Constitutive Modelling of Polyimide Pipeline for Cryogenic Applications

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***Abstract*-Polyimide pipelines are used as a part of fluid transmission in cryogenic engines. The low density and high flexibility makes this material ideal for accommodating thermal stresses under large thermal gradients. Being a new material, its properties and behaviour under different loading conditions are mostly unknown. Polyimide pipes are made by manually winding polyimide tape on a bentonite mandrel which is later dissolved and removed after the curing of the product. Structural properties of the polyimide pipes are highly process dependent, even though material properties of the polyimide film (Kapton DuPont) are available. The main objective of the study is the characterisation of the material through experimental and finite element analysis. The actual behaviour of the polyimide pipe under different loadings would be studied using SHELL elements. Also the effect of insulation will be studied in comparison with similar bare pipelines. An attempt was made to study the effect of aramid coating over polyimide pipeline at LN2 using the young's modulus obtained in the studies by considering aramid fibres as orthotropic shows that aramid have a significant role in providing compressive strength to the pipeline.**

Keywords- Polyimide pipelines; Bentonite mandrel; Finite Element model; Cryogenic;

I. INTRODUCTION

India now has the ability to put satellites weighing more than two tonnes in orbit, joining the elite club of the U.S., Russia, France, Japan and China who have mastered this perilous technology of using cryogenic propellants such as liquid oxygen at 90 K and liquid hydrogen at 20 K. The cryogenic stage employs the use of polyimide pipes, which has high flexibility, low density and accommodates high thermal deformation. In human body how much the veins are important like that way pipelines are the artery of the cryogenic application in space vehicles.

Fig. 1. Polyimide Pipeline

Polyimide pipeline is a unique material which is extensively used in cryogenic rocket stage applications for use as plumbing line material. The significance of the material is that it has very low modulus of elasticity and density compared to steel; which is the other material widely used in cryo stage. These properties are essential to take up the large thermal loads generated at cryo temperature during different regimes of operation. The peculiar properties of discussed above makes the polyimide pipeline more demanded and meant for further research in the cryogenic application.

However, polyimide pipes, unlike polyimide tapes, are composites and manually made. Thus standardisation of these pipes is not possible. Polyimide pipes need to be characterised to predict its behaviour under various loading conditions. The pipes are loaded to displacements well below the elastic limit. Further extrapolation is carried out through finite element analysis.

II. POLYIMIDE PIPELINE

A polyimide pipe is basically polyimide tape wound around a solid core. Polyimide tape, 25mm wide and 20µm thick is used. It does not have self-sticking properties. Therefore, it is coated with FEP (Fluorinated Ethylene Propylene) on one side. A bentonite mandrel of desired shape is made with steel adapters at the end. Polyimide tape is wound over the mandrel with 50% overlap. It is taped at the ends to the steel adapters since it has a tendency to peel off. FEP also does not have sticking properties at the room temperature. Thus the pipe formed has to be cured at elevated temperature. The fabrication technique is summarized in Figure 2.

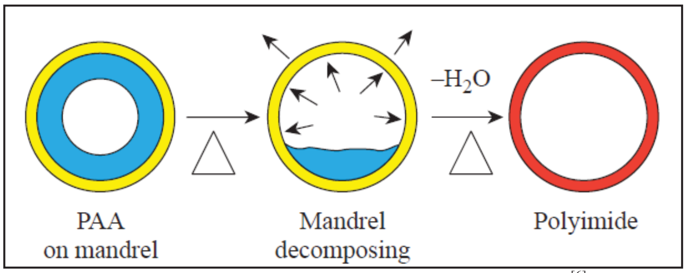

Fig. 2. Sequence of operations used to make polyimide shells [6]

Fig. 3. Bentonite mandrel arrangement and winding

While curing, FEP melts. After curing, FEP solidifies again sticking the two polyimide surface together. The pipe is coated with aramid fibres to improve surface finish, structural stiffness and reduce mechanical wear of polyimide tapes. Curing temperature has an effect on the strength of polyimide. Thus, curing temperature should be wisely chosen.

