Experimental and analytical study of thermal stresses during pipe freezing

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Abstract: A review of experimental investigations on stress development during the blockage of a water-filled pipe by freezing was undertaken with the parallel development of an effective finite element thermal stress model. A wide spread of measured stress values was noted as well as a degree of uncertainty in the cases when the gauge output did not return to zero at the end of the freezing cycle. A methodical examination of stress– and temperature–time histories showed that it is possible to divide a freeze into three stages: filling, constant wall temperature and thawing. Since each stage produces quantitatively and qualitatively different stress states, it needs to be examined separately. The filling stage causes stresses through the pipe wall, which vary from tensile on the outside surface to compressive on the inside. These stresses can be significant but are also short lived and their magnitude may be greatly affected in practice by the way that the coolant is applied. During the constant-temperature phase, when the pipe wall temperature is maintained at the coolant temperature, the stresses are mainly compressive, their variation is small within the freezing jacket and they appear to depend on the diameter–thickness ratio. A significant difference between the behaviour within the jacket and at the end of the jacket is sometimes observed. Finally, tensile stresses arise during the reverse process of thawing. Comparison of experimental data with numerical predictions confirmed the above observations regarding the magnitude, distribution and nature of the developing stresses. There are important quantitative and qualitative differences between measured and predicted values, which can be explained by the uncertainty and scarcity of data as well as the simplicity of the adopted material model for ice behaviour.

Keywords: experimental study, analytical study, thermal stresses, pipe freezing

NOTATION

A	designation for tests by Ashfield [2]
D_i	pipe inner diameter
D_m	pipe mean diameter
F	designation for tests by Fugro [4]
K	designation for tests by Keary *et al.* [3]
L	designation for tests by Lannoy and Flaix [5]
L_j	jacket length
r	radial coordinate
t	pipe thickness
T	temperature
T_c	cooling temperature
z	axial (longitudinal) coordinate (origin at the cooling jacket centre)

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1 INTRODUCTION

The technique of freezing the contents of a water-filled pipeline in order to provide a temporary blockage and to isolate a section of it is widely used in many industries both onshore and offshore. A jacket is fitted around the pipe over a length typically twice to three times its diameter and then filled with a cryogen such as liquid nitrogen, which boils at −196 °C. Alternatively, the pipe may be cooled at higher temperature levels by pumping a refrigerant through tubes wrapped around it. As the pipe cools, ice is formed on the inside of the pipe over the length of the coolant jacket. The ice grows radially inwards, forming a constriction in the pipe. Eventually, the duct closes at or near the centre-line. Ice growth continues in the axial direction until a stable ice plug with concave ends is fully formed.

There is concern over the level of stresses that the pipe is subjected to during freezing, which inhibits the application of the process, especially in cases where the consequences of pipe failure would be dangerous or expensive. Stresses develop as a result of temperature gradients in the pipe wall and differential contraction between ice and steel. Their actual level has not been quantified with satisfactory accuracy and completeness. Several experimental studies have been carried out over the past 18 years but the wide variation in the experimental conditions, i.e. pipe geometry, freezing methods and the level of instrumentation, makes it difficult to compare the results in order to reach definitive conclusions.

Information on pipe failures during or related to pipe freezing are extremely rare and not widely publicized. Some limited information, covered by commercial confidentiality, was made available to the present authors. This was mostly in the form of metallurgical studies, tracing the origin of failures rather than providing detailed information on the corresponding freezing conditions. Pipes were reported to fail mostly by brittle fracture initiated within or near the edge of the freezing jacket. There was always some evidence of additional stresses due to causes other than freezing. No failures occurred during the initial cooling and, in all but one case, failure occurred after the plug was fully formed. It was also noted that fracture did not necessarily originate from a weld in the pipe. It appears likely that thermal stresses due to the freezing process, combined with residual or other mechanically induced stresses, and the presence of defects combined with the low fracture toughness of steel at low temperatures were responsible for the reported failures.

The review of investigations into the stress development during pipe freezing found significant inconsistencies among the available experimental data. One study [**1**], which used extensive instrumentation on freezes under a number of different conditions, resulted in quite different stress patterns compared with other, previously or subsequently obtained data [**2–4**]. On the other hand, no published record could be found of any earlier attempt at numerical modelling of the thermal–mechanical interaction between forming ice plug and steel pipe wall. Simple stress analyses have been proposed but they are restricted to modelling the behaviour of only the pipe material. Solutions have been obtained for temperature gradients in the radial, axial and circumferential directions assuming simple interaction models between ice plug and pipe wall [**5, 6**]. Ice interacting with other solids has been analysed by the finite element method (FEM) but within engineering contexts and conditions imposing very different modelling requirements on the respective formulations. Recent examples of such applications include simulations of ice indentations [**7, 8**] and interactions with offshore structures [**9, 10**]. Common characteristics of these problems are predominantly compressive stresses, relatively high temperatures, viscoelastic ice behaviour and, possibly, strength-reducing damage due to crack formation.

The aim of the work described in this paper was a systematic study of the stress measurements during freezing, which have been reported as a result of several test programmes. The specific objectives were to assess the consistency between the various sets of results and to obtain an empirical relation for the prediction of stresses generated under particular freeze conditions. A finite element model for stress prediction, initiated during the early stages of pipe freezing research at the University of Southampton [**3, 11**], was developed further into a more versatile analytical tool for application to various freezing conditions. This model was applied to the several test conditions reviewed as a means of its own validation as well as for gaining a better insight into the whole pipe-freezing process.

