested model has collapsed. This design is designed specifically made based on the guidelines provided by SIRIM for testing the break pressure of PVC fittings for both the elbow and tees.

3.4 LIST OF MATERIALS

After finish with choosing best design of testing, then go the selection of materials involved. The material selected must parallel to the testing requirement. Before proceeding to next step, we have to prepare the list of materials that we need so that it will make our work easier when surveying for the prices. The prices are needed for the making of the bill of materials. Below are the lists of materials:

i. 3” 90° Elbow
ii. 3” equal diameter tee
iii. 3” PVC Cap
iv. ½” Nipple Connector
v. PVC Solvent Cement
vi. PTFE Tape
vii. Araldite Epoxy
viii. Hand Pressure Test Pump

3.4.1 Manual Hydraulic Pump

The pump is that component of the hydraulic circuit that converts mechanical energy into hydraulic pressure, which in turn produces force in the cylinder. The mechanical energy can be supplied by hand, by an electric motor, or by air pressure. Used less often are gasoline driven internal combustion engine pumps. Hydraulic pumps are classified under the broad category of pumps known as positive displacement. Positive displacement (PD) pumps can produce fluid pressure either by rotating meshing gears of by piston action. Sometimes in the case of two-stage pumps, both gears and pistons are utilized. PD pumps require a provision of over-pressure protection. The discharge pressure of hydraulic pumps has been standardized at 10,000 psi (pounds per square inch). The hand hydraulic pump uses the simple principle of a handle providing leverage to an internal piston. The piston forces hydraulic fluid through a conductor (a hose) into the cylinder port. This style pump is available in numerous sizes and can be used in nearly all cylinders lifting, pushing, and pulling applications.

The mobility provided by the feature of no external power is a plus. Because they can be comparatively slow and necessarily labour intensive, their recommended use is limited to less frequent service needs like occasional maintenance tasks. Hand pump fluid volume and fluid delivery speed can also become limiting considerations. Manual hydraulic pump being used is up to 10MPa.

Figure 3.9: SY 100X Hand Pressure Test Pump

In figure 3.9, it shows the picture of hand pressure test pump or usually known as manual hydraulic pump. The presence lever system, valve and also pressure gauge can be clearly seen in the picture. The pump is bought from the supplier at Kuantan rather than fabricating one because the aim of this research is not about making a pump but to study the burst pressure of polyvinyl chloride fittings.

3.5 Fabrication and Testing

In this section, the detail discussion for fabrication and testing will be carried out. For the fabrication, it includes the jointing method, the tester and also the leakage prevention procedures. While for the testing, the introduction of local thinned area and general steps in testing are being discussed.

3.5.1 Fabrication detail

The very first step is to look forward for the tester apparatus. Manual hydraulic pump is the best pump to be used for the testing process as it is can be easily and manually controlled. Surveys made to find the most suitable pump and finally a manual hydraulic pump that can give pressure up to 10MPa complete with the gauge and reservoir.

This pump has a valve that will ensure there is no backflow during applying huge pressure inside the fitting. Water will be used for the testing procedure as it is easy to handle. From the connection available on the pump, the testing model is designed to suit for the connection. Each elbow and tee will be closed by Polyvinyl Chloride caps. A hole is made on the cap and Polyvinyl Chloride connector will be inserted and glued together with the cap. The plug will be the connector for the fitting models with pump through the high-strength hose. In fitting connection, there must be a straight connector fitting to connect between fittings. It means that there will be a straight fitting connecting between the elbow and the cap or between the tee and the cap. We cannot have direct connection between fittings. The straight fitting connector must be harder or stronger than the tested fitting especially in the case of perfect fittings. Weak connector will cause collapse to happen at the connector not the fittings being tested. This is applied to both elbow and tee. In addition, there connection between connector and fittings must be very smooth, no additional stress between the end of the connector and the fittings. If the connection is in stress, this will affect the collapse load value as the model will undergo break due to the connection stress. Perfect and valid data will be achieved if the collapse starting from the centre of the fitting and moving outward.

Figure 3.10 The PVC cap with socket connector

In figure 3.10, it shows the joint that made between the cap and the socket connector. The socket is glued both from inside and outside of the cap to prevent any leaking. There must be a very strong connection for the socket as the small part will be most affected by the internal pressure being applied. The threaded part of the socket ensures there is no leaking of connection between the hose and the tested fittings model.

Polyvinyl Chloride solvent cement is used as it is the most strong and reliable glue for connection between PVC parts. But before applying glue, visually inspect the inside of the pipe and fitting sockets and remove all dirt, grease or moisture with a clean, dry rag or cloth. If wiping fails to clean the surfaces, a chemical cleaner must be used. To ensure for stronger bond between the cement and the polyvinyl chloride surface, the joint faces must be made rougher to increase friction. This is done by applying sand paper on the polyvinyl chloride surfaces. In order to have cleaner and better surface, primer is applied first before the pvc cement. This is to removes some kind of protective surface coating that has been intentionally applied to the pipe during manufacturing. The job of the primer is also to soften the PVC so when you apply the "glue" it will cause the 2 pieces to combine on a molecular level so the 2 are now 1.

Check for possible damage such as splits or cracks and replace if necessary. This gluing process is carrying out with a serious care as to avoid any leakage. A critical part of the solvent cementing process is to make sure the cement is well mixed. Periodically cover the container and shake the cement to make sure it stays mixed and uniform. Apply the solvent cement evenly and quickly around the outside of the pipe and at a width a little greater than the depth of the fitting socket while the primer is still wet. Apply a lighter coat of cement evenly around the inside of the fitting socket. Avoid puddling. Apply a second coat of cementing to the pipe end.

