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Quality and reliability of flexible steel pipes

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SYNOPSIS

Flexible steel pipes are now commonly used in the offshore industry for both flowline and riser applications, even if they are a very recent development in comparison with rigid pipelines.

The flexible steel pipe is a composite structure and the design of several layers of different materials is relatively complex. In these conditions, the validation of design features and mechanical strength characteristics is less than straightforward.

This paper describes a study by Coflexip and Bureau Veritas of how an independent body validated, first the computer-based design of non-bonded flexible steel pipes used as flowlines, and secondly their fabrication. For this purpose, the actual computer program was checked and its results were compared with relevant measurements recorded during a very comprehensive programme of tests. Following this first part of the study, certification aspects of materials and assembly procedures are also discussed.

At the end of this paper, the foreseen work for the validation of the dynamic behaviour of the flexible steel pipes and their lifetime is introduced.

NOTATIONS

Elongation

ε : FSP elongation
L : length of the pipe
$d\varepsilon$: error in the FSP elongation
$d\chi$: error in the measurement
dL : error in the length of the pipe
δ : error due to the recording chain

Outer diameter

dD : error in the outer diameter
$d\chi$: error in the measurement
δ : error due to the recording chain

Torsion per unit length

θ/L : torsion per unit length
L : length of the pipe
$d(\theta/L)$: error in the torsion per unit length
$d\theta$: error in the torsion
δ : error due to the recording chain

Torque

$C = F \cdot L$: torque
dC : error in the torque
dF : error in the recorded force
dL : error in the length of the lever arm in the determination of the torque
δ : error due to the recording chain

Dr J Mallen joined Coflexip in 1978. He is one of the two leaders of the team in charge of the completion of the flexible steel pipes study.

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INTRODUCTION

In comparison with rigid pipelines flexible steel pipes (FSPs) are a very recent development. Although their first successful operational use was in the World War 2 operation Pluto they have been slow to find wide commercial application.[1] Today, however, FSPs are used in many new applications and are available from a number of suppliers.

The FSPs produced by Coflexip, were invented in 1970 by the Institut Francais du Petrole (IFP)[2] and were first deployed as flowlines in 1972 in the Emeraude Field (Congo). Shortly afterwards – in 1973 – Coflexip was founded as a company. The next significant milestone in the development of FSPs was their application in 1975 as risers in the Poleng field in Indonesia.

The first floating production system in the North Sea to use a FSP as a riser was the Balmoral floating production system

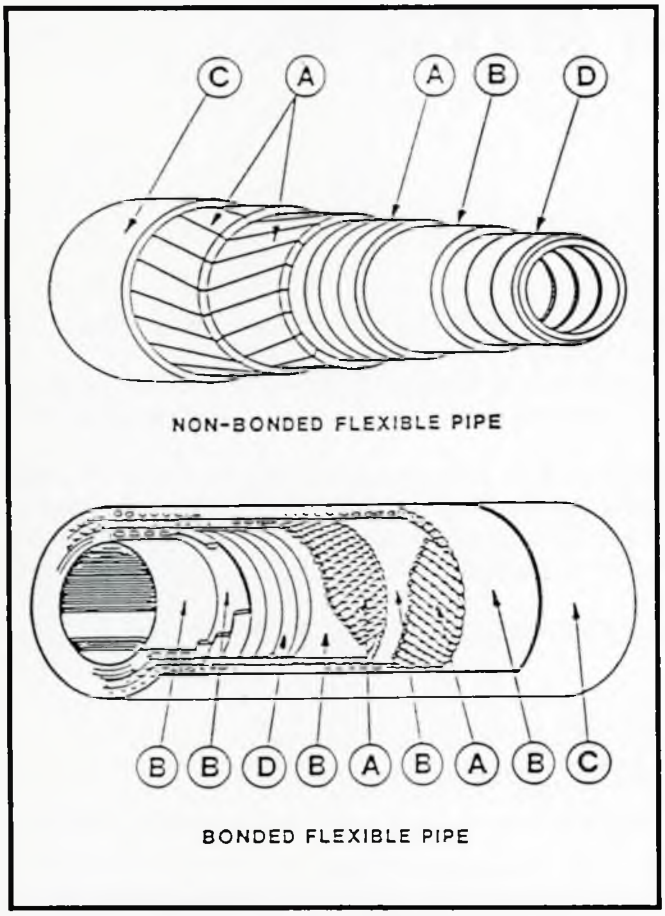


Fig 1: Example of construction for flexible pipe designs (from RP17B)
A Reinforcement windings
B Fluid-containing liner
C Outer jacket
D Structural members

(1986)[3]. For this application rigid risers were, at first, seriously considered but the advantages of a clear moonpool and virtually assured continuous operation were significant in the final decision to use FSPs. Today new technology, such as subsea wellheads, has extended the domain of FSPs. Advantages associated with the use of FSPs are:

1. onshore manufacture of long length;
2. relatively easy installation from reels;
3. limited or no field joints required;
4. no offshore welding required (field joints are mechanical couplings)[1].

Despite the fact that more than 1500 km of FSPs are today in service throughout the world[4], there are very few regulations or standards dealing specifically with their design, manufacture, or use. Some regulations do exist for steel-reinforced rubber flexibles but these generally deal with relatively low pressure applications.

One of the first of these was BS 1435 – Specification for Rubber Hose Assemblies for Oil Suction and Discharge Service – (1975) which refers to BS 3592 – Specification for Steel Wire for Rubber Hose Reinforcement – (1972) for steel armours or reinforcements. A second regulation which deals with flexible pipes, entitled Specification for Rubber, Reinforced, Smooth Bore, Oil Suction and Discharge Hose for Offshore Moorings, was issued by the Oil Company International Marine Forum (OCIMF) in 1978.

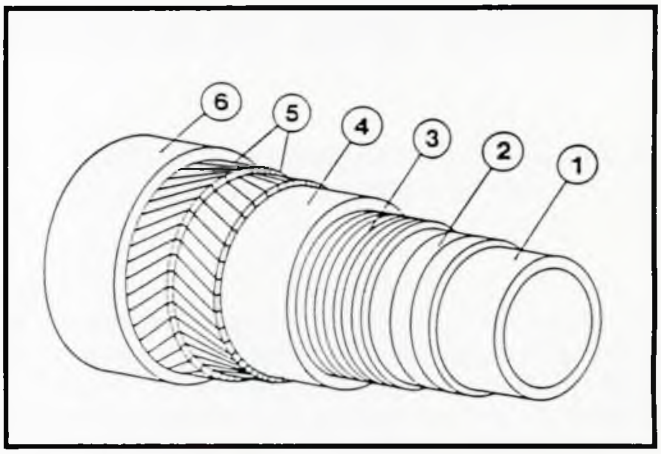


Fig 2: Flexible pipe construction (from ref 1)
1 Plastic inner core with stainless steel liner
2 Steel ZETA spiral
3 Flat steel carcass
4 Plastic intermediate sheath
5 Cross-wound steel armour
6 Plastic outer sheath

FSPs are first mentioned in a technical note, TN 503 – Flexible Pipes and Hoses for Submarine Pipeline Systems – issued by Det Norske Veritas in 1981. This specification introduced for the first time the concept of structural analysis in the design of FSPs by requiring an analysis based upon accepted principles of statics, dynamics and strength of materials.[5] In June 1988, the American Petroleum Institute (API) issued a Recommended Practice for Flexible Pipe (API RP 17 B).

Recognising the lack of a comprehensive standard for FSPs a detailed study was undertaken with the folowing two main objectives:

1. to validate and certify the design and technical specifications (materials, manufacturing, inspection and tests) used by Coflexip, with the objective of producing certification likely to be accepted by governmental agencies such as DEn or NPD;
2. to define guidance notes for the design of FSPs.

This study was also intended to clarify the influence of the different parameters on the behaviour of the FSPs.[6]

FLEXIBLE STEEL PIPES

FSPs may be divided into two types depending on their construction, non-bonded layer and bonded layer, as illustrated in Fig 1.[7]

Bonded layer flexible pipe consists of several layers wrapped or extruded individually and then bonded together through the use of adhesives or by applying heat and/or pressure (such as vulcanising) to fuse the layers into a single construction. Non-bonded flexible pipe consists of several individual and separated layers having no adhesion between them. Each succeeding layer is wrapped or extruded over the previous layer in a continuous process along the entire length. Coflexip FSPs are of the non-bonded type. The plastic layers, obtained by extrusion of special kinds of thermoplastic polymers, such as polyamid or polyethylene, ensure they are leak free. The steel layers provide resistance to various loads, ie internal or external pressure, axial force and torque. A typical manufacturing design is shown in Fig 2 and consists of:

1. an inner plastic sheath which seals and protects the steel against transported fluid or gas – stainless steel liner may also be present;
2. one wound steel wire, called the ZETA spiral (pressure armour);
3. one flat steel carcass to reinforce the ZETA spiral if necessary;
4. a plastic intermediate sheath;
5. cross-wound steel wires (tensile armours);
6. an outer plastic sheath to seal and protect the inner steel components against the outer environment.[8]

Specific operational needs will require some variation of principles. The inner core contains the fluid and is a proprietary plastic material. For gas and oil applications, it is usual to include an interlocking spiral austenitic steel liner. This provides mechanical protection against pig damage and prevents collapse of the plastic core in the case of rapid decompression in a gas line. Mechanical strength to resist the pressure loads is provided by interlocking and flat steel spirals winding around the plastic tube. Two cross-wound armour layers provide mechanical strength to withstand axial loads.

In some low-pressure applications the FSP may be manufactured without any pressure armours.

Pipe materials should be selected with regard to the chemical conditions to which the pipe will be exposed during its life. It is important that any adverse substances found in produced fluids and chemical treatments, as well as batch treatment chemicals to be used in production-well stimulation, be identified as they may affect the service life of the pipe.

Examples of adverse substances are H_2S, CO_2, sand, water and chlorides.