2 DESCRIPTION OF EXPERIMENTS

The unique pattern of stress distribution and magnitude, observed during a particular experimental investigation [**1**], has already been studied in some depth [**3, 6, 11**]. Since these results did not conform to other existing experimental data, they were not included in the present review. The present authors had access to a number of other sources originating mainly from industry and, therefore, not in the public domain. The data provided by these sources were carefully examined but found inadequate because they were incomplete or irrelevant or, in some cases, clearly unreliable.

Data were collected and analysed from four test programmes identified as having produced results of satisfactory breadth, relevance and a certain degree of consistency. Each test series was designated a capital letter for subsequent reference and identification. The respective pipe and jacket dimensions are listed in Table 1 while the location of instrumentation used is shown in Fig. 1. In all cases, the pipe was horizontal, unconstrained in the axial direction, fully filled with water and frozen using liquid nitrogen. Conditions particular to each programme are briefly described next.

2.1 Ashfield (tests A)

This work [**2**] was the most complete of several pipe-freezing projects carried out at the University of South-

Table 1 Dimensions of pipes used in experiments

Test programme	Mean diameter D_m (mm)	Wall thickness t (mm)	Jacket length L_j (mm)
A [**2**]	53.65	3.65	150
L [**5**]	196	23	520
K [**3**]	264	10	528
F [**4**]	420.4	14	840

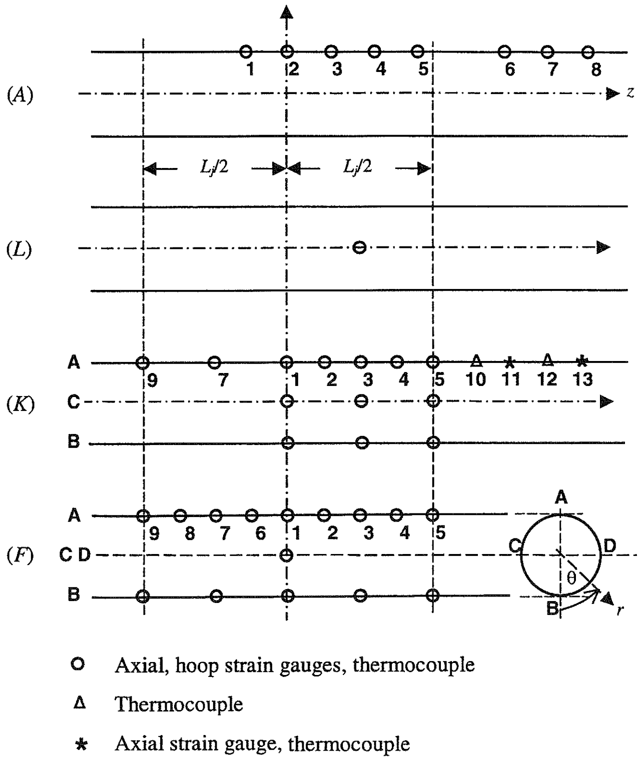

Fig. 1 Strain gauge locations in the four reviewed test programmes (see Table 1)

ampton in the early 1980s, which produced substantial information on the time as well as the space variation in thermal strains on the top surface of the pipe. The tests were performed on a seam-welded pipe 1.1 m long instrumented as shown in Fig. 1 (tests A). The pipe remained unpressurized throughout each freeze. For the purpose of the present review, measured data from three freezes were converted to hoop and axial stresses at certain points in time.

2.2 Lannoy and Flaix (tests L)

A series of freezes was performed using pipes of various sizes and materials [**5**]. A complete set of results was displayed from one test with a stainless steel pipe at three circumferential locations, i.e. top ($\theta = \pi$), middle ($\theta = \pi/2$) and at $\theta = 2\pi/3$, all at the same axial distance, approximately 290 mm, from the longitudinal centre of the jacket as shown in Fig. 1 (tests L). The test was performed under a constant pressure of 0.2–0.3 MPa and a flowrate of 0.06 kg/s due to convection. These conditions are not expected to have affected the measured stresses significantly. The reported long freezing period implied that the deviation from axisymmetry must have been rather strong but it was not possible to confirm this without stress measurements from the bottom surface. Since the stresses measured at the neutral axis of the pipe cross-section are expected to be the closest to those produced under ideal axisymmetric conditions, they were given more weight in the present review. The reported measurement error for stresses was ±15 MPa.

2.3 Keary *et al.* (tests K)

A number of tests were carried out [**3**] with a total of 11 strain gauge pairs as shown in Fig. 1 (tests K). The results discussed here were obtained from two tests both performed under atmospheric pressure throughout. Test K1 involved freezing plain tap water while, in test K2, a convection-inhibiting gel was mixed with the water in order to generate heat transfer conditions as close as possible to axisymmetric. The gel itself was not expected to have any effect on the thermomechanical properties of ice.

In order to assist the development of axisymmetric freezing conditions, the jacket was filled from the bottom (location B), as quickly as possible and without impingement on the pipe. Before each freeze, the water was drained and the pipe wall cleaned, by brushing and rinsing, to ensure that the water and pipe wall did not become rusty. The pressure inside the pipe was maintained at atmospheric pressure. This investigation included 'dry' tests, i.e. freezing without water inside the pipe to measure stresses due only to temperature gradients in pipe wall and thus, indirectly, assess the effect of ice adhesion. Figure 2 shows the complete time histories of both hoop and axial stresses obtained from test K2 at gauge locations 7A and 3C, which can be identified by reference to Fig. 1 (tests K). A logarithmic time-scale was adopted in order to accommodate the long thawing phase into the same single plots.