A. Mechanical properties of polyimide pipeline

- Very low modulus of elasticity
- Low density compared to steel
- Take up the large thermal loads generated at cryo temperature
- Different mechanical properties along hoop and meridional directions
- Low specific gravity
- Low stiffness
- Ability to retain higher percentage elongation at cryogenic temperature
- Withstand thermal shock and inherent
- Flexibility

B. Importance Of Polyimide Pipeline

The primary design parameter for the polyurethane component of a pipe support is density because this determines the compressive strength. For components used in pipe supports with densities from 10 to 40 pounds/cubic foot (160 to 640 kg/cubic meter), particularly those produced in moulds, the compressive strength is essentially the same in all directions. Thermal conductivity is another design parameter of concern for the pipe support designer. For rigid foam polyurethane's, thermal conductivity increases with density. Fortunately, the 10 to 40 pound-density materials are less sensitive to the choice of blowing agent and aging, two concerns for industries which use low density foams to achieve very low thermal conductivity.

In this paper the effects of PUF insulation is also considered. In experiment and analytical investigation polyimide pipeline with PUF insulation and without PUF is studied and the different advantages and effects of PUF are verified.

III. POLIYIMIDE PIPE TEST RESULTS

Different load test like three point bending test and cantilever loading test are conducted for the material characteristics of polyimide pipelines at product level. Effects or aramid coating on polyimide pipelines are also attempted by comparing test results and finite element analysis. The results obtained through tests emphasise an outlook towards young's modulus of polyimide pipeline at different pipe conditions.

The basic problem of stress analysis of polyimide pipes involves determining its material properties in various loading directions. Theoretical determination of the material properties is not sufficient since curing temperature and tension in the polyimide tape is not taken into account.

A. Three Point Bend Test

Test Procedure:-

The pipe analysed had the following dimension:

1. 1000 mm length, with end steel adapters
2. 1.2 mm wall thickness (as measured on the ends of the pipe and averaged, assumed uniform)
3. Inner diameter 55 mm
4. Length of the steel adapter 55 mm.

Three point bending test is carried out in UTM. The loading set up is arranged as shown in fig. 5.2. End condition is provided as simply supported and the load is provide up to a maximum of 25Kg is applied at the middle portion of the pipeline through a disc of diameter 100 mm and thickness of 50 mm.

Fig. 4. Three point bending test experimental set up in UTM (Universal Testing Machine)

Discussion on Test Results:-

In 3 point bending test after loading local crushing was visible at the point where point load is applied instead of buckling since polyimide is very flexible and of layered texture. Local crushing may be due to the high compressive stress in the top fibre at the point of loading. Hence the 3 point bending test is obsolete in polyimide pipeline bending test and cantilever loading test is carried out which provides the maximum failure condition. This could not meet the design specifications and hence decided to change the test method. However, the properties are evaluated from the test data up to the range it has been tested.

B. *Cantilever loading experiment*

The most common method to measure the fatigue resistance of a material is the cantilever beam test. A cylindrical specimen is mounted on a motor driven chuck with a weight suspended from one end. As the specimen is loaded periodically, it is stressed in tension and compression under the force of gravity.When the specimen is loaded, the stress at any given point goes through a complete cycle from maximum tension to maximum compression.

Test Procedure:-

Polyimide pipeline (test article) is assembled to the base plate as shown in the Fig. 5. and split halves are mounted on the pipeline with M6 fasteners applying torque of $5.5^{\pm 0.5}$ Nm. Subsequently split halves are fastened to the base plate with M6 fasteners applying torque of $5.5^{\pm 0.5}$ Nm. The test is carried out in two phases. In phase one the load is applied with an increment of 0.5Kg until 35mm deflection is achieved. Then load is released with a decrement of 0.5Kg to reach its initial conditions. This cycle is to be repeated for two times. Stabilization time was given between loading & unloading till reading was stable. Also, deflection values were noted for each load increment or decrement. 4 Nos. of displacement transducers are mounted to read to deflection at location as shown in Fig 5. Also 6 Nos. of Strain gauges are bonded on one indigenous pipeline. In phase two the tests are repeated with pipelines without insulation.