Any leakage will cause pressure drop and the test will fail. In addition, any weak connection causes it to break during the test. The connection will break earlier before the fittings break. Finish with the model, another requirement is to fabricate a stand for the model, this ensure the fitting will be in a stabilize condition during the test. Then, to avoid any harmful exploded out, the testing model will be enclosed by a strong cover. So, a cover is designed so as to suit with the entire testing procedures and then fabricated. The last requirement is to fabricate a trolley that act as the pump holder and also to store all the equipment and material. The trolley also makes it easy to carry the test equipment as it is a mobile experiment set up. After finish dealing with the fabrication, the whole parts will be attached to the pump for burst pressure test. However, before that, all fabricated parts, the model must be ensured to be strong enough before any test being carried out. There will always be a final inspection.

3.5.2 General Steps For fabrication

a) Prepare a nipple for each fitting and two caps for an elbow and three caps for tee.
b) Drill a hole through the cap as the placement for the nipple connector and the hole made follow the nipple’s dimension.
c) Assembles all components which are nipple connector to the cap’s hole and fitting to the caps.

d) Apply the PVC solvent cement on all jointed surfaces. Follow the steps shown at the container of the PVC solvent cement in order to produce a tight connection.
e) Allow the cement to dry for about more than 24 hours according to the instruction given at the container.

Figure 3.11 Complete assembly of elbow model

In figure 3.11 it shows the completed assembly of the elbow model. Previously, the connecter between the cap and fitting can be seen, which mean the cap and the fitting does not directly meets. This kind of connection actually brings to a serious leaking problem .There are more parts with high possibility of leaking. In addition, that type of connection actually use much more PVC cement and ineffective. Above model is the best model designed for elbow hydrostatic burst test. The final model can be tested to get its burst pressure directly without encountering any leaking problem that faced in previous models.

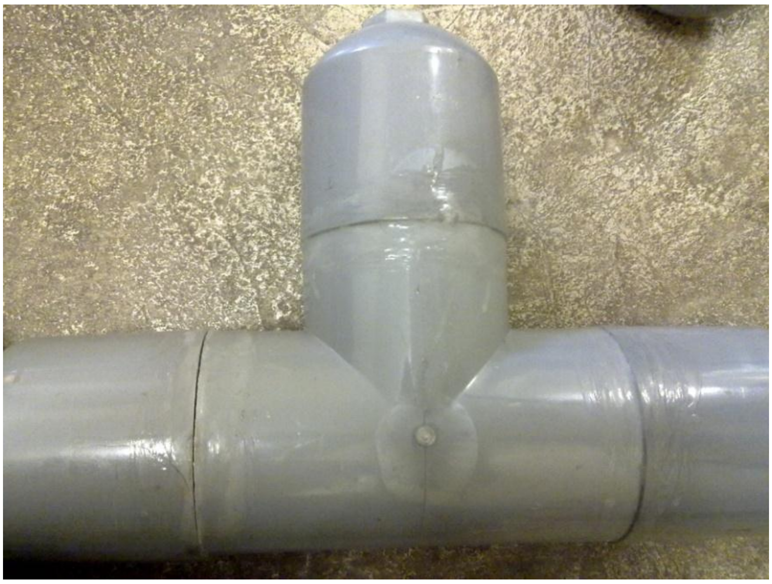

Figure 3.12 Complete assembly of tee model

In figure 3.12 it shows the complete assembled model for tee. In every connection, PVC cement is used to join the cap and tee. PVC cement is also used to attach the socket to the cap. Before connection, the PVC cement is primarily applied to the inside of the fitting and cap. Then after the assembly, thick layer of PVC cement is applied externally right on the connection. This is to prevent any possibility of leakage and ensure the fitting hold the cap tightly.

3.5.3 Testing detail

Testing will be carried out after the model has achieved strong connection and the glue has fully dry. The model will be put on a stand and enclosed by a cover to avoid any danger, while the pump will be held on a trolley. For the testing process, two persons instead of doing it alone are much more recommended. First person is to pump the fitting and the second person to read the pressure reading. Before any vigorous pumping, small pressure is applied to check any leakage. The hose must be ensured to have strong connection to the cap of the model. As mentioned earlier, water will be used and avoid use air. The use of air for testing will be very harmful as it will cause small and detail break of the Polyvinyl Chloride fittings. The fitting will possibly not only break but burst. The burst pressure test will be carried out on both model of with defect and without defect. The depth of the defect introduced might is varied to obtain required relations. For every criteria introduced, a series of tests will be carried out. As soon the fitting starts to break, the pressure recording will be read right away as the pressure will drop quickly as the leakage getting big.

3.5.4 General procedures for testing

a) Fill the fittings with water and check whether there is any leaking at the connection. If there is no leaking, then the experiment can be continued. If there is a leak then apply the solvent cement at the leaking place again.
b) Connect the hose with the pump and to the connector of the assembled fittings.
c) Start the experiment by pumping the test pump until the models collapse or break.
d) Read and record the pressure reading during the collapse of the fittings.
e) If there is a leak after the pressure had been exerted, gluing process will be carried out again but after the model has been fully dried. Usage of epoxy is recommended to produce stronger and leak-free joint.
f) Sixth step is the introduction of defect. Introduce a defect at the middle of the tee section and on extrados for elbow using a drill size of 3.0 mm. Then proceeds to steps 1-4.
g) Repeat step 6 using different depth of local thinned area of the same size of drill.