All pipe materials used in H_2S service should be capable of resisting degradation over the life of the pipe. Many polymers are susceptible to degradation and blistering when in contact with H_2S. They may become brittle and fail in flexure. Many metals are subject to sulphide stress cracking. For this our service requirements, NACE-MR-01-75 – Sulphide Stress Cracking Resistant Metallic Materials for Oil Fields, are to be met.

Those materials used by Coflexip which do not meet the NACE-MR-01-75 requirements, have been tested according to NACE-TM-0177-86 – Testing of Materials for Resistance to Sulphide Stress Cracking at Ambient Temperature.

CO_2 is highly corrosive in the presence of water. The materials should be resistant to such corrosion if CO_2 and water are present in sufficient quantities to be detrimental. Some polymers may also be chemically degraded under the acidic conditions of wet CO_2.

When the fluid (produced or injected) is anticipated to contain chloride, care should be taken in the selection of materials to avoid the possibility of chloride stress corrosion cracking. Polymers used in flexible pipe are generally not affected by contact with chlorides, except in the presence of a second reactive component.

Well stimulation acids or other batch treatment chemicals may be highly corrosive or may cause degradation of polymers in flexible pipes.

Some methods of controlling internal corrosion are discussed in NACE-RP-01-75 – Control of Internal Corrosion in Steel Pipelines and Piping Systems.[7]

Intermediate and external layers utilise appropriate plastic materials to prevent intermetallic fretting and external corrosion, respectively.[1]

SCOPE OF STUDY

The study can be divided into three parts:

1. the certification of the design of flowline FSPs.
2. the certification of the materials, fabrication and inspection during manufacture of the FSPs.
3. the certification of FSPs used as risers.

The first part consisted of studying the means used to design the FSPs considered as flowlines. For this purpose, the EFLEX computer program developed by the Institut Francais du Petrole, and used for many years by Coflexip to design their FSPs, was submitted to a theoretical study. The main characteristic parameters affecting the behaviour of the FSPs, computed by EFLEX were then compared with the relevant values recorded during actual physical tests.

The second part of the study can be subdivided into three parts which were carried out simultaneously:

1. review of the technical specifications used for the fabrication of a FSP and the way they are realised.
2. certification or review of the materials composing the different layers of the FSP, the way they are used and their behaviour under loads.
3. witnessing of the tests performed on the FSPs after completion of manufacture.

The third part relates to the dynamic behaviour of the FSP when used as a riser. This includes a fatigue analysis (or, more precisely, a wear analysis).

Once this study has been completed it will be possible to check the quality and the reliability of non-bonded FSP for any service.

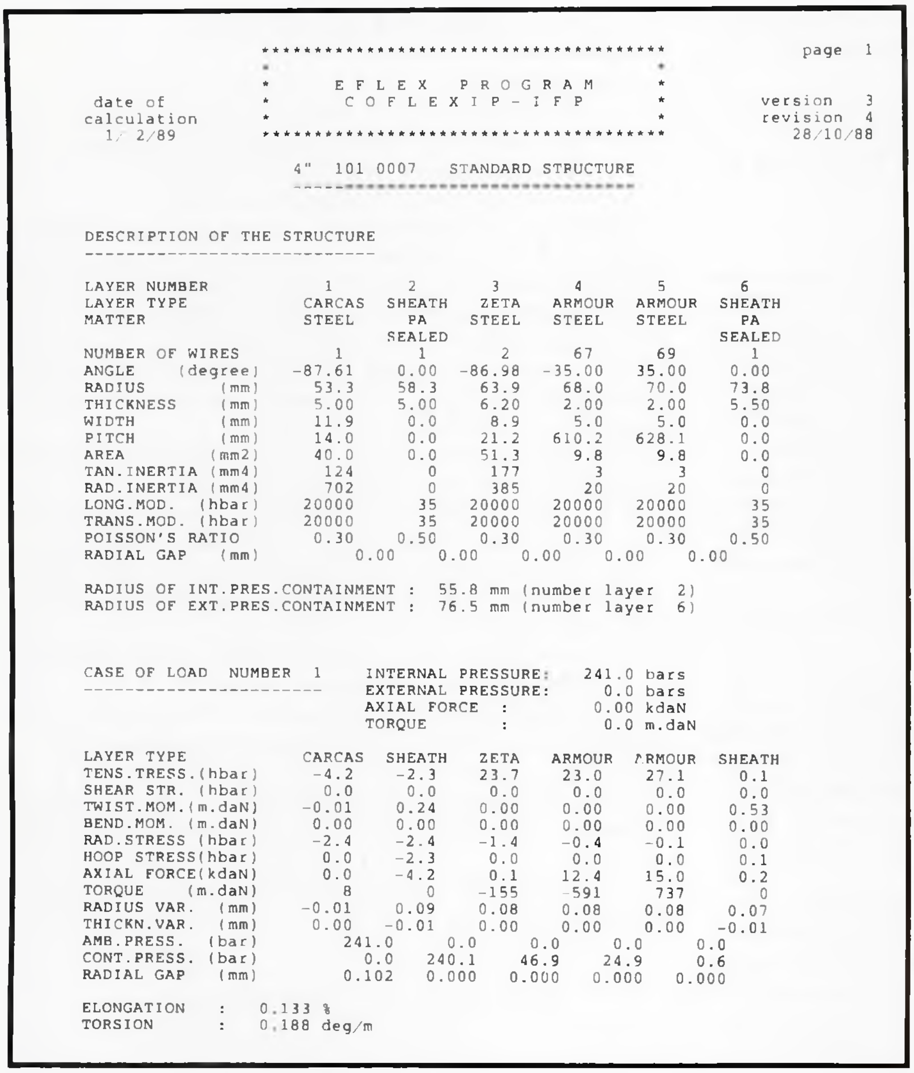
A flow chart illustrating the study programme is given in Appendix II.

FSP DESIGN CERTIFICATION

The Coflexip FSPs which are to be used as flowlines, ie mainly subjected to internal pressure when in service, have

Table I: Synopsis of EFLEX program

Input	*Output*
Layer by layer description of the flexible pipe Geometrical data and mechanical properties of the materials. Loadings: internal and/or external pressure, axial force, torque.	**For layers** Stresses Part of external load taken by the layers (tensile force, contact pressure with adjacent layer, torque). Radius and thickness variations.
Boundary conditions may be taken into account Free or restrained elongation of the pipe. Free or restrained rotation of the pipe.	**For the pipe** Elongation Rotation



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 date of          *        C O F L E X I P - I F P      *           version  3
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                        4"  101 0007   STANDARD STPUCTURE
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 DESCRIPTION OF THE STRUCTURE
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 LAYER NUMBER             1       2       3       4       5       6
 LAYER TYPE            CARCAS  SHEATH   ZETA   ARMOUR  ARMOUR  SHEATH
 MATTER                STEEL     PA    STEEL   STEEL   STEEL     PA
                               SEALED                          SEALED
 NUMBER OF WIRES          1       1       2      67      69       1
 ANGLE    (degree)   -87.61    0.00  -86.98  -35.00   35.00    0.00
 RADIUS       (mm)     53.3    58.3    63.9    68.0    70.0    73.8
 THICKNESS    (mm)     5.00    5.00    6.20    2.00    2.00    5.50
 WIDTH        (mm)     11.9     0.0     8.9     5.0     5.0     0.0
 PITCH        (mm)     14.0     0.0    21.2   610.2   628.1     0.0
 AREA        (mm2)     40.0     0.0    51.3     9.8     9.8     0.0
 TAN.INERTIA (mm4)      124       0     177       3       3       0
 RAD.INERTIA (mm4)      702       0     385      20      20       0
 LONG.MOD.  (hbar)    20000      35   20000   20000   20000      35
 TRANS.MOD. (hbar)    20000      35   20000   20000   20000      35
 POISSON'S RATIO       0.30    0.50    0.30    0.30    0.30    0.50
 RADIAL GAP   (mm)         0.00    0.00    0.00    0.00    0.00

 RADIUS OF INT.PRES.CONTAINMENT :  55.8 mm (number layer  2)
 RADIUS OF EXT.PRES.CONTAINMENT :  76.5 mm (number layer  6)


 CASE OF LOAD  NUMBER  1    INTERNAL PRESSURE:   241.0 bars
 -----------------------    EXTERNAL PRESSURE:     0.0 bars
                            AXIAL FORCE  :        0.00 kdaN
                            TORQUE       :         0.0 m.daN

 LAYER TYPE            CARCAS  SHEATH   ZETA   ARMOUR  ARMOUR  SHEATH
 TENS.TRESS.(hbar)     -4.2    -2.3    23.7    23.0    27.1     0.1
 SHEAR STR. (hbar)      0.0     0.0     0.0     0.0     0.0     0.0
 TWIST.MOM.(m.daN)    -0.01    0.24    0.00    0.00    0.00    0.53
 BEND.MOM. (m.daN)     0.00    0.00    0.00    0.00    0.00    0.00
 RAD.STRESS (hbar)     -2.4    -2.4    -1.4    -0.4    -0.1     0.0
 HOOP STRESS(hbar)      0.0    -2.3     0.0     0.0     0.0     0.1
 AXIAL FORCE(kdaN)      0.0    -4.2     0.1    12.4    15.0     0.2
 TORQUE    (m.daN)        8       0    -155    -591     737       0
 RADIUS VAR.  (mm)    -0.01    0.09    0.08    0.08    0.08    0.07
 THICKN.VAR.  (mm)     0.00   -0.01    0.00    0.00    0.00   -0.01
 AMB.PRESS.  (bar)        241.0     0.0     0.0     0.0     0.0
 CONT.PRESS. (bar)          0.0   240.1    46.9    24.9     0.6
 RADIAL GAP   (mm)        0.102   0.000   0.000   0.000   0.000

 ELONGATION    :   0.133 %
 TORSION       :   0.188 deg/m
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Fig 3: Example of EFLEX program printout

their main design parameters computed by EFLEX. The EFLEX program is based mainly on the separation of the function of the different layers of the FSP, and their limited interaction. As previously indicated, the FSPs are principally composed of two groups of elements:

1. the steel armours, which are helices, and which give the FSP its mechanical strength;
2. the plastic layers, the main purpose of which is to ensure leak-free seals, and which are cylindrical shells.