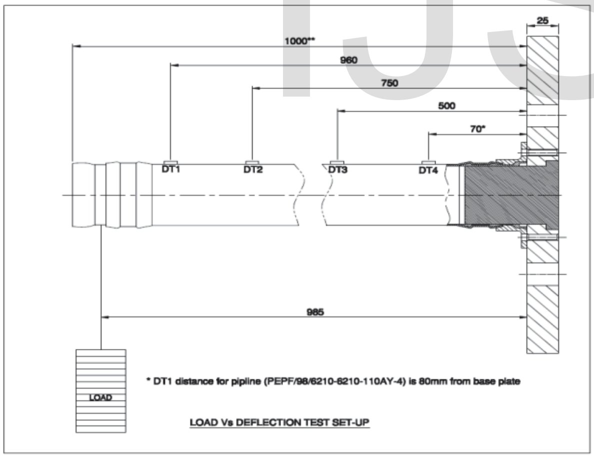

Fig. 5. Cantilever load testing set-up

Fig.6 Test set up for cantilever loading of polyimide pipeline

TABLE I HARDWARE USED FOR CANTILEVER LOAD TESTING

H/w. Idn No.	Remarks	Thickness (mm)
R1	Russian uninsulated (Hardware 1)	$1^{+0.2}$
R2	Russian uninsulated (Hardware 2)	$1^{+0.2}$
R11	Russian insulated (Hardware 1)	$1^{+0.2}$
R22	Russian insulated (Hardware 2)	$1^{+0.2}$
I1	Indigenous Uninsulated	2.68/3.12*
I2	Indigenous insulated	2.10/2.85*
I3	Indigenous Uninsulated	2.17/2.85*

Discussion on test result for cantilever loading:-

Test conducted at room temperature is carried out to generate load Vs deflection data. This data will be used for finding out the Young's Modulus (E) value of both uninsulated & insulated pipelines of Russian and indigenously developed.

In loading test the deflection obtained from uninsulated polyimide pipeline is more compared to Polyurethane Foam (PUF) insulated polyimide pipeline. The maximum deflection obtained from the four strain gauge results are used for plotting load deflection curves and thus the young's modulus.

IV. FINITE ELEMENT ANALYSIS OF POLIYIMIDE PIPELINE

This chapter deals with finite element simulation of the beams which includes selection of element type, creating beam geometry, meshing and obtaining the results. Then the results are validated with the experimental test results.

A. Finite Element Modelling

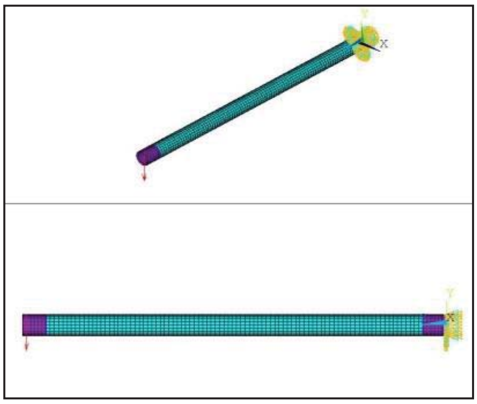

Fig. 7. Finite element model of polyimide pipeline with adapters

The pipe was modelled using 3D shell elements (SHELL181 in ANSYS element library). It gives the benefits of a simpler geometry, better mesh, easy contact element formation and high solving speeds. A better mesh is defined as the one having rectangular(2-D) or cuboidal(3-D) elements. Triangular and tetrahedral elements are not recommended since these are stiff in bending, leading to erroneous results. SHELL181 is suitable for analyzing thin to moderately thick shell structures.

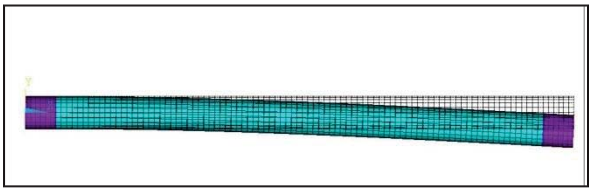

Fig. 8 Deformation pattern obtained from ANSYS FE analysis for uninsulated polyimide pipeline (sample)

It is a 4-node element with six degrees of freedom at each node translations in the x,y and z directions and notations about the x, y and z axes. If the membrane option is used, the element has translational degrees of freedom only.