2.4 Fugro (tests F)

In this programme [**4**], four tests were performed designated freezes F1 to F4. A total of 16 strain gauge pairs (hoop and axial) were used, all located within the jacket as shown in Fig. 1 (tests F). The pipe was pre-cooled with nitrogen gas to approximately 0 °C before filling the jacket with liquid nitrogen. After plug closure, the nitrogen flow was maintained for 30 min before the plug was left to thaw.

There were variations among the four freezes in terms of the pipe orientation relative to the liquid nitrogen inlet position as well as the applications of pressure. In freezes F1 and F2, the location A shown in Fig. 1 (tests F) was at the bottom of the pipe, with the nitrogen inlet directed on to it in line with gauge 7. It may be presumed that, depending on the inlet pressure, the nitrogen impinged on the pipe directly above the inlet, then fell back to the bottom of the jacket and filled it from the bottom

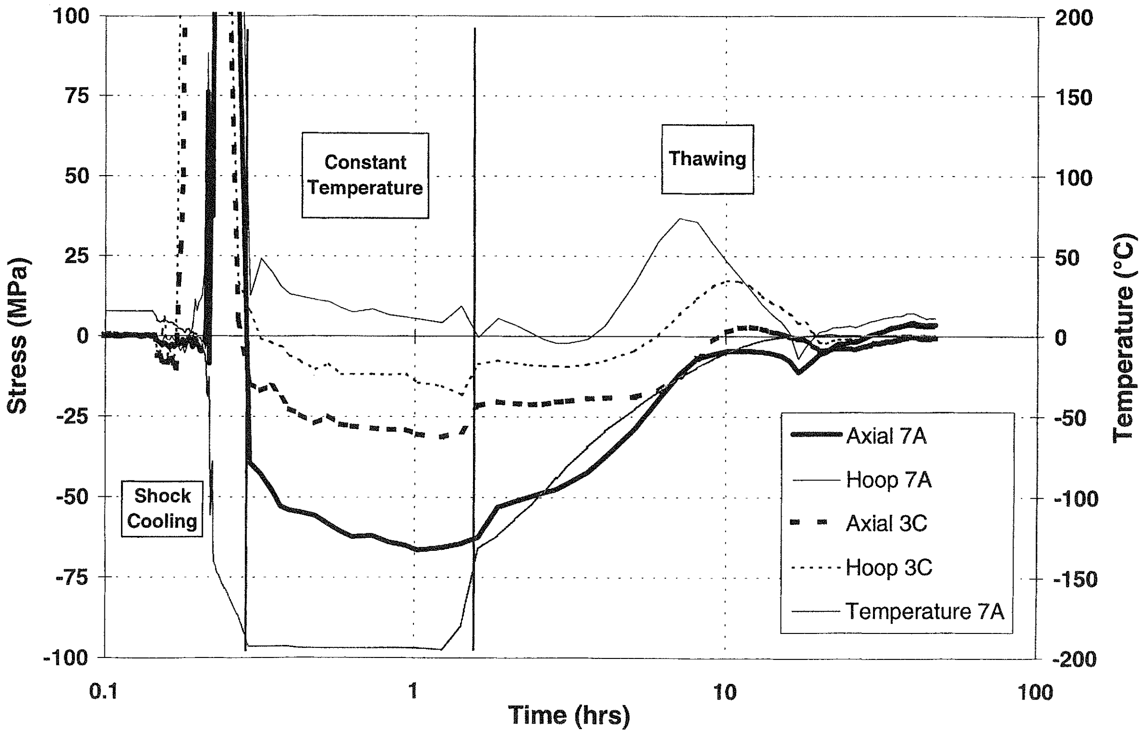

Fig. 2 Measured stress– and temperature–time histories from test K2 [**3**]

upwards. The pressure was maintained at 1 MPa throughout the freeze.

In freeze F3, the pipe had been rotated through 180° so that location A was on top. In this case, the liquid nitrogen would have impinged on the pipe at the top and drained around the pipe into the bottom of the jacket. During this test, the pressure was maintained at 1 MPa throughout freezing but released immediately prior to thawing. In test F4, the pipe orientation relative to inlet was as in test F3 but the pressure was held at atmospheric pressure during freezing. After plug closure, the closed end of the pipe was pressurized to 1 MPa, held for 10 min and then depressurized. Both ends of the pipe were then pressurized to 1 MPa, held for 10 min and then depressurized; finally the plug was allowed to thaw.

The initial temperatures in tests F2 and F4 were less than 0 °C, suggesting that the plug from the previous freeze had not completely thawed. The measurements were adjusted to give zero stresses at the start of an experiment; therefore they do not include the effect of the internal pressure of 1 MPa. Typical axial as well as hoop stress–time histories obtained from gauges 3A and 6A, during test F1, are shown in Fig. 3.

3 EXPERIMENTAL OBSERVATIONS

From the time histories of Figs 2 and 3, it is clear that the pipe-freezing process can be divided into three stages: filling of the jacket, plug formation with a constant pipe wall temperature and, finally, thawing. Because of the differences in nature, magnitude, distribution and duration of stresses developed during these stages, each will be presented and discussed in detail separately.