The equations governing the mechanical behaviour of these two kinds of elements subjected to external loads (internal pressure, axial force or torque) have been theoretically studied. For each of them, due to the separation of the function between the layers, the stresses and the deformations can be computed either by the equations of static equilibrium or by the Castigliano theorem.

In addition to these equations, applied separately to each layer of the FSP, some assumptions relating to the whole FSP have to be considered:

1. the FSP is assumed to stay in a straight line while subjected to various loads; so no P–δ effect is to be considered.
2. no friction is to be considered between the spiral lines in the cross-wound tensile armours.
3. strain and torsion are the same for all the layers. This condition is in fact imposed by the end-fitting of the FSP.
4. all calculations are made in the elastic domain. No buckling or plastic deformation of any of the layers is to be considered.

The system formed by all the above mentioned equations is solved using the Jordan method which is a modified Gauss method. The data, which is introduced in the EFLEX program, and the results, are summarised in Table I and an example of output is shown in Fig 3.

After the theoretical study of the EFLEX program was completed, the next step was to correlate the computations with the relevant measurements recorded during a comprehensive test programme. The design of the FSP used as flowlines by the EFLEX program could then be validated.

For this purpose, Bureau Veritas used the results of a series of tests performed during the fabrication of two FSPs (3 inch and 8 inch inside diameter) at the request of a Coflexip customer and one series which was carried out on two FSPs (4 inch inside diameter) which were specially instrumented for this correlation study. All the FSPs used in these studies may be considered normal production pipes.

The test programme, carried out for the certification of the design of Coflexip FSPs by the EFLEX program, was developed in order to show the influence of each type of load on the behaviour of the FSPs.

The FSPs were subjected to the following boundary conditions:

1. free in elongation and torsion;
2. free in elongation and restrained in torsion;

and to several loading conditions:

1. internal pressure only;
2. axial force with/without internal pressure;
3. torque with/without internal pressure and axial force.

During these tests, the characteristic parameters, which are listed below, were recorded:

1. FSP axial elongation;
2. FSP torsion per unit length or restraining torque;
3. outer diameter variation;
4. outer tensile armour wire elongation;
5. bursting pressure.

To allow an acceptable correlation between the EFLEX results and the relevant measurements recorded during the tests, error ranges on each measurement were evaluated and actual clearances between layers together with the actual mechanical properties of materials were introduced in the EFLEX computations.

All measurements were carried out according to Coflexip specifications and the error ranges were evaluated according to the following formulae.

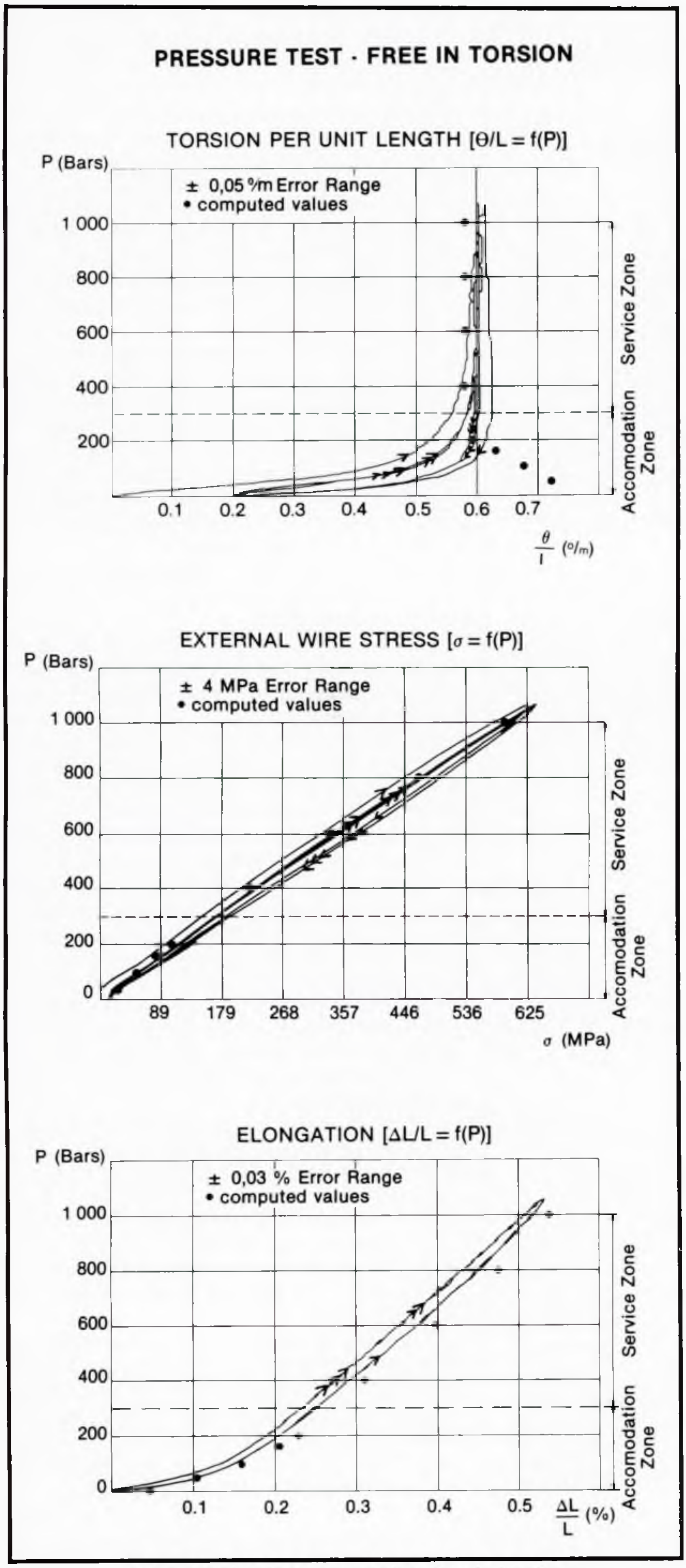


Fig 4: Mechanical test results - free in torsion

Elongation

$$d\varepsilon = (d\chi + \varepsilon \cdot dL)/L + \delta$$

For the different tests, the average value was estimated to be 0.03%.

Outer diameter

$$dD = 2(d\chi + \delta)$$

The average value obtained during the tests was 0.235 mm, the outer diameters varying from 146 to 276 mm.

Torsion per unit length

$$d(\theta/L) = [d\theta + (\theta/L) \cdot dL]/L + d\delta$$

The average values computed by this formula vary from 0.03 per m to 0.05 per m.

Torque

$$dC = L \cdot dF + (C \cdot dL/L)/\, d\delta$$

This gives an error range of 7 m·daN.

Outer tensile armour wire elongation

The error range of the strain gauge measurements can be estimated to be within 0.002% of the recorded values.

The program of these tests can be divided into the three following groups.

1. Study of the mechanical behaviour of the FSP subjected to internal pressure only and with the following boundary conditions:
   a. free in elongation and torsion
   b. free in elongation and restrained in torsion
2. Study of the mechanical behaviour of the FSP subjected to axial force and:
   a. without internal pressure and with the following boundary conditions:
      i. free in torsion
      ii. restrained in torsion
      iii. subjected to given torque
   b. with internal pressure and the following boundary conditions:
      i. free in torsion
      ii. restrained in torsion
      iii. subjected to given torque
3. Study of the mechanical behaviour of the FSP subjected to torque and:
   a. internal pressure only
   b. axial force only
   c. internal pressure and axial force

After the completion of these tests, a bursting test was carried out.

Once the tests were completed the recorded measurements were compared with the relevant EFLEX computations. Examples of these comparisons are shown in Figs 4–6. As can be seen from these Figures, the correlation between the EFLEX program results and the test measure-