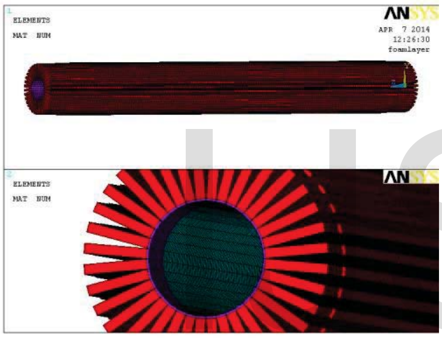

Fig. 9 ANSYS model for PUF insulated polyimide pipeline (sample

V. COMPARISON BETWEEN TEST RESULTS & FEA

Using finite element model deflection values are obtained for the same loading condition of test conducted and the corresponding thickness matches with the test results are studied. Polyimide pipeline of same size (ID 55 mm) is studied using FE model for the measured thickness values.

There is no measured thickness value for Russian pipelines, thus nominal thickness is considered for study. But for indigenous pipelines (manually wound) the thickness varies. Therefore, the variation of FE analyses results for the minimum and maximum thickness w.r.to average thickness have been studied and found to be 5 to 15 %. Thus the study is carried out for nominal or average thickness of the pipe line.

A. Evaluation Of Young's Modulus From Test Results

Equation used for finding young's modulus (e),

- Young's modulus (for cantilever loading) is calculated manually using the formula

$$E = \frac{PL^3}{3\delta I} \quad (1)$$

Where, P = Loading (in N),L = Effective length of loading, I = moment of inertia, δ = Deflection from test

- Moment of inertia for hollow pipeline

$$I = \frac{\pi(Do^4 - Di^4)}{64} \quad (2)$$

Where, Do = Outside diameter, Di =Inside diameter

Evaluation of E_{avg} value at average thickness:-

TABLE II. Evaluation of young's modulus of Polyimide pipelines from test data

Types of polyimide pipeline	**Avg Thickness (mm)**	**Thickness of PUF insulation (mm)**	**E_{avg} value from test result of PP (N/mm^2)**
Russian (insulated) 1	1.5*	30	3405
Russian (insualted) 2	1.5*	30	2622
Indigenous (insulated)	2.5	30	3220
Russian (uninsulated) 1	1.5*	--	2298
Russian (uninsulated) 2	1.5*	--	2071
Indigenous (uninsulated)	2.9	--	2349
Indigenous (uninsulated)	2.5	--	2641

** not measured value(may vary from 1 mm to 2 mm)*

B. Validation of FE model assuming the material as isotropic and determination of E of polyimide pipeline at LN2

FE analyses have been carried out assuming material as orthotropic and isotropic. For studying the variation of isotropic and orthotropic properties of pipelines the isotropic characteristics and is compare with the test result.Inputs for isotropic and orthotropic pipelines are given from the young's modulus obtained from test results. The orthotropic properties are provided by different parameters like meridional (m), tangential (θ) and radial (r) direction. The results are checked with the transverse deflection, bending stress and strains. The young's modulus for each pipeline in meridional direction is given from test results while in hoop direction 3500 N/mm^2 at 300K temperature, 1.67 g/cc density and 45 MPa ultimate strength are given for all the pipeline. Sample inputs are provided in THE table .For Indigenous uninsulated pipeline (t_{avg}=2.9 mm) the strain values are also noted in the cantilever loading test by keeping strain gauges at a distance of 115 mm from the fixed end . Loading is done for the maximum load of 5.5 Kg, since the strain data showed linear trend during loading and unloading.