3.1 Filling stage

Stresses arise during the filling stage primarily due to the high temperature gradients generated through the pipe wall. They are termed 'shock cooling' stresses because they are caused by the thermal shock resulting from the sudden application of liquid nitrogen. This event causes equal surface stresses in the hoop and axial directions, which are tensile on the outer surface and compressive on the inner surface. As soon as liquid nitrogen is applied, the wall is cooled on its outer surface, giving a local steep temperature gradient. Very high stresses are anticipated during this phase but only for a short length of time. The temperature profile stabilizes quickly to a 'steady state' logarithmic form and the 'shock cooling' stresses drop to their 'steady state' values as heat is conducted out through the pipe wall. The temperature on the inner surface drops to 0 °C and, as soon as ice starts to form, the temperature difference through the wall and therefore the 'shock cooling' stresses decrease rapidly.

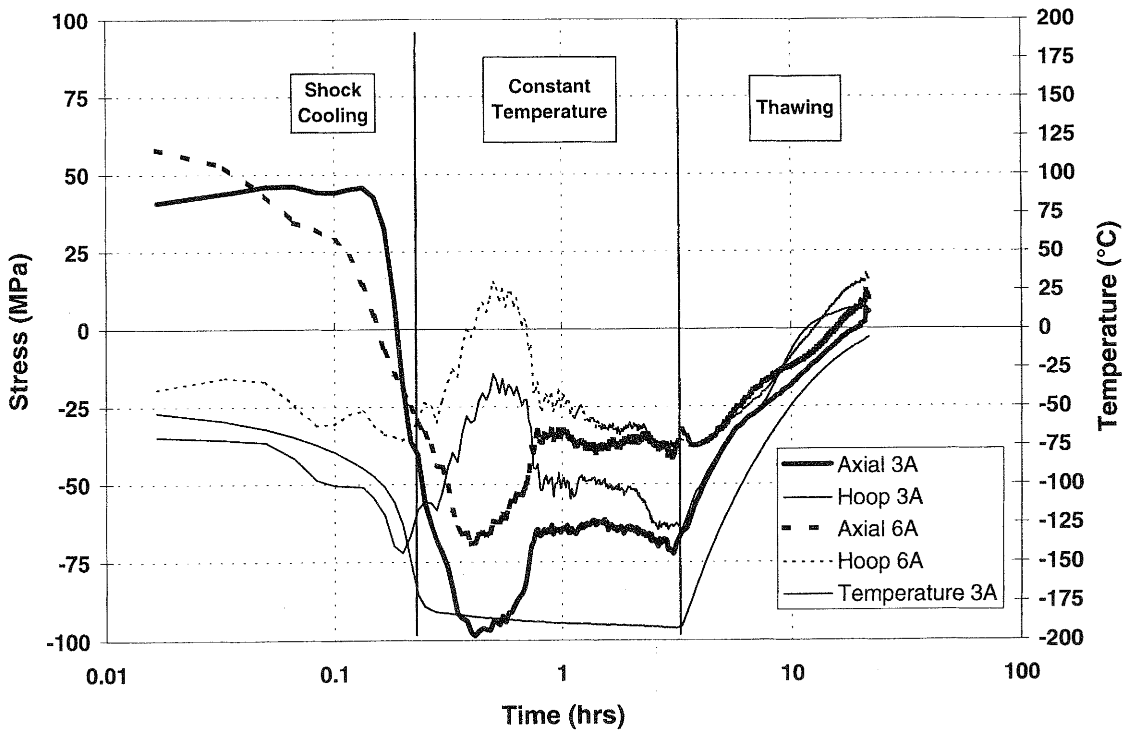

Fig. 3 Measured stress– and temperature–time histories from test F1 [**4**]

3.2 Constant-temperature phase (CTP)

Once the pipe is covered in liquid nitrogen, the temperature on the outside of the pipe stabilizes at around −196 °C within the jacket. This is clearly seen in the stress–time histories in Figs 2 and 3. The stresses generated within the freezing jacket during this phase result from the action of the forming plug on the pipe, while the stresses at the ends of the jacket are also affected by the axial temperature gradient, which changes as the plug grows. In contrast with the 'shock cooling' stresses, the stresses generated during the constant-temperature phase (CTP) persist over a longer period. During this phase, the fracture toughness of the pipe wall is reduced through its thickness. Invasive work carried out on the pipe is likely to cause additional loads, increasing the risk of fracture.

A preliminary examination of the experimental data during this phase showed that, although the stress levels vary from gauge to gauge, they remain roughly constant with time while the stress patterns appear approximately repeatable between experiments. The data were then studied in greater detail to confirm quantitatively the validity of this observation but also to assess their deviation from the ideal symmetric behaviour assumed in analysis. In the tests reported by Ashfield [**2**] and Lannoy and Flaix [**5**], the freeze times were short so that the CTP did not constitute a significant proportion of the experiment time. The significant amount of raw experimental data produced by Keary *et al.* [**3**] and Fugro [**4**] was reduced by identifying their average and extreme values.

3.2.1 Time variation

The variation in the measured stresses was found to be within ±10 MPa from their mean values for the majority of gauges and experiments. The clear exception was Fugro test F3 where wide stress deviations were observed at most gauges. Since the cause of this was not clear, the data from this freeze were discarded. In all other cases, the variation in stresses was considered sufficiently low for the mean value to be used as the representative CTP stress for each gauge location.