3.5.5 Defect introduction detail

Defect on the fittings will be introduced by producing local thinned area on the fittings. This kind of defect will symbolize erosion. As mentioned earlier, erosion can be caused either by simple impingement of solid particles on the pipe wall, or by a combination of degradation and embrittlement of the pipe’s surface, allowing the fluid flow to erode the surface. While Polyvinyl Chloride is plastic in general, typically have better resistance to abrasion than most metals, they are still susceptible to erosion and wall thinning due to solids in the process streams. Standard engineering practices, such as using wide sweeps at changes in direction will be useful for Polyvinyl Chloride as well as other materials.

The size of local thinned area introduced is based on theoretical calculation involved as insignificant area or depth of defect will give no change on the collapse load. If the local thinned area is too small, the value of collapse load will still be the same as the one of perfect condition. Introduction of defect is carried out using the vertical drill machine. The size of drilled used is 3mm.Several depth of drilling is introduced on the surface of fittings depend on the thickness of the fittings involved. In the case of elbow, the defect will be introduced on extrados area. The elbow has a thickness of 3mm so the depths introduced will be 1mm and 2mm. In case of tee, it has thickness of 4mm; therefore the depths of defect introduced are 1mm, 2mm and 3mm.

Figure 3.13 (2 mm) defect introduced on tee

In figure 3.13, it shows the defect introduced on surface of the tee. The area of the defect introduced is kept constant in every model, only the depth is varied. The depth of defect introduced in above tee is 2 mm. The wall has thickness of 4 mm, which means there is only 2 mm left by the internal pressure to encounter with the tee breaks. The internal pressure inside the tee is predicted to use the weak spot to break the tee surface. The limit of defect depth is 3 mm as the wall has thickness of 4 mm.Make a defect that too close to its wall limit will give a risk to completely penetrate the wall. In addition, local thinned area that made too deep will cause the experiment to end very fast and this will give a problem in recording the burst pressure.

Figure 3.14 (2 mm) defect introduced on elbow

In figure 3.14, it shows the defect being introduced on the extrados part of the elbow. The defect area for elbow is also kept constant and the depth of defect is made deeper in the next models. The depth limit of defect for elbow is 2 mm as elbow of the dimension tested has 3mm thick of wall. In addition, elbow has lower collapse pressure than tee, so it is vital to ensure the local thinned area made is not too deep as this will give difficulty on the recording data process if the experiment ends too fast. As in tee, the bend movement of the inside internal pressure is predicted to give a great effect on the strength of the elbow's wall. In addition, introducing defect of too small of difference in depth using the vertical drill available is too difficult and risk of completely penetrate the wall.

3.6 TABLE OF RESULT

Table 3.1: Elbow‘s table of result

Defect's Depth (mm)	**Burst Pressure (MPa)**
No defect	
1.0	
2.0	

In table 3.1, it shows the table of result for elbow model. The data for perfect and defected will be combined together in the table. This way, the effect that will be brought by defect on the burst pressure of the tested model can be clearly seen. While walking down through the table, the collapse load is expected to get lower. While in table 3.2, it shows the table of result for tee model. The same thing is applied for tee. The data of perfect and defected tee is combined together. The difference is tee table has more data as the tee is being introduced of more variety of depths.

Table 3.2: Tee‘s table of result

Defect’s Depth (mm)	**Burst Pressure (MPa)**
No defect	
1.0	
2.0	
3.0	

3.7 DATA MEASUREMENT ANALYSIS

The experimental result will be analyzed to see its pattern after defect being introduced. The significant of defected fittings can be reviewed and proves the effect of defected fitting toward the burst pressure of Polyvinyl Chloride fittings. Before the test, the approximation of the burst pressure is being calculated first. The theoretical data is obtained using previous mathematical approach done by Xuan’s, Good all’s and also Miller’s. Then the gauge reading after the test will be compared to the calculated value. It is important to see the how big is the difference between theoretical and experimental value. This will also prove the reliability of the solution done by previous researches on predicting the collapse pressure of PVC fittings whether perfect or defected. The burst pressure also being compared to the standard operating pressure for the Polyvinyl Chloride fittings. This is important to see whether the industrial has put enough safety level on the rating provided.

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

In this chapter, the result and discussion on the result will be explained. The result of this research is obtained from the experiment that has been carried out and theoretical values from related equations of previous researches. The experimental and theoretical value will be compared to see whether there are significant differences or they are just the same. The results will be analyzed and limitations involved will be discussed.

4.2 RESULTS

In this section, both data will be presented which are the theoretical and experimental results which both of them are to be analyzed. There will be a comparison for both them to see whether a significant difference is exist or not between them.

4.2.1 Experimental result

Several experiments had been conducted in order to determine the actual burst pressure of the polyvinyl chloride fittings due to internal pressure. The experiments involved fittings with no defect and with defect introduced on them. In every experiment conducted, the data obtained will be directly recorded in the table of result introduced in the methodology. This is done to ensure valid and reliable data we obtain. Here are the results obtained from the short time hydrostatic burst test:

(1) Elbow

Table 4.1 Experimental result for elbow

Defect (m)	Collapse Pressure (MPa)
None	2.3
0.001	2.0
0.002	1.2

From Table 4.1, total of three PVC elbow models are tested to get their burst pressure. One of them is defected free while another two are defected model with different depths. As the depth increase, the burst pressure is getting lower. However, the drop pattern is inconsistence and the biggest drop of collapse pressure is when 2mm depth of defect is introduced on the third model. This inconsistence might be due to the existence of additional weak spots on the surface of the elbow. This kind of primary defect gives a significant effect on the collapse pressure of the elbow.