TABLE III. SAMPLE SPEC VALUES USED FOR FE ANALYSIS FOR ORTHOTROPIC AND ISOTROPIC CONDITIONS ON RUSSIAN UNINSULATED PIPELINE

Properties for Pipes	**Young's modulus (test res.) (MPa)**	**Poisson's ratio**	**Shear Modulus (MPa)**
Orthotropic	$E_\theta = 3500$	$\nu_{m\theta} = 0.35$	$G_{m\theta} = 1296$
	$E_m = 2298$	$\nu_{mr} = 0.001$	$G_{mr} = 1148$
	$E_r = 2298$	$\nu_{r\theta} = 0.001$	$G_{r\theta} = 1148$
Isotropic	2298	0.34	--

TABLE IV. COMPARISON OF DEFLECTION VALUES FEA VS TESTS

Type of polyimide pipeline	**Deviation of deflection value(test Vs FEA) for avg thickness (%)**		
	For E from lit. (Isotropic)	**For E from test (Isotropic)**	**For orthotropic properties (lit.)**
Russian (insulated) 1	18	0.07	3
Russian (insualted) 2	20	0.23	5
Indigenous (insulated)	14	1.58	11
Russian (uninsulated) 1	5	1	6
Russian (uninsulated) 2	18	2.7	5
Indigenous (uninsulated)	4	2.5	4
Indigenous (uninsulated)	20	0.13	13

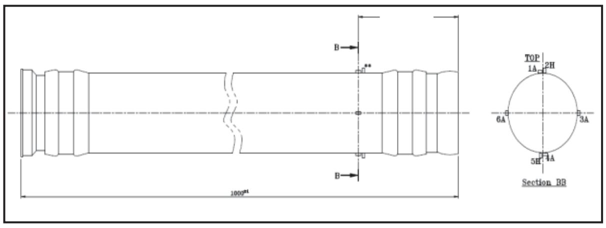

Fig. 10. Position of 6 nos. of stain gauges

Deflection values obtained for isotropic and orthotropic properties are compared with test results. For isotropic condition, deflections are predicted for the Young's modulus values obtained from test and literature. From the comparison it is visible that for isotropic condition the test results are matching with FEA results within a limit of 3 % while for orthotropic condition, it varies from 3 to 13 %.

In strain value comparison on indigenous pipeline uninsulated (I1) for FEA and Test results for the maximum load of 5.5 Kg is done since the strain data showed linear trend during loading and unloading. The polyimide material is assumed as isotropic for the analysis invoking the Young's modulus value along meridional direction. The meridional strains are matching with the test results with 5 to 9% variation.Using FE analysis the young's modulus of PUF is obtained by providing different iteration of values of young's modulus PUF which matches the deflection curve of the test results. Thus the young's modulus of PUF is deduced from FE analysis effectively. Since the values of cycle 1 and cycle 2 are approximately same only cycle 1 is mentioned in the following sections. However the Young's modulus value of polyimide obtained from test is used for the analyses. Like in previous section with different trials in FE model young's modulus of PUF is deduced as follows.

For Russian insulated pipeline the deflection curves from test results and FEA values are matching when the E_{PUF} values are increased to a range of 10 to 17 N/mm^2. For indigenous insulated pipeline the deflection curve matches when the Epuf is around 25 N/mm^2

Young's modulus of different polyimide pipe at room temperature was determined in the previous sections. In order to find the young's modulus of polyimide pipe at LN2 from FEA using test data a polyimide pipe section of 1000mm with 55 mm internal diameter and thickness 2.3 mm is considered and the inputs are provided as shown in table below for matching the test results. Several trials for young's modulus of pipeline are made for matching the deformation value of test results and FEA. Finally the young's modulus of polyimide pipe at LN2 condition was determined using FEA analysis. Young's modulus value of PUF is assumed to be that at room temperature assuming small variation in E value at cryogenic temperature compared to RT. Similarly for LN2 condition using FEA analysis with different trials by adopting E for PUF as 25 N/mm^2, 0.4 N/mm^2 as internal pressure, load applied is 37.2 Kg the deflection value of 91.8 is matched when E=5500 N/mm^2 is applied for pipeline. Hence E value of polyimide pipeline at LN2 is obtained as 5500 N/mm^2.