3.2.2 Repeatability

The difference between the maximum and minimum stresses measured at each gauge from all freezes in each test programme was evaluated. This gave an indication of the range of values obtained from successive freezes under nominally similar conditions. In the case of Fugro tests F1, F2 and F4, the stresses were repeatable within 20 MPa for 82 per cent of the gauges. There was less than 17 MPa variation between stresses measured by Keary *et al.* during tests K1 and K2. These results allowed the use of the average (over freezes) of the mean (over time) stress as the characteristic stress value for a particular measurement location.

3.2.3 Axisymmetry

In an axisymmetric freeze, the difference between measurements at various circumferential locations is expected to be small. A significant and consistent difference between the stress on the side of the pipe closest to the liquid nitrogen inlet and the stress on the opposite side can be attributed to non-axisymmetric cooling. The inlet side is being cooled for a longer period and therefore cooling on this side extends over a greater length than that on the opposite side. This causes bending stresses, tensile on the cooler inlet side and compressive on the opposite side.

The difference between stresses on the inlet and non-inlet sides was evaluated at the locations where there were gauges on both sides of the pipe, namely locations 1 and 3 in the tests performed by Keary *et al.* and locations 1, 3 and 7 in the Fugro tests (Fig. 1). As anticipated, the stresses measured on the inlet side of the pipe were higher than those on the opposite side in both test programmes. This difference was therefore an indication of non-axisymmetric cooling. The average of the two values at each location is a reasonable estimate of the stress that would have developed under ideally axisymmetric conditions.

On average, the results obtained by Keary *et al.* were found to conform more to axisymmetric behaviour than those obtained by Fugro. This may be attributed to the efforts by the former investigators to ensure freezing conditions as close as possible to axisymmetric as well as the fast filling of the jacket in the latter experiments. Apart from one exception, all other values of variation from average difference were less than 20 MPa.

3.2.4 Longitudinal symmetry

The condition of symmetry with respect to the centre of the jacket appears to be less evident in all experimental results. Significant axial variation in both axial and hoop average stresses can be noted by referring to Fig. 4 which was based on data obtained by Ashfield, Keary *et al.* and Fugro. The axial stress distribution is approximately symmetric and of a 'bell' form, with one side steeper than the other. The hoop stresses show a similar variation to the axial stresses on one side of the centre-line but remain constant at around their central value on the other side. It is also noted that the hoop stresses measured by Keary *et al.* are a mirror image of the corresponding results of Ashfield and of Fugro. The low magnitude of Ashfield's data does not allow a clear comparison with those from the other two studies but plotted as ratios to their range do generally show the same trends in both axial and hoop stress. Changing the inlet location to a symmetric location with respect to the centre of the jacket did not affect the longitudinal stress distribution in Fugro's freezes. Thus the cause of longitudinal asymmetry in certain stress distributions within the jacket is not obvious. Such a variation was noted by Keary *et al.* also in 'dry' freezing tests, i.e. in the absence of ice formation inside the pipe [**3**].

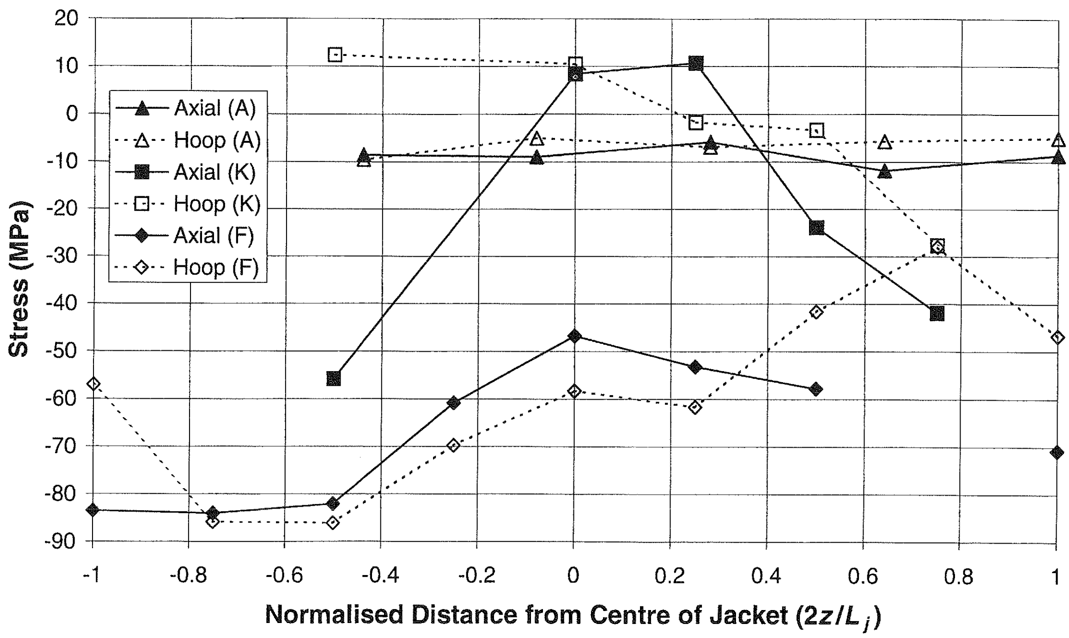

Fig. 4 Longitudinal variation in the average measured CTP stresses

3.3 Thawing phase

During the thawing phase, the nitrogen supply is stopped and the plug is allowed to warm up. This is a very slow process controlled by the heat transfer from the outer surface of the pipe to the surroundings through convection. The plug warms up almost isothermally.