Figure 4.1 Cracked perfect elbow

In figure 4.1, it shows the cracked perfect elbow that can be seen to be started on the centre part of the flank area of the elbow. From the cracked pattern, we can see that without defect, the intrados part will be the weakest area or least resistance to internal pressure. The crack not only focused on the centre of the intrados but also propagate of moves to the outer area of the intrados. Ability to burst on the fitting section has proven the practicality of the designed model in obtaining the burst pressure of elbow. The connection and joint are strong enough to face the applied internal pressure. Other part of the model will not burst as they are much stronger than the elbow section. The attachment of the socket to the cap is also proven to be a perfect connection method in connecting the testing model with the hydraulic pump as it seems to stand with the strong internal pressure applied to them without any crack or leakage. The gauge gives a reading of 2.3 MPa for the burst pressure of the cracked elbow. This shows that if there is such magnitude of pressure being applied on perfect elbow in piping system, it will burst. However, the value of 2.3 MPa is too big to reach up to PVC piping application as the weaker straight pipe will burst first before it gives any big effect on the fittings. But if the PVC fitting is used to joint stronger material, the internal pressure involved must be ensured not to reach that magnitude of internal pressure.

Figure 4.2 Cracked defected elbow

In figure 4.2, it shows the cracked on the intrados of defected elbow. Originally, the defect has a circle shape. After fully cracked, the defect shape has changed and it proves that the crack actually propagates to the closest area. For defected elbow, the weakest point is no longer the intrados, but on the defected area. The internal pressure will focus on the weak point and finally breaks the wall. The crack that occurred on the defected zone has proven that local thinned area introduced with difference depth has given significant effects on the burst pressure of the elbow.

(2) Tee

Table 4.2: Experimental result for tee

Defect (m)	Collapse Pressure (MPa)
None	3.4
0.001	3.1
0.002	2.7
0.003	2.4

Table 4.2 shows the experimental result of hydrostatic burst pressure for PVC tee. Total of four models are involved, one of them is defected free while three others are introduced with defect of different depths. Basically the collapse pressure for tee is higher than elbow's collapse pressure as tee has thicker wall. As the depth increase, the burst pressure is getting lower. A defect of 3 mm depth has given a 1MPa difference in collapse pressure compared to the perfect one. As the depth of defect, the resistance to the internal pressure applied has becomes lower.

Figure 4.3 Cracked defected tee

In figure 4.2, it shows the defected tee that has cracked after the hydrostatic burst test. The tee has a defect of 3 mm previously which has 1 mm left for the internal pressure to overcome with. The original shape of defect introduced to tee model is also circle like being introduced for elbow model. After cracked, the cracking shape has changed. There is small propagation of crack on the surface of the tee wall starting from the defect point. The internal pressure to crack the wall at other non-cracked area is much bigger than the defected point. The internal pressure uses the defected point to penetrate the wall.

4.2.2 Theoretical result

Theoretical result for both fittings which are elbow and tee are obtained from their respective solution of estimation by previous researches. The solution that are chosen for the prediction of burst pressure are picked up from the most reliable and practical solution of previous researchers that are widely used by industry today.

(1) Perfect elbow

In order to obtain the theoretical result for the perfect PVC elbow, the formula used is as shown below. Goodall gave the asymptotic solution for Tresca and limited interaction yield criteria for the collapse load P of a pressurized elbow as:

$$P=\frac{\sigma_y t}{r}\frac{(1-\frac{r}{R})}{(1-\frac{r}{2R})} \quad \text{For short elbow, R= r}$$

Where,

P = collapse pressure (MPa)
σ_y = Yield stress for PVC
t =elbow thickness (m)
r = mean elbow radius (m)
R = elbow bend radius (m)

Example calculation

$$P=\frac{44.8(0.003)}{0.04}\frac{(1-\frac{0.04}{0.08})}{(1-\frac{0.04}{2(0.08)})}$$

$$P=2.24\ \text{MPa}$$

Previous research on plastic elbow has lead to Goodall's solution of predicting the collapse pressure of perfect elbow. The solution involved the elbow thickness, mean elbow radius and also bend radius as the main parameters that lead to a ratio that will be multiplied to the PVC yield stress in order to get their collapse pressure of corresponding elbow size. From the calculation, it is proved that the value is close to the experimental value, difference about 0.6 MPa lower than the experimental value. This lower value is act as the safety value as sometimes we cannot handle the existed primary defect that usually occurs on PVC fittings. Goodall solution has given enough parameter to describe the model that being tested.

(2).Elbow with defect

For the theoretical result, we will be using the formula derived by Miller. Folias factor,M must be calculated first

$$M=[1+0.6275\left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)-0.003375\left(\frac{L}{D}\right)^4\left(\frac{D}{t}\right)^2]^{\frac{1}{2}}$$

$$\text{For}\quad \left(\frac{L}{D}\right)^2\left(\frac{D}{t}\right)\leq 50$$

Collapse load of thinned elbow

$$\frac{P_E}{p^*}=\frac{A_o-A}{A_o-AM^{-1}}\frac{(\frac{R}{r}+1)}{(\frac{R}{r}+\frac{1}{2})}$$

Where,

p = collapse pressure (MPa)

p*= collapse pressure for defected free

L = length of local thinned area

D = mean diameter of elbow

A_o= Projection area before local thinning,A_o= Lt

A = Projection area of local thinned area, A = Ld

r = mean elbow radius (m)

R = elbow bend radius (m)