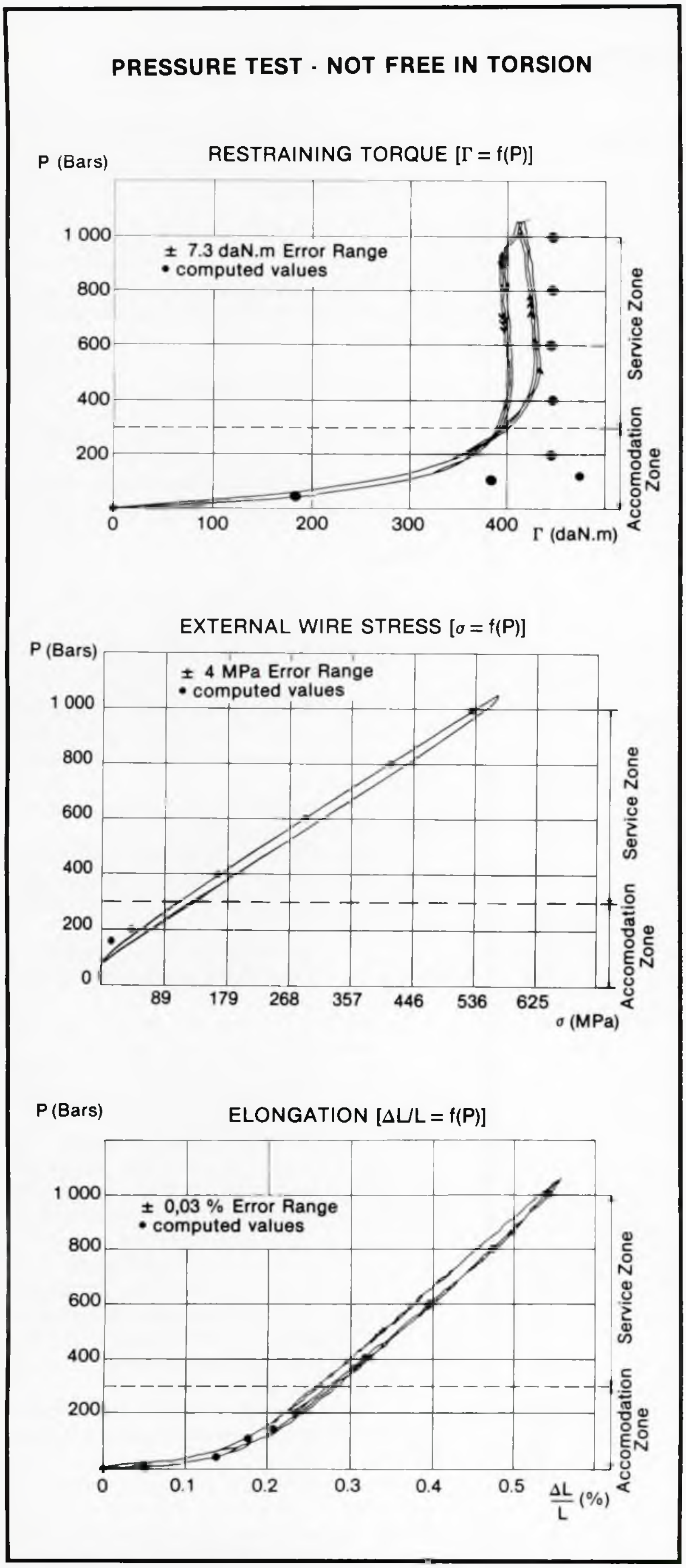


Fig 5: Mechanical test results – not free in torsion

ments is found to be very good as soon as the internal pressure reached a given level for which, as can be seen on EFLEX outputs, the clearances that were introduced in the EFLEX data had disappeared. Before that, the EFLEX program, which is based on a linear system, cannot represent with good accuracy the non-linear behaviour of the FSP. But one important fact is that during this phase, which can be considered to be a transitory phase, the EFLEX results are conservative with respect to those obtained during the tests. A second important fact is that the pressure level at which the behaviour of the FSP alters significantly is well below the service pressure.

As previously indicated, we introduced into EFLEX data, clearances between layers, together with actual mechanical and geometrical properties of materials in order that we could demonstrate an acceptable correlation between the EFLEX results and the measurements recorded during the tests. This is not, of course, the usual way of using the EFLEX program. But all the computations we have made lead us to conclude that:

1. clearances between layers have no influence on the determination of the bursting pressure;
2. the use of standard values for the mechanical and geometrical properties of materials result in conservative bursting pressure values (see Table II).

It is significant to note that in all previous standards relating to flexible pipe or hose the only strength test criteria required relate to bursting pressure. The results we have observed lead us to believe that bursting pressures for non-bonded FSPs can be confidently predicted by calculation.

In the Journal *Offshore Mechanics and Arctic Engineering*, Vol 109 (1987), approximate formulae, based on the disjunction of the behaviour of the non-bonded FSPs, were indicated, given the main parameters used in FSP design.[2] In addition, J J Ferret & C L Bournazel[2] introduced in this paper the calculation of the stresses due to bending, which are necessary in the dynamic analysis of FSPs. The conclusions of this first part of our study can be summarised as follows:

1. it is possible to compute bursting pressure.
2. it is possible to compute the stresses in all the layers of the FSPs at service and test pressures.
3. there is good correlation between computed and measured values.
4. the validity of the computed results are equivalent to those obtained for rigid pipelines.

Finally it should be noted that as a result of the above programme Bureau Veritas has now certified the design of flowline FSPs by the EFLEX program.

END-FITTING DESIGN

The previous sections of this paper have described the design and certification of the line only.

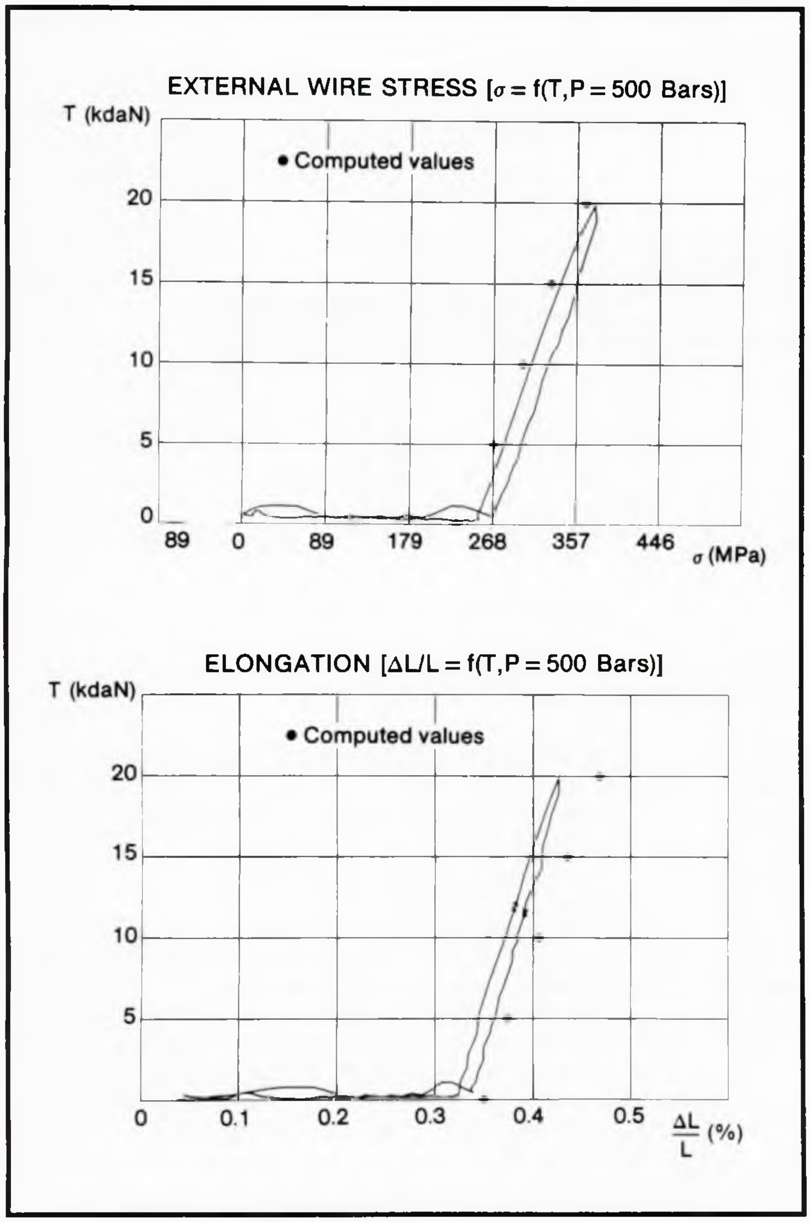


Fig 6: Tensile test results

The design of the end-fittings requires additional data which is not available from the EFLEX program. This data includes the local configuration of the connection, the possible presence of a bending limiter, etc.

The end-fitting (Fig 7) is a complex structure which has to replace each layer of the FSP without any brutal break in the strength properties of the line. In addition, it has to withstand specific forces such as bending moments due to local configuration.

The end-fitting can be split into five main functional parts:

1. the front crimping pieces, the main function of which is to ensure internal tightness and to transmit the forces acting in the pressure armours.
2. anchoring of the tensile armours.
3. the rear crimping pieces, the main function of which is to ensure external tightness.
4. the connection between the vault and the cap.
5. the termination, the main function of which is to connect the FSP to another section of pipe or to other components.

The end-fitting is designed with the aid of a computer program which takes into account the strength of the materials with reference to one of the following codes:

1. API Spec 6A – Specification for Wellhead and Christmas Tree Equipment – issued in 1986 by the American Petroleum Institute.
2. ANSI B16-5-1981 – Pipe Flanges and Flanged Fittings – issued in 1981 by the American National Standard Institute.

The validity of the design method was confirmed by the observations made during the different bursting tests. No failure occurred in the end-fittings, even in the bursting test which was carried out with an internal temperature of 100°C.

CERTIFICATION OF MATERIALS MANUFACTURING AND TESTING

The second part of this study relates to the fabrication of the FSPs themselves. For this phase the role of Bureau Veritas was to review the technical specifications of the materials used in the fabrication of the FSPs, and to check that all relevant material tests had been satisfactorily carried out. The manner in which the materials reacted to loads and service conditions (temperature or bending) was investigated, and the FSP manufacturing and test procedures were examined.

The method adopted by Bureau Veritas for this part of the study was to follow a FSP through each step of its fabrication, from design to packing. For each step, the technical means used by Coflexip were studied.

Table II: Correlation of burst pressures – calculated and measured

Structures: Internal diameters [mm (in)]	*EFLEX results (MPa)*	*Test results (MPa)*	*Burst pressure to design pressure ratios*
63 (2.5)	194.0	229.0	2.69
76 (3)	77.5	90.0	2.57
76 (3)	98.5	145.5	3.23
76 (3)	141.0	168.5	2.59
76 (3)	245.0	245.0	2.25
101 (4)	159.0	173.0	2.47
101 (4)	147.0	166.0	2.37
101 (4)	68.0	75.0	2.50
201 (8)	46.0	50.0	2.50