The manner by which the ice plug forms, i.e. by cracking and refreezing, gradually increases the mass of ice in the plug. This results in some stress relief during freezing but, during thawing, the ice expands again as it becomes warmer and the difference between expansion rates of ice and steel may cause compressive stresses in the ice and tensile in the pipe wall. As the temperature increases, the growth of these stresses may be limited by the viscoelastic behaviour of ice. The experimental results obtained by Keary *et al.* and Fugro show this form of stress development during thawing, which was not noted in the 'dry' experiments performed by Keary *et al.*

4 ANALYSIS

A closed-form solution exists for the 'steady state' 'shock cooling' stresses [**12**]. In certain experiments, however, the measured 'shock cooling' stresses were found to be greater than those predicted by the 'steady state' solution. In order to explain this, a numerical solution based on the finite difference method was developed for the coupled thermal stress and heat transfer equations governing the transient axisymmetric temperature and stress distributions through the pipe wall before any ice has been formed.

A more elaborate numerical model was required for stress prediction in the longer term, i.e. including the CTP when ice gradually grows to form a plug. The analysis developed for that purpose was based on ANSYS, a general-purpose finite element package [**13**], available on Silicon Graphics workstations. The time-dependent ice growth was simulated by dividing the plug into discrete layers and solving the problem in a series of steps in which 'new' ice was added, the temperature distribution updated and the stress recalculated. The problem was assumed to be axisymmetric and also symmetric with respect to the centre of the jacket. The time history of ice plug formation was calculated separately using a solidification model [**14**], which provided the ice/water interface geometry and temperature distribution during ice growth for input into the ANSYS finite element program. The ice layers had variable thickness to represent the uneven ice growth in the axial direction.

The selection of an appropriate material model for ice is particularly difficult because of the complex ice behaviour under pipe-freezing conditions. Since its thermal expansion coefficient is higher than that of steel, the ice is forced into tension during freezing. Ice is normally expected to creep at high temperatures but turns brittle at the low temperatures of a liquid nitrogen freeze. Because of its relatively low strength, it fractures but its surface cracks refill with water, which freezes, forming new stress-free ice. This is a mechanism of stress relief, which limits the magnitude of the developed stresses in ice without removing its strength altogether. For this reason, ice was modelled as elastic–perfectly plastic as the closest approximation of this behaviour available on ANSYS, with a 'yield' stress increasing with decreasing temperature. Published ice strength data [**15, 16**] indicated that the yield stress of polycrystalline ice is approximately 1 MPa at 0 °C and rises to 2 MPa at −25 °C. In the absence of any other relevant data at lower temperatures, this input was arbitrarily extrapolated to 9 MPa at −200 °C in the finite element simulations based on the assumption that the strength of ice will continue to rise as the temperature drops.

The originally developed analytical procedure [**3, 11**] starts with the application of the solidification model [**14**] to the given freezing conditions. Results for the plug profile and temperature distribution are extracted at certain points in time corresponding to equal increments in ice thickness. The plug profiles are entered into an ANSYS batch file with the appropriate solid modelling commands to generate the geometry of the pipe and the ice layers. After this file is run, the areas are meshed and the nodal locations are written to a text file. Then, the temperature predictions of the solidification model are interpolated to the nodal locations of the finite element model and stored for each load step. ANSYS reads and applies these nodal temperatures sequentially to the corresponding freeze stage, thus generating the transient solution for the series of the adopted load steps.

This elaborate procedure was simplified to make it directly applicable to different freezing conditions. The aim was a single unified ANSYS program requiring as input only the inner pipe diameter, the jacket length, the wall thickness as well as the coolant temperature. This was achieved by generating a dimensionless solution for the plug profiles and temperature distributions, which could then be scaled to the given conditions.

The scaling method relies on a reference set of data for plug growth produced by the solidification model which is then transformed into an ANSYS input command file generating an incrementally expanding finite element model and a series of data input files containing the corresponding temperature distributions read as load steps. Temperature profiles were extracted at times corresponding to equal ice thickness increments at the longitudinal centre of the plug. Thus, a total of ten load steps were produced with load step 1 corresponding to the 'shock cooling' stage when there is no ice and the temperature difference through the pipe wall is large. The eleventh load step was extracted just after plug closure while six more steps were obtained at times of uniform plug growth in the axial direction.

Dimensionless radial and axial coordinates were defined by

$$\bar{r} = \begin{cases} \dfrac{r}{D_\mathrm{i}}, & r \leqslant 0.5D_\mathrm{i} \\ 0.5 + \dfrac{r - 0.5D_\mathrm{i}}{t}, & r > 0.5D_\mathrm{i} \end{cases} \tag{1}$$

$$\bar{z} = \begin{cases} \dfrac{2z}{L_\mathrm{j}}, & z < 0.3L_\mathrm{j} \\ 0.6 + \dfrac{z - 0.3L_\mathrm{j}}{D_\mathrm{i}}, & z \geqslant 0.3L_\mathrm{j} \end{cases} \tag{2}$$

where D_i is the inner pipe diameter, L_j the jacket length and t the wall thickness. Thus r is scaled with respect to D_i inside the pipe and with respect to t through the wall thickness. The axial coordinate z is scaled with respect to the jacket length L_j within the inner 60 per cent of the jacket, where the axial temperature gradient has been predicted to be negligible by the solidification model. Outside this range, z is scaled with respect to D_i so that the temperature profile is not distorted by variations in the jacket length. Thus, the scaling can be applied to freezes with any jacket length. Finally, the coolant temperature T_c is used to define a dimensionless temperature by