C. Effects of Aramid Coating on polyimide pipeline

For finding the effects of aramid coating LOX feed line (at LN2) was taken as shown in figure. In the testing of LOX feed line one end is mounted on a wall and at the other end pull load of 410 N was given horizontally. The displacement obtained was noted as 28 mm horizontally, 11.7 mm vertically. The meridional strain was 2962 as compressive strain and 3966 as tensile strain. In order to simulate FE model material properties of aramid was given as orthotropic and pipeline was considered as isotropic. The young's modulus of pipeline at LN2 temperature was given as 5500 N/mm^2. This young's modulus was determined by FEA analysis by using straight polyimide pipeline (2.3mm) at LN2 in the previous sections.

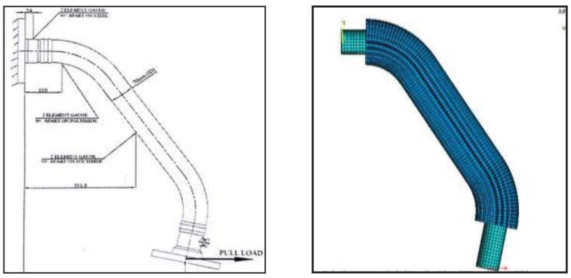

Fig.11. LOX feed line test setup and FE model

TABLE V. COMPARISON BETWEEN FEA AND TEST RESULTS

Results	With aramid coating & PUF insulation		
	FEA-50μm thick	FEA-30μm thick	Test Results
Displacement-horizontal (mm)	31.4	29.8	28
Displacement- vertical (mm)	12.5	11.78	11.7
Meridional strain	-3443/3256	-3327/3356	-2962/3966

Using the properties of the polyimide pipeline at LN2 condition with PUF insulation deduced in the previous sections are assigned as isotropic and orthotropic properties of aramid at room temperature given as in the FE model as shown in above table.

FE model are developed for aramid having thickness as 50 μm and 30μm and it is found that the deflection obtained from tests are more matching for the results of FE model with 30μm thickness of aramid. However the strains are not giving a good match as the predicted compressive strains are more while the tensile strain is less compared to test values. The variation in bending strain is expected due to the variation in orthotropic properties assumed for aramid at RT instead of the properties at LN2 condition.

VI. CONCLUSION

Three point loading experiment conducted for the polyimide pipeline work gave an outlook of the failure pattern of the pipeline. Local crushing was prevailed on that experiment and thus cantilever testing was carried out for further studies. Using cantilever loading test with average thickness of polyimide pipeline young's modulus for bare pipeline was obtained and it is in the range of 2071 to 2641 N/mm^2.Comparison of the deflection and strain (meridional) values between the isotropic and orthotropic condition of pipeline using FEA with test results shows that the polyimide pipeline is more closer towards isotropic in nature than orthotropic condition. Young's modulus of PUF insulation for Russian and Indigenous polyimide pipeline was obtained in a range of 10 to 25 N/mm^2.Using a straight indigenous polyimide pipeline young's modulus at LN2 condition from FEA by matching test data was observed as 5500 N/mm^2.An attempt was made to study the effect of aramid coating over polyimide pipeline at LN2 using the young's modulus obtained in the studies by considering aramid fibres as orthotropic shows that aramid have a significant role in providing compressive strength to the pipeline.

Comparing the experimental and analytical results, it was found that at RT condition the Young's modulus of indigenous pipelines are varied from 2700 N/mm^2 to 2900 N/mm^2 and the young's modulus of PUF insulation is obtained as 25 N/mm^2. Similarly at LN2 condition the young's modulus of polyimide pipeline is obtained as 5500 N/mm^2. The deviation in actual thickness from measured thickness of pipes was as high as 18%. Thus, polyimide pipes cannot be standardized and every pipe manufactured must go through non-destructive tests and their behaviour at different loading conditions should be estimated using FE analysis.

VII. FUTURE RESEARCH

The strength of the polyimide pipeline can be taken for the further studies. Variation of polyimide pipeline under different thermal condition and the property variations can be analysed. The buckling characteristics can be found using different load conditions. Ovality in bend pipeline under different load conditions and its impacts can also be developed. Application of polyimide pipeline on subsea for oil or natural gas transmission can be developed.

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