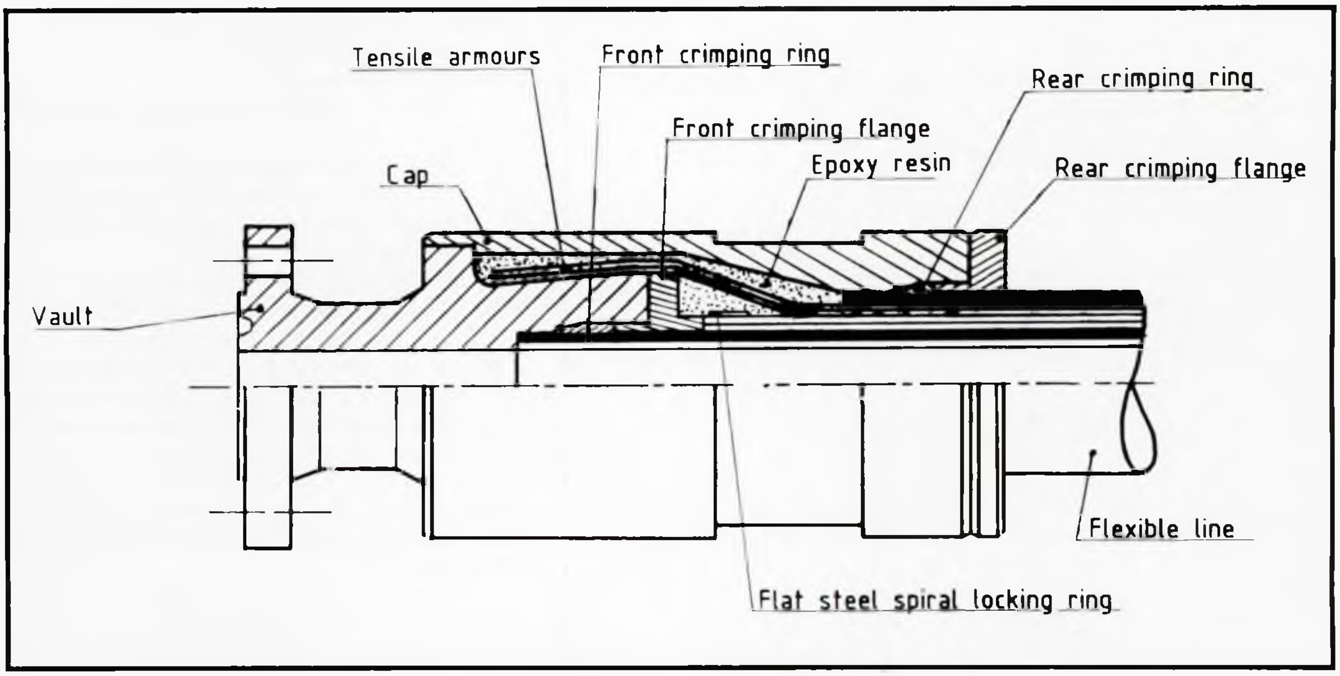


Fig 7: Cross-section of end-fitting

The design phase of a FSP is based on the data given by the customer, ie the internal diameter, the maximum outer diameter if necessary, the service pressure and the chemical characteristics of the transported fluid. Taking this data into account the FSP is then designed using the EFLEX program, and, where necessary, other programs for the determination of the bending stiffness or the minimum bending radius. These results are summarised in data sheets, which are sent to Coflexip customers; they are also used to produce an internal technical specification for use by the factory during fabrication. Known as the *cahier des charges* (CDC), this specification shows for each layer the following items:

1. the relevant material specification (STM);
2. the fabrication procedure (MET);
3. the test procedure (DQC);
4. the welding and repair procedures.

The CDC only concerns the line itself.

At the end of the design phase, two documents are issued by the design department for the fabrication of the FSP:

1. the CDC, for the line;
2. a drawing for the end-fittings together with a standard procedure for their installation.

The CDC defines the fabrication stages of the FSP, and indicates the tools which have to be used by the workshop. The system is entered into a computer, which can be used to record any relevant remarks arising during manufacture.

In parallel with the CDC a test programme is issued. This specifies the various tests which have to be performed during the fabrication of the FSP, and the way they have to be carried out.

In addition to the monitoring of the fabrication of the FSP, the materials are checked according to the relevant STM.

For these different steps, the role of Bureau Veritas was to check the different specifications, and to ensure that they were implemented correctly.

The materials used for the manufacture of the FSPs belong to one of the following three categories:

1. forged steel, which is used for the end-fittings.
2. wire steel for the pressure and tensile armours.
3. plastics.

End-fittings are forged in AISI 4130 steel, which corresponds to ASTM A 382.

Its mechanical properties can be summarised as follows:

minimum yield stress, 415 MPa;
minimum tensile strength, 620 MPa;
minimum elongation, 22%.

The material must also meet additional requirements. These are listed in the Coflexip STM, and include impact tests in both the longitudinal and transverse directions.

The different armours of the FSPs are made with wire steel. Three kinds (FM15, FM35 and FM72) are used by Coflexip. Two of them (FM15 and FM72) have been used by Coflexip for many years either for the ZETA spiral (FM15), or for the tensile armours (FM15 and FM72). More recently a new wire steel (FM35) has been introduced and was used for the Amerada Hess project.

This new wire steel, the chemical analysis of which is given in Table III, has been manufactured according to a process and specifications defined by Coflexip and IFP, in association with the main British and French steel manufacturers.

The manufacture of this wire steel was surveyed by Bureau Veritas, both in the United Kingdom and in France.

The conformity of FM35 with NACE requirements has been tested successfully in the IFP laboratory, according to NACE-TM-0177-86, with a tensile stress of 450 MPa.

Three kinds of thermoplastic resins are currently used for the plastic sheaths:

polyamid 11 (Rilsan)
high density polyethylene
COFLON fluorinated polymer (Coflexip's registered trademark)

The choice of the material is determined, firstly by the available production facilities, and secondly by the specification of the application, which can be summarised as follows:

1. service specification – liquid and gaseous hydrocarbon phases frequently contain gases such as H_2S and CO_2 together with water.
2. temperature and pressure – generally temperatures of the carried fluids are less than 100°C.
3. physicochemical resistance.

4. hydrocarbon swell and blister resistance – prolonged contact with organic materials causes physical reactions. One of the main effects of this reaction is to cause organic materials to swell. When such materials are subjected to sudden variations in pressure and decompression, they can deteriorate rapidly. Blistering and cracking may then occur.
5. mechanical resistance.

The different thermoplastic resins, which are used for manufacturing the internal sheath, have been subjected to in-depth analysis with regard to their chemical, mechanical and physicomechanical properties in order to make a more accurate assessment of the temperature range at which they can be used.

Assessing the permeability of polymers under various temperature and pressure conditions is also very important in analysing the behaviour of selected organic materials with regard to petroleum products.[9]

The last important point for plastics, and one of the main questions asked by the operators, is ageing resistance. The ageing of plastic is generally a complex phenomenon involving several mechanisms of chemical, thermal or physicomechanical origins. Depending on its chemical nature, and on the ageing test conditions, each plastic will be more or less sensitive to each such mechanism. Ageing tests have been performed in accordance with the D638 ASTM standard. The results of the tests can be summarised by the curve shown in Fig 8, indicating in logarithmic co-ordinates how critical time, t_c, varies as a function of inverse temperature for crude oil of different origins.[9] As an example, at 90°C, critical time is 20 years, instead of 10 years for a temperature of 100°C.

In order to allow the determination of the mechanical resistance of the inner plastic sheath of the Coflexip FSPs, two groups of tests were performed.

The first one was carried out on a 3 inch FSP (working pressure of 45 MPa) and included the following sequences:

1. pressure test (70 MPa) with internal temperature of 20°C;
2. pressure test (70 MPa) with internal temperature of 100°C;
3. bursting test (115 MPa) with internal temperature of 100°C.

The second sequence of tests was carried out on a 3 inch FSP (working pressure of 90 MPa) and included the following sequences:

1. pressure test (115 MPa) with internal temperature of 100°C;
2. bending test (50 cycles) with internal temperature of –23°C;
3. pressure test (115 MPa) with internal temperature of 20°C.

The different systems used for these tests are shown on Figs 9 and 10.[10,11] These tests were witnessed by Bureau Veritas surveyors.

Table III: Chemical analysis of FM 35

Components	Minimum value (%)	Maximum value (%)
Carbon	0.30	0.38
Manganese	0.50	0.90
Silicon	0.10	0.35
Sulphur	–	0.025
Phosphorus	–	0.025
Aluminium	–	0.07

The two groups of tests have shown that:

1. a service with high internal temperature, even if it is followed by a confined creep of the polyamid inner plastic sheath through the ZETA layer clearances, has no consequence on the mechanical properties of the polyamid sheath, and that the bursting pressure was higher than the guaranteed one.[10]
2. the second group of tests, including bending test at low temperature (–23°C) after pressure test at 100°C, is partly representative of the mechanical integrity of the polyamid inner plastic sheath during dynamic application of FSPs.

At this level of the study, the design of the Coflexip FSPs and the proposed method of fabrication have been checked and validated. Verification of the materials used during manufacture and that manufacture was in accordance with stated procedures was also undertaken.

Once their fabrication was achieved, different tests were performed on several FSPs, the main characteristics of which can be summarised as follows:

1. internal diameter from 2.5 to 8 inches;
2. working pressure from 20 to 110 MPa;
3. with/without ZETA armours and lay angle of the tensile armours varying from 25 to 55°.

A comprehensive description of these FSPs is given in Table IV. Some of them were tested with the presence of welds on the ZETA layer. The tests were carried out with the FSP being either in a straight line or bent.

These tests have already been described in the section of this paper relating to the FSPs' design certification. During