$$\bar{T} = \frac{T}{-T_\mathrm{c}} \tag{3}$$

The main assumption of the adopted scheme is that, for a particular pipe geometry and coolant temperature, it generates a nodal temperature distribution, which is approximately the same as that predicted by the solidification model. This was found to be inaccurate when the coolant temperature was varied because the temperature dependences of the thermal conductivity and heat capacity of ice affects the temperature distribution. The scheme had therefore to be refined further by obtaining two sets of reference data for two coolant temperatures: T_c1 and T_c2. Each set was scaled separately to give two nodal dimensionless temperatures $\bar{T}_1$ and $\bar{T}_2$ from which the final dimensionless nodal temperature was obtained by linear interpolation between these two values:

$$\bar{T} = \bar{T}_1 + \frac{T_\mathrm{c} - T_\mathrm{c1}}{T_\mathrm{c2} - T_\mathrm{c1}}(\bar{T}_2 - \bar{T}_1) \tag{4}$$

The plug geometries obtained from the two runs were shown to be almost the same. The analysis of a freeze is thus performed in the following stages: the element and material types are defined, the parameters D_i, t, L_j and T_c are specified and the nodal locations are calculated automatically, using the inverse relations of equations (1) and (2):

$$r = \begin{cases} \bar{r}D_\mathrm{i}, & \bar{r} \leqslant 0.5 \\ 0.5D_\mathrm{i} + (\bar{r} - 0.5)t, & \bar{r} > 0.5 \end{cases} \tag{5}$$

$$z = \begin{cases} 0.5L_\mathrm{j}\bar{z}, & \bar{z} < 0.6 \\ (\bar{z} - 0.6)D_\mathrm{i} + 0.3L_\mathrm{j}, & \bar{z} \geqslant 0.6 \end{cases} \tag{6}$$

The finite element mesh is directly generated and symmetry conditions applied relative to the centre of the jacket. The analysis then enters the incremental solution phase. At the beginning of each load step, the elements belonging to the 'new' ice layer are activated, the new temperature distribution, automatically calculated using equations (3) and (4), is read in and the current stress distribution calculated.

In the present application of the finite element model, the reference plug growth data were obtained for coolant temperatures $T_\mathrm{c1} = -100\,°\mathrm{C}$ and $T_\mathrm{c2} = -200\,°\mathrm{C}$, a pipe of 50 mm diameter with a wall thickness of 2.5 mm and a jacket length twice the diameter. Figure 5 shows the resulting geometry of the reference finite element model with a sample input temperature distribution corresponding to the tenth load step, i.e. just before plug closure. The contour plot indicates the variation in the temperature change from the ambient temperature. The dark-grey areas, adjacent to the water areas in the ice region have an above-zero temperature and therefore are not yet activated.

The scheme for generating ANSYS input from standard dimensionless data was tested by applying it to Fugro's geometric data (Table 1) with a coolant temperature $T_\mathrm{c} = -50\,°\mathrm{C}$. The stress results were compared with corresponding predictions by the more rigorous solution method, which relies on input generated by a parallel run of the solidification model. The good agreement between these two sets of results for both hoop and axial stresses confirmed the validity of the scheme.

Simulating thawing by FEM has also been attempted [**11**], assuming that the plug does not change significantly and remains elastic through this phase. If the stresses are uniformly zero just before the plug melts off the pipe wall, then the stress history and distribution since the end of the freeze can be back-calculated from the stress changes due to temperature history during thawing. Such temperature distributions were determined by applying a thermofluid model specifically developed for pipe freezing [**14**] and then entered as input to a stepwise application of the FEM stress model. This approach is based on superposition, which is not really valid for a non-linear process. A more realistic non-linear analysis

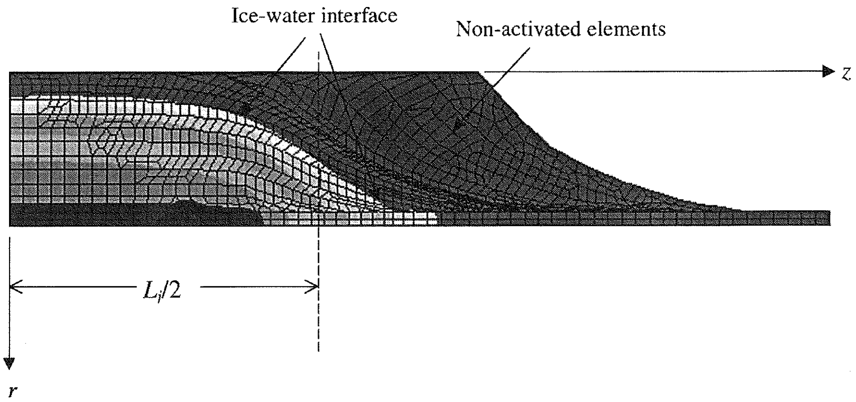

Fig. 5 Finite element model with the temperature distribution for an intermediate load step

of the thawing phase must be combined with a reliable assessment of stresses at the end of the freeze. It is also important to account for the viscoelasticity of ice, which is more pronounced at the later stages of thawing when the temperature is closer to zero.

5 RESULTS AND DISCUSSION

5.1 'Shock cooling' stresses

The maximum tensile stresses recorded within the jacket during the filling process in both hoop and axial directions were identified and averaged for each set of experimental results. These average values are listed in Table 2, together with the corresponding maximum values recorded and the theoretical predictions from the 'steady state' solution. The low stresses measured by Fugro [**4**] show the effect of pre-cooling the pipe with nitrogen vapour. Ashfield [**2**] measured particularly low stresses, the result of having a thin pipe wall, which cooled quickly.