Example Calculation

$$M=[1+0.6275\left(\frac{0.10}{0.08}\right)^2\left(\frac{0.08}{0.003}\right)-0.003375\left(\frac{0.1}{0.08}\right)^4\left(\frac{0.08}{0.003}\right)^2]^{\frac{1}{2}}$$

$$M=4.60$$

$$\frac{p}{p^*} = \frac{3(10)^{-4} - 1(10)^{-4}}{3(10)^{-4} - 1(10)^{-4}(4.60)^{-1}} \frac{(\frac{0.08}{0.04}+1)}{(\frac{0.08}{0.04}+\frac{1}{2})}$$

$$\frac{P_E}{p^*} = 0.86$$

$$P_E = 1.93$$

Crack or material loss on the surface of PVC fittings are actually normal phenomenon. The huge argument is whether the fittings need to be directly changed or still can be used up to certain point. There must a reliable approach that can define the strength of the cracked fittings. Miller has developed a mathematical approach to specifically predict the collapse pressure for defected PVC elbow. This solution allows us to predict the strength left by the fittings. Therefore, a suitable adjustment can be made to ensure the fittings do not be made involved in application that reaches its left strength. This solution by Miller also have the complete parameter to describe the defect involved and also the parameters describing the dimension the fittings involved. The parameters are area of local thinned area, elbow radius and also elbow bend radius. In addition, what makes Miller solution reliable is the calculation of folias factor. Folias factor is the calculation to describe the level of weakening undergoes by the fittings or a weakening factor. The calculation is to be multiplied by the defected free collapse pressure of the elbow of same dimension.

Table 4.3: Theoretical result using Goodall's and Miller's solution

Defect (m)	**Collapse Pressure (MPa)**
None	2.24
0.001	1.93
0.002	1.05

Table 4.3 shows the theoretical data obtained from Good all’s and Miller’s solution. The trend shown by the theoretical value is the same as the experimental data. When defect is introduced, the collapse pressure drops to a lower value and as the depth getting deeper, the collapse pressure is getting lower. The biggest drop is when 2 mm depth of defect is introduced to the elbow.

Table 4.4: Comparison between experimental result and theoretical result for elbow

Defect (m)	Experimental Collapse Pressure (MPa)	Theoretical Collapse Pressure (MPa)
None	2.3	2.2
0.001	2.0	1.9
0.002	1.2	1.0

Table 4.4 shows the comparison between experimental and theoretical result for elbow. The smallest different that exit between both data is 0.1 MPa in the case of defected free and 1mm depth of defect which gives 4% of difference. The largest difference that exists between both data is up to 0.2MPa in the case 2 mm depth of defect which gives 8% difference. The percentage of difference between experimental and theoretical data for the case of elbow is in the range of (4-8) percent which is a small percentage of difference. This infers that the theoretical calculation is reliable enough to predict the collapse pressure of the elbow.

(3) Perfect Tee

Xuan developed an approximate solution for plastic limit pressure of equal diameter tees. The value of j^p is weakening factor of equal diameter tee under internal pressure

$$P_L = \frac{\sigma_f j^p 2T_m}{D}$$

$$j^{p}=\frac{0.393\frac{T_m}{D}+2\sqrt{\frac{T_m}{D}}-0.215\frac{r}{D}}{0.215(\frac{r}{D})^2+0.25+0.5\frac{T_m}{D}+0.429\frac{rT_m}{D^2}-0.535(\frac{T_m}{D})^2+2\sqrt{\frac{T_m}{D}}-2\frac{T_m}{D}\sqrt{\frac{D}{T_m}}}$$

D = mean diameter of pipe

P_L =limit pressure without crack

P_c =limit pressure of cracked tee

r = radius transition between branch and run pipe

T = mean wall thickness of run pipe

T_m =average value of actual wall thickness

σ_f = flow stress

J^p = weakening factor of equal diameter tee under internal pressure

Example calculation

$$j^{p}\ =\frac{0.393\frac{T_m}{D}+2\sqrt{\frac{T_m}{D}}-0.215\frac{r}{D}}{0.215(\frac{r}{D})^2+0.25+0.5\frac{T_m}{D}+0.429\frac{rT_m}{D^2}-0.535(\frac{T_m}{D})^2+2\sqrt{\frac{T_m}{D}}-2\frac{T_m}{D}\sqrt{\frac{D}{T_m}}}$$

$$j^{p}=\frac{0.393\frac{0.004}{0.08}+2\sqrt{\frac{0.004}{0.08}}-0.215\frac{0.04}{0.08}}{0.215(0.5)^2+0.25+0.025+0.429(0.025)-0.535(0.05)^2+2\sqrt{0.05}-0.1\sqrt{20}}$$

$$= 1.063$$

$$P_L=\frac{\sigma_f j^{p} 2T_m}{D}$$

$$P_L=\frac{45(1.063)2(0.004)}{0.08}\ =4.78\text{ MPa}$$

In piping, fittings are the strongest parts in the joint. However, there is a vital need to predict the collapse pressure of the fitting as there is a possibility of inconsistent internal pressure that may exist during the bend. In case of tee, Xuan has developed a solution to specifically predict the burst pressure of equal diameter tee. Xuan solution is well-known to be a practical estimation of tee collapse pressure in industrial application. It involves enough parameters to describe the dimension of tee involved such as the diameter of the tee, the wall thickness , the run pipe thickness and radius transition between branch and run pipe. In addition, it also the flow stress which stress of water flow inside the fitting. The calculation for weakening factor also involved in the solution. The involvement of many factors makes the prediction better. The experimental burst pressure for defected free tee is 3.4MPa while the theoretical value gives higher value of 1.38 MPa differences which is 4.78 MPa. The theoretical predict that the tee has higher strength. The low experimental value of the tee may due to the additional primary defect existed in the tee. However, the percentage difference exist between both value is only 40%, which is still acceptable.