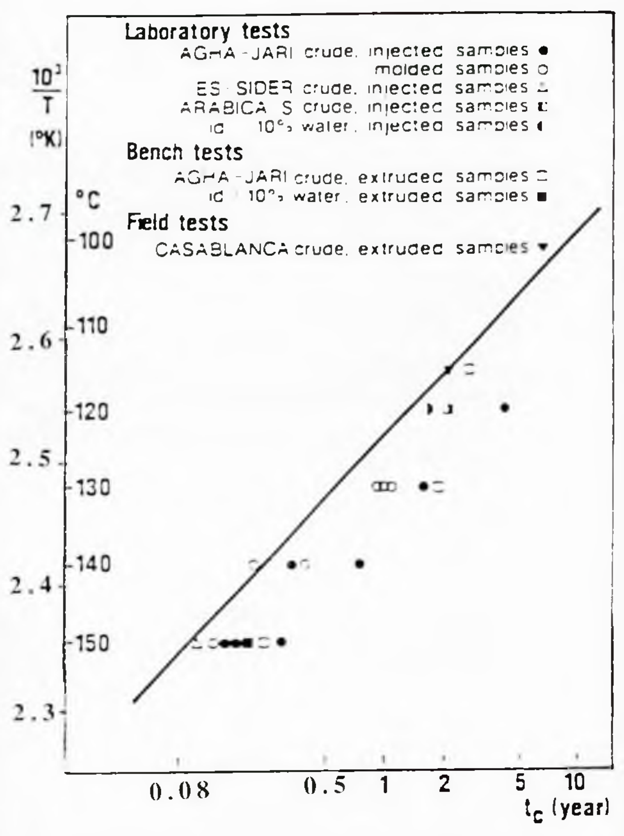


Fig 8: Critical time versus temperature curve

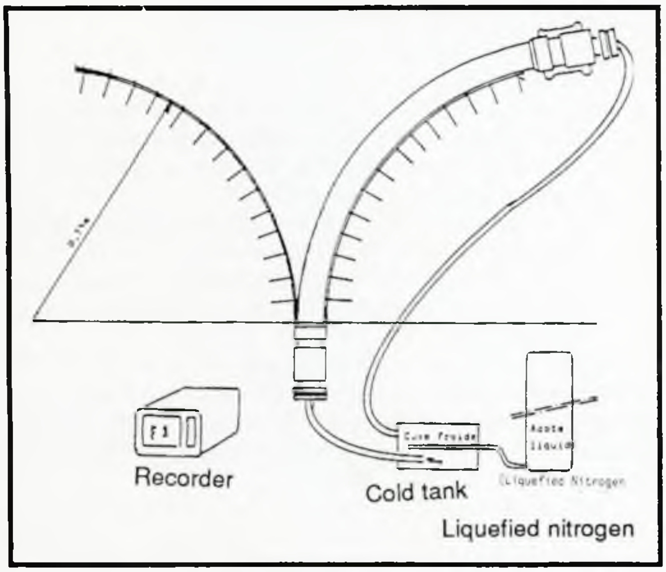


Fig 9: Bend test rig

these tests, the following main characteristics of the FSPs were studied:

1. pressure test – the FSP being free in torsion; elongation, torsion per unit length and external wire stress have been recorded.
2. pressure test – the FSP being restrained in torsion; elongation, restraining torque and external wire stress have been recorded.
3. tensile test with internal pressure – elongation and external wire stress have been recorded.
4. torsion test with internal pressure – elongation and external wire stress have been recorded.
5. bursting test – the obtained values are indicated in Table II. As can be seen, the ratio of the bursting pressure to the design pressure is always in excess of 2.25 and in some cases is even greater than 3.0.

During the realisation of our programme very extensive new rules were issued by the American Petroleum Institute – Recommended Practice for Flexible Pipes API RP 17B. It will be seen however that the tests, listed above, meet the requirements for flowlines, corresponding to the following three levels indicated in API RP 17B:

1. prototype tests, which are recommended to satisfy the user that technical requirements are fulfilled relating to each special design of flexible pipe and/or method of manufacture. In this category are the hydrostatic internal pressure burst test, the tension test and the torsion resistance test.
2. acceptance tests, which are to be used as part of the quality assurance sequence and as final verification of the manufacturing process. The hydrostatic tests can be considered to fulfill this function.
3. special tests, which are to be considered when the nature of the application requires special or unique structural, chemical or safety aspects. In this category are the weathering tests which are either low temperature, high temperature or a combination of both.

Due, however, to the methodology used the study included

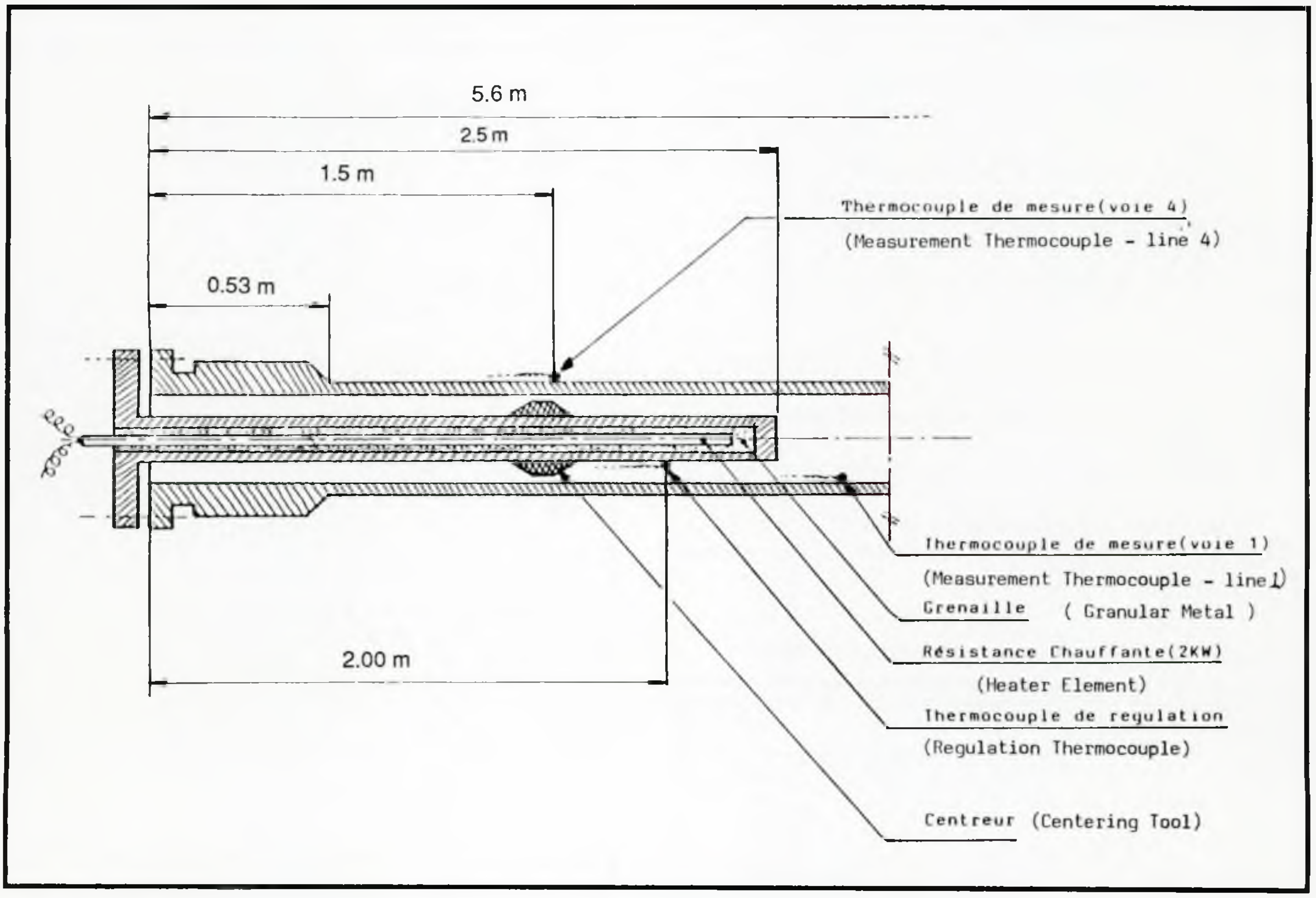


Fig 10: Details of thermocouple locations

Table IV: Characteristic parameters of FSPs

Structures: Internal diameters [mm (in)]	*ZETA spiral angles (α°)*	*Steel carcass angles (α°)*	*Tensile wire angles (α°)*	*Design pressures (MPa)*
63 (2.5)	85.3	83.6	40.0	85.0
76 (3)	86.3	–	25.0	35.0
76 (3)	85.8	–	35.0	45.0
76 (3)	85.9	84.2	35.0	65.0
76 (3)	85.9	84.4	35.0	110.0
101 (4)	88.4	85.4	35.0	70.0
101 (4)	86.8	85.3	35.0	70.0
101 (4)	–	–	55.0	30.0
201 (8)	87.9	–	30.0	20.0

additional points not covered by API RP 17B. These were:

1. analysis of the design criteria and calculation basis;
2. verification of the correspondence between this analysis and the fabrication and control specifications;
3. quantification of the main characteristics of the FSPs;
4. correlation between the computations and the test results.

Based on the knowledge resulting from this study, Bureau Veritas will issue a Guidance Note for the Design, Fabrication, Control and Testing of Flexible Steel Pipes, used as flowlines.

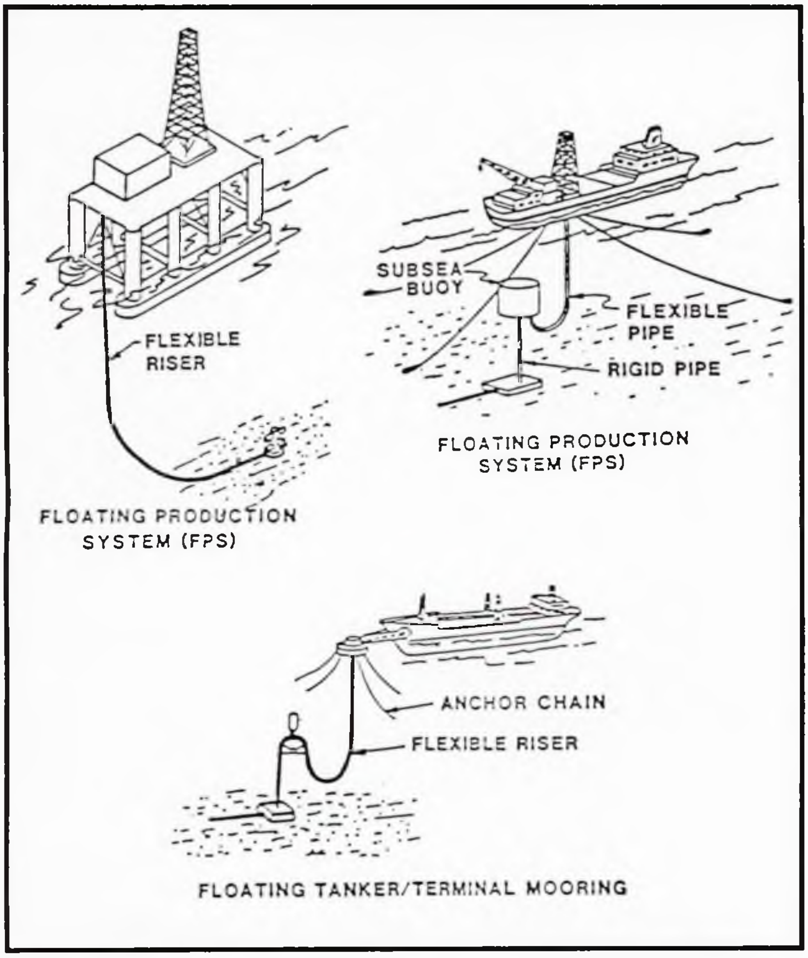


Fig 11: Examples of dynamic applications of flexible pipes (from API RP 17B)

DYNAMIC FLEXIBLE STEEL PIPES

The first two parts of our study, now achieved, were mainly, if not exclusively, related to FSPs intended for use as flowlines. It will be noted that the second part of this study was more concerned with the product than the service for which it was intended. The largest offshore application of FSPs is however as risers (Fig 11) and with this in mind it was considered essential to investigate the dynamic behaviour of FSPs, and a start has now been made on this section of the study.