(4) Defected Tees

In case of cracked tee, from the viewpoint of the effective wall thickness and the equivalent straight pipe concept, Xuan developed a semi-experiential solution for the limit load of the cracked tees under internal pressure. For the case of crack at the flank area the solution is

$$P_c = \frac{2\sigma_f T_m}{D} j^p \frac{1-\left(\frac{a}{T_m}\right)^2}{1-\frac{\left(\frac{a}{T_m}\right)^2}{\left[\frac{1+2.1c^2}{DT_m}\right]^{\frac{1}{2}}}}$$

Where

a = depth of crack

T_m = average value of actual wall thickness

D = mean diameter of pipe

σ_f = flow stress

c = half length of crack

J^p = weakening factor of equal diameter tee under internal pressure

Example calculation

$$P_c = \frac{2(45)(0.004)}{0.08}(1.063)\frac{1-\left(\frac{0.001}{0.004}\right)^2}{1-\frac{\left(\frac{0.001}{0.004}\right)^2}{\left[\frac{1+2.1(0.0015)^2}{0.008(0.004)}\right]^{\frac{1}{2}}}}$$

P_c = 4.49 Mpa

With the presence of defect, there are huge possibilities for the fitting to burst instead of the thinner straight pipe. Therefore, it is a vital approach to predict the left strength of defected fitting especially for tee. Xuan has provided both solution for defect fee and defected equal diameter tee. The parameters involved are also specific in describing the dimension of tee being tested which is the mean diameter of the tee wall thickness. In addition, in order to predict the defected tee, the crack parameter must also involve which are the length and depth of the crack. Other than, the flow stress inside the tee is included like the previous xuan solution for defect free tee. The last parameter that play important rule is the weakening factor.

Table 4.5: Theoretical result using Xuan's solution

Defect (m)	Collapse Pressure (MPa)
None	4.78
0.001	4.49
0.002	3.53
0.003	2.10

Table 4.5 shows the theoretical data obtained from Xuan solution for both perfect and defected equal diameter tee. The trend present for theoretical data is the same as experimental data. The highest burst pressure will be the one of defect free tee. As the depth of defect getting deeper, the collapse pressure drops significantly.

Table 4.6: Comparison between experimental result and theoretical result for tee

Defect (m)	Experimental Collapse Pressure (MPa)	Theoretical Collapse Pressure (MPa)
None	3.4	4.78
0.001	3.1	4.49
0.002	2.7	3.53
0.003	2.4	2.10

4.2.3 Theoretical data comparison

For another theoretical result, we will be using the formula derived by Netto . This will be applied to both fitting.

$$\frac{P_{def}}{P}=\left[\frac{1-\frac{d}{t}}{1-\frac{d}{t}\left(1-\left(\frac{c}{\pi D}\right)^{0.4}\left(\frac{l}{10D}\right)^{0.4}\right)}\right]^{2.675}$$

Where,

P_{def} = collapse pressure of the defective pipe (bar)

P = collapse pressure of the perfect pipe (bar)

D = outside diameter of the pipe (mm)

d = maximum depth of the defect (mm)

c = maximum width of the defect (mm)

l = maximum length of the defect (mm)

t = wall thickness of the pipe (mm)

(1)Elbow

Table 4.7: Comparison of theoretical result between Miller and Netto for elbow

Defect (m)	Theoretical collapse pressure using Miller solution (MPa)	Theoretical Collapse Pressure using Netto (MPa)
0.001	2.20	2.17
0.002	1.90	2.00

(2)Tee

Table 4.8: Comparison of theoretical result between Xuan and Netto for tee

Defect (m)	Theoretical collapse pressure using Xuan solution (MPa)	Theoretical Collapse Pressure using Netto (MPa)
0.001	4.49	4.70
0.002	3.53	4.50
0.003	2.10	4.00

4.3 DISCUSSION

From the result shown in Table 4.1, we can see that the actual burst pressure in defected free elbow case is 2.3 MPa which is higher than the pressure rating given by industry which is 1.5 MPa for all 3 inch fittings. This proves that rating given by industry is designed to be smaller than the actual burst pressure to increase safety. The same situation is in the case of tee. From table 4.2, the collapse pressure of defected free tee is 3.4 MPa which is much higher than the industrial rating. The result in table 4.1 also shows that as the depth of defect introduced on the extrados of the elbow increases, their collapse pressures are getting lower. The wall of the PVC fittings is getting weakened and less resistance to the circumferential stress or internal pressure being applied as the depth of defect increase and as a result, the collapse load getting smaller. The decrease of collapse load as the defect getting deeper also happens in tee case. From Table 4.2, there will be a significant drop of break pressure of the tee in every mm increase of depth of defect. Theoretical calculation to obtain the burst pressure of fittings has been derivate previously in several researches. The question is whether how efficiently the theoretical calculation can represent the actual burst pressure.

The burst pressure for defected free elbow is predicted using Goodall's solution. The calculated value is 2.24 MPa .The difference between the theoretical and experimental value in case of free defect elbow is 0.6 MPa. The theoretical value has lower burst pressure. The percentage of difference between these two values is 26 %. Small percentage of difference is involved. Then for the case defected free tee, Xuan solution is used. The calculated value obtained is 4.78 MPa and this give significant difference of 1.38 MPa between calculated and experimental value of defect free tee and 38% difference is involved. In case of defect free tee, the theoretical value has higher value of burst pressure. However, the small value of experimental collapse pressure may sometimes due to primary defect of the fitting itself. In addition, the difference of collapse load value between theoretical and experimental in case of defect free tee is still acceptably small.

In case defected elbow, Table 4.4 shows that there is a consistence small difference between the theoretical and experimental burst pressure. This concludes that Miller's solution is a good representative solution for defected collapse load value. While in the case of defected tee, Xuan's solution give consistently higher value of collapse load compared to the experimental value. This is can be seen from Table 4.6. However the difference is not big and Xuan's prediction is still efficient to predict the collapse load of defected tee. The prediction solutions for fittings are still considered as a few. In order to see the reliability of theoretical predictions for fitting, another theoretical solution is used or both fittings. Formulation from Netto is chosen. Table 4.7 shows comparison between theoretical value from Miller and Netto for elbow case. There is only a small difference between them. For example, in 0.001 mm depth defect, the collapse pressure obtained from Miller equation is 2.20

MPa while the collapse pressure calculated from Netto is 2.17 MPa.It concludes that Netto formulation is reliable in predicting the collapse load of elbow.

Then from Table 4.8 for comparison between Xuan solution and Netto, the there are a quite big difference between them. Calculate burst pressure for tee of 0.002 mm depth of defect from Xuan solution is 3.53 MPa while Netto gives 4.5 MPa. This proves that Netto solution is less reliable for predicting collapse pressure for tee. The difference in theoretical and experimental value is caused by irregularity of structures in fitting, both elbow and tees. Each part throughout the whole fitting structures has slight difference in their strength. The biggest difference for example is between the extrados and intrados in elbow. Extrados portion is slightly stronger than intrados. This difference will give significant change in the collapse burst pressure of experimental data. In addition, the theoretical calculation is derived such way to give lower value. This is to act as maximum operating pressure for the fitting. Such calculation is used for the pressure rating in piping industries. However, the experimental value in ideal condition must be higher than the one that obtained in real experimental situation. This is due to the structures aging in the PVC fitting structures due to the environment exposure.

Another cause is the primary defect that occurs during manufacturing. This affects the strength of the fitting structures. In addition, chemical such as glue will also lead to the softening of PVC structures. The glue will have chemical reaction with the PVC During the time where the experiments were conducted, there are several problems and limitations that we encountered. As example, there were leakages occurred during the experiments. This is because the lack of experiences handling with PVC pipes and joining them with connectors. The building of the samples for the experiment as example need a very thorough work as the connection need to withstand high pressure in order to make sure that the pressure is released at the body of the PVC pipe rather than broke out at the connections.

A long period of time was used in order to perfect the experiment before the real experiment was finally conducted. Apart from that, there are also with the price to make the samples. This is because components such as PVC cap is very costly and once the cap is joined with the PVC pipes, the cap cannot be reused as it stick with the pipes almost permanently. Therefore, if there is a mistake then a new cap had to be bought this means more money. Besides the cap, the Araldite that been used as the final touch up to strengthen the bonding between the cap and the pipe is also very costly. The need to finish up a sample is almost equal to a set of Araldite itself. Therefore, the cost to conduct the research is quite high. The items for the experiment are also sometimes very hard to be found. As example, the hydraulic test pump that had been used for the research is hard to be found. Besides that, the chemicals that supposedly to be used to clean the surface of the pipes before the PVC cement is put onto the surface is very hard to be found. Therefore, the Araldite had to be introduced in order to add more strength to the bonding between the PVC pipes and the caps.

CHAPTER 5

CONCLUSIONS

5.1 Conclusion

Basically, the main objective of this project is to get the actual burst pressure of fitting which are elbow and tee both defected and defect-free fittings due to internal pressure. The objective is met by conducting series of short-term hydrostatic test that involve elbow and tees. From the results obtained, it proves that the actual burst pressure for fitting is lower than the theoretical value calculated and pressure rating from industry but still in acceptable difference. This is happened in both fittings. There are many factors that lead to the drop in collapse pressure even in fitting that has not been introduced to any defect. Primary defect during production and chemical reactions are among of the factors.

From the main objective has allowed us to see the effect of defected or corroded fittings that occurs on the PVC surface has brought to its collapse pressure. There are significant differences in the value of collapse pressure between defect free and defected fittings. The flow and circumferential stress will use the weak spot caused by the defect to break the fittings starting from the local thinned area. As the depth of local thinned area increase, the collapse load will become lower and lower.

The conclusion reached by the study firstly, the usage of fittings that involves high pressure must consider a lower value of collapse pressure compared to the rating pressure given provided by industry or the calculated collapse pressure from theoretical solution. In addition, this research also allow us to evaluate the defect that occurred on fitting whether it is accepted or not as the cost of changing new fitting is huge .In case of elbow, defect on intrados must be taking seriously as intrados area has the lowest collapse pressure compared to the other location. For final conclusion, the actual experimental burst pressure of fittings give us to see the reality of fitting bursting and as a guidelines of handling high internal pressure involving PVC fittings.

5.2 Future research and Recommendations

The research can be further expanded to ensure the better performance. Several areas could be investigated such as:

i. The best method of jointing fittings to safely carry out hydrostatic test without any leaking

ii. Better method of crack introduction that will give equal depth along the crack especially for curve part such in elbow.

iii. Introducing multiples type of defect on different location such in elbow, the defect can be introduced on the extrados, crown and also intrados.