The dynamic analysis of FSP systems almost always requires three-dimensional time-domain non-linear and numerical analysis. Dynamic analysis results will include:

1. displacement, force and moment time histories;
2. maximum forces, moments and deformations;
3. mode shapes;
4. natural frequencies;
5. transient response to impulsive loadings.

The system should generally be analysed for both operating and extreme sea states to allow an estimate of the service life to be made. Although analysis of the system in irregular seas will generally provide the best estimate of response, regular wave analyses may be useful in estimating maximum system response.

Response time histories are the basis for short- and long-term performance predictions. They can also be used to evaluate interference between components and to estimate service life.

Response maxima can be compared with pipe design limits for radius of curvature, end angles, angle of twist and elongation. An examination of maximum forces, moments and deformations may also indicate sections of the pipe where a detailed analysis may be required.

The mode, shapes and natural frequencies of the pipe are necessary for the evaluation of flow-induced motions.

Impulsive loadings which may be significant include abrupt changes in loads, constraints and connections.

Of particular concern to the FSP users is to foresee their service life in dynamic application.

The evaluation of the service life is based on two aspects related to the steel armour's behaviour:

1. the fatigue;
2. the wear.

The fatigue aspect requires the knowledge of:

1. the static stresses induced by the loads and the bending;
2. the dynamic stresses induced by the bending variation;
3. the endurance limit of the steel armours.

As for the wear aspect, it is important to know:

1. the contact pressure between the layers;
2. the relative slip between the layers;
3. the wear rate.

An approach to these calculations has been made by J J Ferret & C L Bournazel from IFP, and J Rigaud for Coflexip.[12]

In conclusion, it can be stated that the subject of dynamic application of FSPs is wide and complex. However, complexity should not mean confusion. For this purpose, a general flow-chart of useful guidelines is given in Appendix III.

It is needless to emphasise that such guidelines should under no circumstances be considered as rigid design rules replacing careful analysis and personal width of vision, in so far as each riser system remains, to some extent, a particular case.

This is no doubt the fundamental reason why this subject is under constant evolution.[13]

CONCLUSIONS

The development of flexible steel pipes will inevitably lead to the introduction of more stringent manufacturing standards, design guidance notes and legislative proceedings.

It is important however not to burden the industry with unnecessarily diverse quality procedures and specifications. This is the reason for which, before issuing any guidance note, Bureau Veritas has undertaken a comprehensive study of the FSPs, in association with Coflexip.

This study, which is now achieved for FSPs used as flowlines, will allow us to issue a guidance note for the design, manufacturing and testing of flexible steel pipes used as flowlines. The next step will be to introduce the dynamic aspect, ie to study the risers.

REFERENCES

1. A J A Parlane & J R Still, 'Pipelines for subsea oil and gas transmission', *Materials Science and Technology*, Vol 4 (1988).
2. J J Ferret & C L Bournazel, 'Calculation of stresses and slip in structural layers of unbonded flexible pipes, *Journal of Offshore Mechanics and Arctic Engineering*, Vol 109 (August 1987).
3. *Offshore Engineering*, pp 38–39 (April 1986).
4. G Chaperon, 'Conduites flexibles en eau profonde', AMO 87.
5. Det Norske Veritas, TN 503, 'Flexible pipes and hoses for submarine pipeline systems'.
6. S Amilhau, P Besse, P Estrier & J Mallen, 'Quality and reliability of flexible pipes', AMO 87.
7. API RP 17B, 'Recommended practice for flexible pipes'.
8. Certification of design for Coflexip flexible steel pipes, Bureau Veritas, Technical Report (November 1987).
9. F A Dawans, J Jarrin, T O Lefevre & M Polisson, 'Improved thermoplastic materials for offshore flexible pipes', OTC Proceedings 5231 (1986).
10. Polyamid Inner Plastic Sheath Behaviour Certification, Bureau Veritas, Technical Report (January 1988).
11. P Savy, Essai API: 'Kill and choke' qualification gaine plastique, Coflexip Report (December 1986).
12. J J Ferret, C L Bournazel & J Rigaud, 'Evaluation of flexible pipes life expectancy under dynamic conditions', OTC Proceedings 5230 (1986).
13. C Pettenati-Auziere, 'Flexible dynamic riser state of art', The Way Forward for Floating Production Systems Conference (December 1985).

Appendix I

LIST OF NOTATIONS, CODES AND DOCUMENTS APPLICABLE TO FLEXIBLE STEEL PIPES

Flexible steel pipes, in common with many new products, are subjected to Codes, Regulations, Standards and Technical Notes which are not specifically intended for them. The list of documents, given below, is representative of the applicable codes and standards, but should not be considered as either all inclusive or exclusive of other standards relating to FSPs.

British Standards Institution

BS 1435 Rubber Hose Assemblies for Oil Suction and Discharge Service

BS 3592 Steel Wire for Rubber Hose Reinforcement

Lloyd's Register of Shipping

ICE/FIRE.OSG 1000/499 Flexible Hoses on Offshore Installations (Fire Tests)

American Petroleum Institute

RP 2Q Design and Operation of Marine Drilling Riser Systems

BUL 5C3 Formulas and Calculations for Casing, Tubing, Drill Pipe and Line Pipe Properties

SPEC 6FA Specification for Fire Test for Valves

RP 6G Through Flowline (TFL) Pump Down Systems

RP 17A Design and Operation of Subsea Production Systems

RP 17B Flexible Pipes

RP 1110 Pressure Testing of Liquid Petroleum Pipelines

RP 1111 Design, Construction, Operation and Maintenance of Offshore Hydrocarbon Pipelines

National Association of Corrosion Engineers

MR-01-75 Sulphide Stress Cracking Resistant Metallic Material for Oil Field Equipment

RP-01-75 Control of Internal Corrosion in Steel Pipelines and Piping Systems

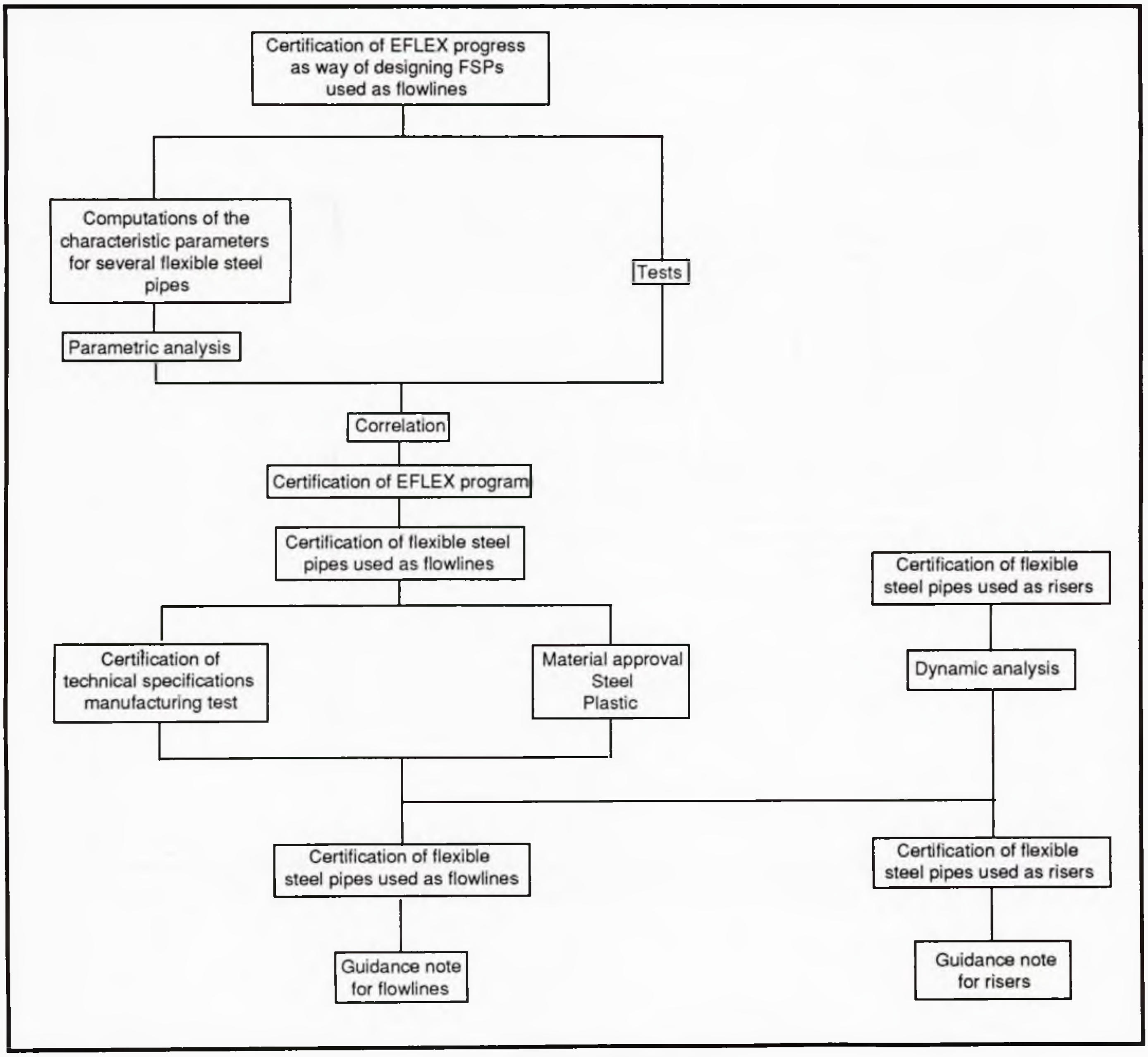
TM-01-77-B6 Testing of Materials for Resistance to Sulphide Stress Cracking at Ambient Temperature