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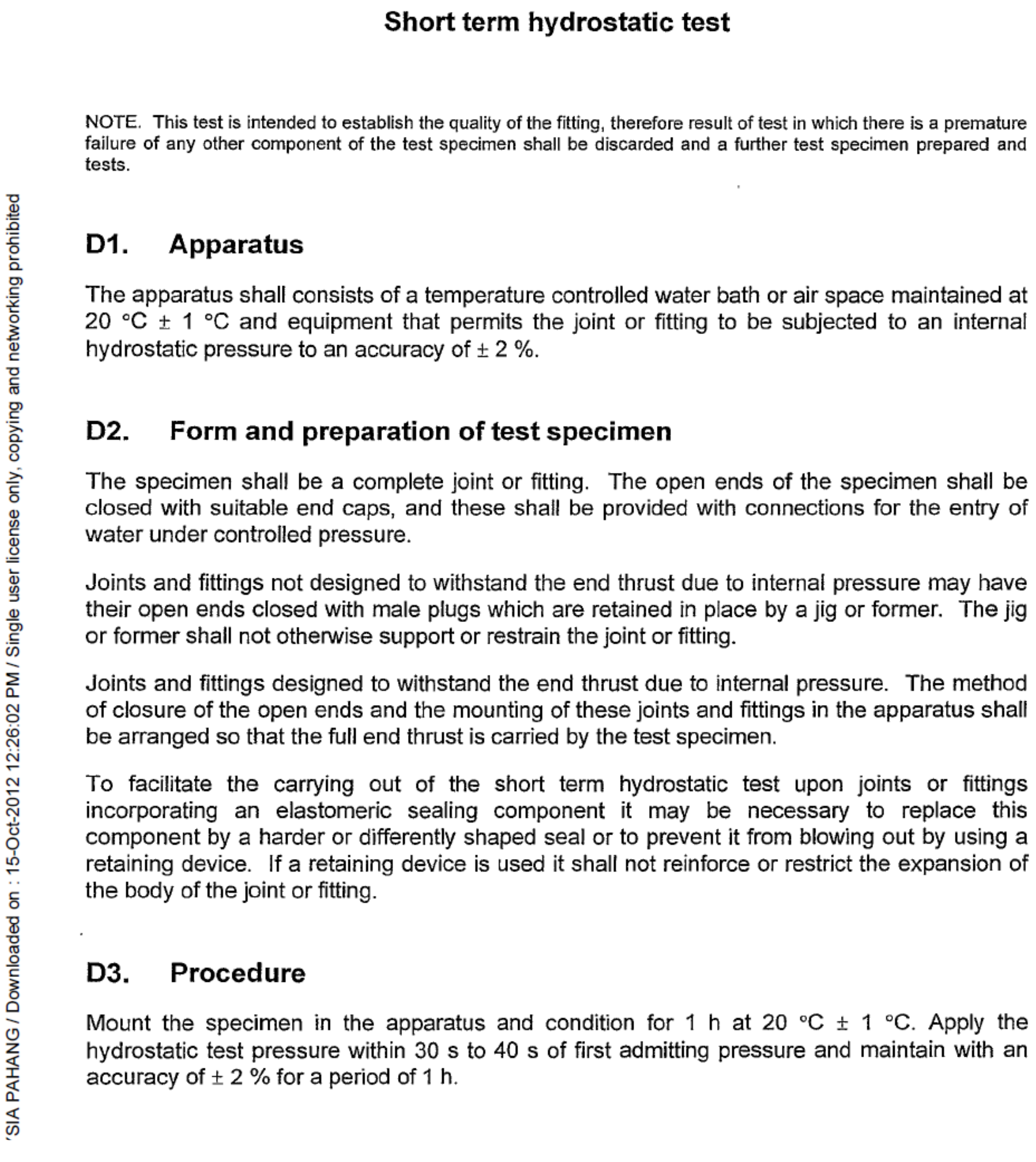
Appendix A

Figure A-1 Standard Procedures for Short Term Hydrostatic Test



Short term hydrostatic test

NOTE. This test is intended to establish the quality of the fitting, therefore result of test in which there is a premature failure of any other component of the test specimen shall be discarded and a further test specimen prepared and tests.

D1. Apparatus

The apparatus shall consists of a temperature controlled water bath or air space maintained at 20 °C ± 1 °C and equipment that permits the joint or fitting to be subjected to an internal hydrostatic pressure to an accuracy of ± 2 %.

D2. Form and preparation of test specimen

The specimen shall be a complete joint or fitting. The open ends of the specimen shall be closed with suitable end caps, and these shall be provided with connections for the entry of water under controlled pressure.

Joints and fittings not designed to withstand the end thrust due to internal pressure may have their open ends closed with male plugs which are retained in place by a jig or former. The jig or former shall not otherwise support or restrain the joint or fitting.

Joints and fittings designed to withstand the end thrust due to internal pressure. The method of closure of the open ends and the mounting of these joints and fittings in the apparatus shall be arranged so that the full end thrust is carried by the test specimen.

To facilitate the carrying out of the short term hydrostatic test upon joints or fittings incorporating an elastomeric sealing component it may be necessary to replace this component by a harder or differently shaped seal or to prevent it from blowing out by using a retaining device. If a retaining device is used it shall not reinforce or restrict the expansion of the body of the joint or fitting.

D3. Procedure

Mount the specimen in the apparatus and condition for 1 h at 20 °C ± 1 °C. Apply the hydrostatic test pressure within 30 s to 40 s of first admitting pressure and maintain with an accuracy of ± 2 % for a period of 1 h.