Oil Companies International Marine Forum

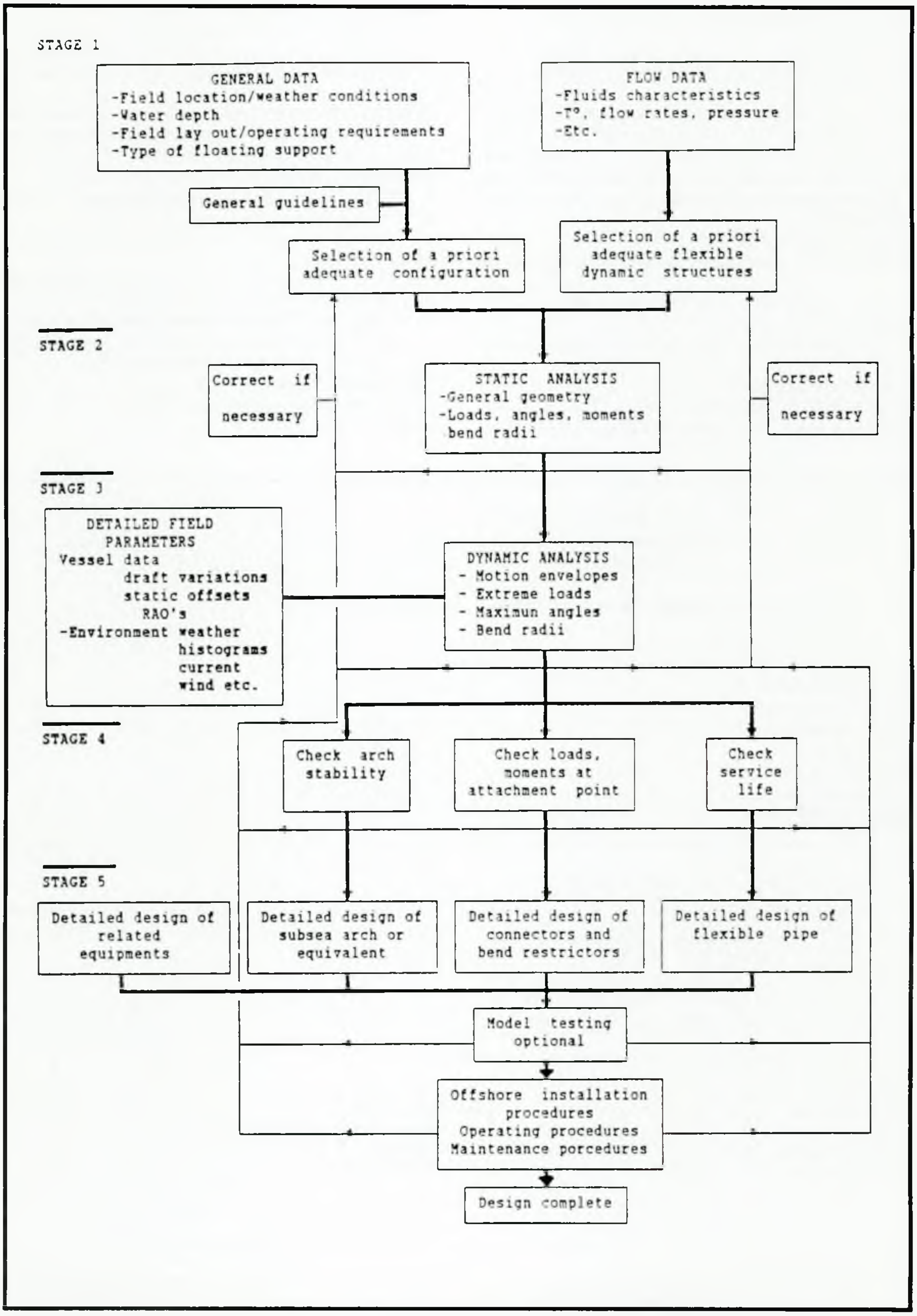
Specification for Rubber, Reinforced, Smooth Bore, Oil Suction and Discharge Hoses for Offshore Moorings

Det Norske Veritas

TN 503 Technical Note for Flexible Pipes and Hoses for Submarine Pipeline Systems



Appendix II: Study flow chart



Appendix III: Dynamic riser systems general design flow chart

Discussion

R V Thompson (President, IMarE) In conclusion Mr Smith (Bureau Veritas) mentioned an on-going experimental programme which is intended to determine the 'dynamic' performance of FSPs. Is it intended that these dynamic tests will investigate fatigue characteristics and, if so, will the tests include the effects of both pressure and temperature?

S G Amilhau *et al* (Coflexip/BV) Bureau Veritas and Coflexip are about to begin an experimental programme which is intended to certify the Coflexip flexible steel pipes in dynamic applications.

This study is based on two main parts:

1. the validation and the certification of computer programmes used by Coflexip.
2. the technical analysis of materials behaviour versus time.

In this second part of our study, dynamic tests will be performed in order to investigate fatigue characteristics (fatigue and wear tests on steel wire), and to study the influence of a dynamic service on the ageing of the plastic sheaths. These tests will include the effects of temperature and pressure.

A Soltanahmadi (Zentech Consultants) Please could the authors comment on the following:

1. the applicability of visco-elastic material properties to flexible riser systems.
2. the effect of compression on the mechanical properties of the pipe such as axial bending and torsional stiffness?

S G Amilhau *et al* (Coflexip/BV) Visco-elastic properties of materials induce visco-elastic behaviour of the flexible risers according to tension, bending and torsion. These phenomena are taken into account in the design of risers, especially with risers affected by vortex shedding.

There is no effect of tension or internal pressure on axial and torsional behaviour. There is a slight influence of tension and internal pressure on bending behaviour.

M K Smith (Shell Expro) By certification I assume Coflexip mean independent validation only. Can Coflexip or Bureau Veritas advise what the latest Department of Energy thinking is on certification of subsea flexibles?

I am impressed by the initiative shown by Coflexip and Bureau Veritas in demonstrating the certification of design and manufacture of FSPs and by the apparent approach to QA in design and construction. Can Coflexip tell us what specific QC and non-destructive testing checks they apply in manufacture to verify that the construction is indeed in compliance with the design?

S G Amilhau *et al* (Coflexip/BV) Our programme, concerning the certification of the Coflexip steel pipes used as flowlines, was presented to the Department of Energy last year. People we met seemed to be very interested in the work that has been performed on a product which is virtually unknown. So we cannot imagine that the Dept of Energy has changed its mind and is no longer interested in the certification of subsea flexibles.

F I Knight (Department of Energy) For the additional high temperature/pressure tests referred to during the presentation:

1. was the elastomeric liner of the test pipe 'Rilsan' or 'Cofluon'?
2. during temperature ramping was the applied pressure backed-off to compensate for thermal expansion of the test fluid?

Could we please have clarification of the 'transient response to impulsive loadings' cited as part of the dynamic test programme, ie whether the form of the applied transients are pressure or tensile loads?

Further to the overhead transparency shown by Dr Marion on elongation performance as a function of temperature for Rilsan material FSPs, is the same general pattern of behaviour observed for Cofluon material FSPs?

S G Amilhau *et al* (Coflexip/BV) The additional high temperature/high pressure tests were performed in answer to the Department of Energy safety alert following the *Ocean Odyssey* accident. These tests were scheduled to determine the performance of the present lines, used as kill and choke lines, in blow-out conditions. For these reasons, the flexible steel pipes, which were tested, included a Rilsan inner liner.

During these tests, the applied pressure was backed-off in order to ensure a constant internal pressure of 1500 psi in the flexible steel pipe.

The impulsive loadings cited as part of the dynamic programme are mechanical loadings, ie tensile force, torque or bending moment. The ageing behaviour of Cofluon is not the same as that observed for Rilsan.

Due to the thermal stability of the Cofluon, we consider that the Cofluon is not affected by the products generally used in our pipes under a certain temperature. We take 130°C as the maximum temperature to be on the safe side.

J S Kennedy (AGIP UK Ltd) Would the authors please give us some view of the problems of gas diffusion and how it is coped with?

There is currently no method of performing effective in-service inspections of FSPs. Are ways and means of doing this being developed? How do you advise operators on this problem?

S G Amilhau *et al* (Coflexip/BV) To evacuate the diffused gas from flowlines we use bursting discs on the pipe or relief valves on the end fitting. For risers, we use gas drainage through upper end fittings.

We usually advise operators to perform visual inspections. We are currently developing in-service monitoring using acoustic emission.

R C Kenison (BP Engineering) The use of the Eflex program has been to evaluate pipe using tension/torsion/pressure. What is the effect of bending and when do the non-linear torsion effects become important – ie lockout?

The temperature/pressure tests to determine long-term ageing have been performed. No clear definition of the criteria of acceptability was provided.

S G Amilhau *et al* (Coflexip/BV) There is no influence of bending on the static stresses in metallic layers of the pipe.

The non-linear effect of the torsion only exists for short lengths of pipe and for important torsion (for example jumpers).

The criteria of acceptability for long-term ageing are relative to the elongation performance: yield elongation > 30%, ultimate elongation > 1.5 yield elongation.

A J Farrand (BP) Is the failure of the thermoplastics used in flexible pipe construction a function of dynamic strain?

S G Amilhau *et al* (Coflexip/BV) The choice of material depends on the functional requirements.

For instance, dynamic risers have an external sheath made of polyamid, while static flowlines have an external sheath made of polyethylene.