As shown in Fig. 6, the 'steady state' stresses essentially depend on the difference between the ambient temperature and coolant temperature and, only weakly, on the diameter–thickness ratio. If the pipe is thick walled and of small diameter, the diameter–thickness ratio will also affect the stress; increasing this ratio above 15 minimizes the effect of geometry.

The transient stresses, shown in Fig. 7, were obtained using the Fugro geometric data with the outside of the pipe suddenly cooled to −196 °C while the inside of the pipe wall is maintained at 20 °C. Initially there is a very steep temperature profile at the outer surface, which evolves over a period of around 10 s to the 'steady state' logarithmic profile. Although this represents an extreme situation, it is worth noting that the resulting axial and hoop stress through the wall are nearly zero in the inner section of the pipe wall away from the cooled region, increasing to maximum tensile values at the outer surface. As the temperature profile becomes more uniform through the wall with time, the tensile stresses on the outer surface decrease to a constant level and compressive stresses develop on the inner surface. The axial and hoop stress–time histories are almost identical and overlay each other in Fig. 7. It is noted that both stresses on the outer surface may reach almost double the 'steady state' level but these stresses develop only through a very small depth and for a short period of time, dropping quickly to the 'steady state' values.

The tensile stresses generated during the filling stage are significant and may add to existing stresses, e.g. from pressurization. However, they are localized, experienced only for a short time, exist when the pipe wall is only partially embrittled and can be minimized by pre-cooling. These stresses will usually have subsided well before work is carried out on the pipe.

Table 2 'Shock cooling' stresses

		Stresses (MPa)		
		Measured		
Test programme	D_m/t	Average	Maximum	Predicted steady state
A	14.7	53	97	319
L	8.5	203	250	310
K	26.4	266	379	328
F	30	39	138	329

5.2 CTP stresses

The time histories of the predicted axial and hoop stresses at any node of the finite element model can be obtained indirectly by converting the load step values back into time for the same freezing conditions, which generated the corresponding plug profiles. The estimated freeze time was taken to be proportional to the square of the pipe

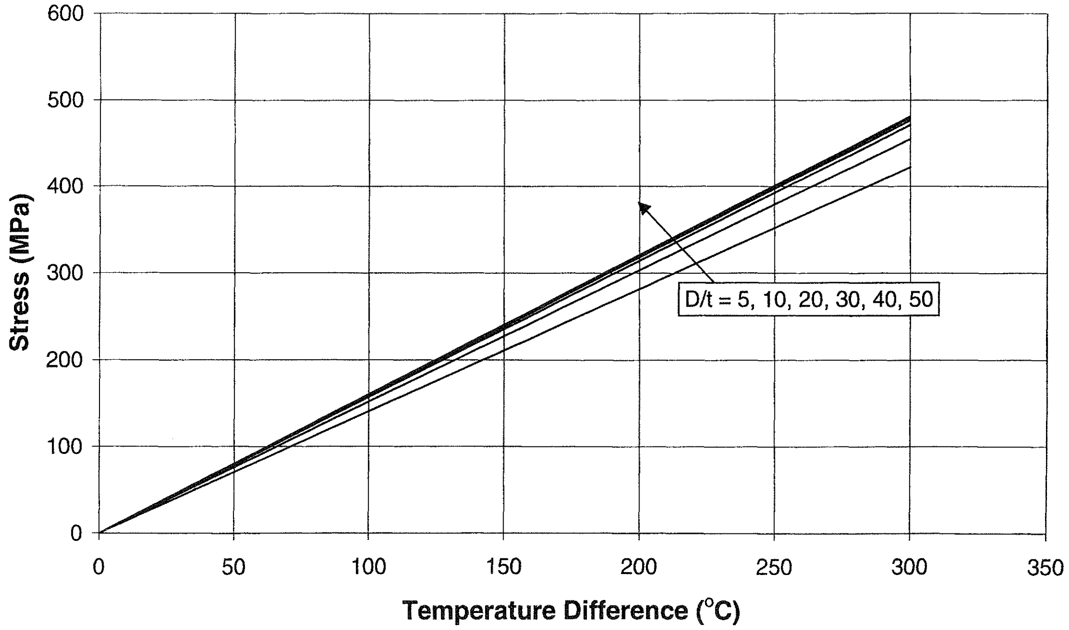

Fig. 6 Steady state 'shock cooling' stresses dependence on temperature difference and D_m/t

diameter; this is accurate for conditions of freezing water initially close to 0 °C [**17**]. Plots of analytical results based on the Fugro test geometry had a qualitative similarity to the respective experimental data shown in Figs 2 and 3.

Figure 8 shows the variations in the predicted axial stress on the outer surface of the pipe at various times (load steps) during freezing for the pipe tested by Keary *et al.* These stresses appear to be generally constant inside the jacket, with increasing magnitude during the freeze. Similar variations were obtained for the Fugro geometric data, as shown in Fig. 9. The corresponding measured stresses are also shown in these two figures, averaged for each longitudinal gauge location. Reasonably good qualitative agreement between analytical and experimental stress patterns can be noted.

One of the objectives of this study was to identify any dependence of CTP stresses on the pipe dimensions. It was noted that the ends of the jacket take longer to reach the CTP because they are partly affected by the axial

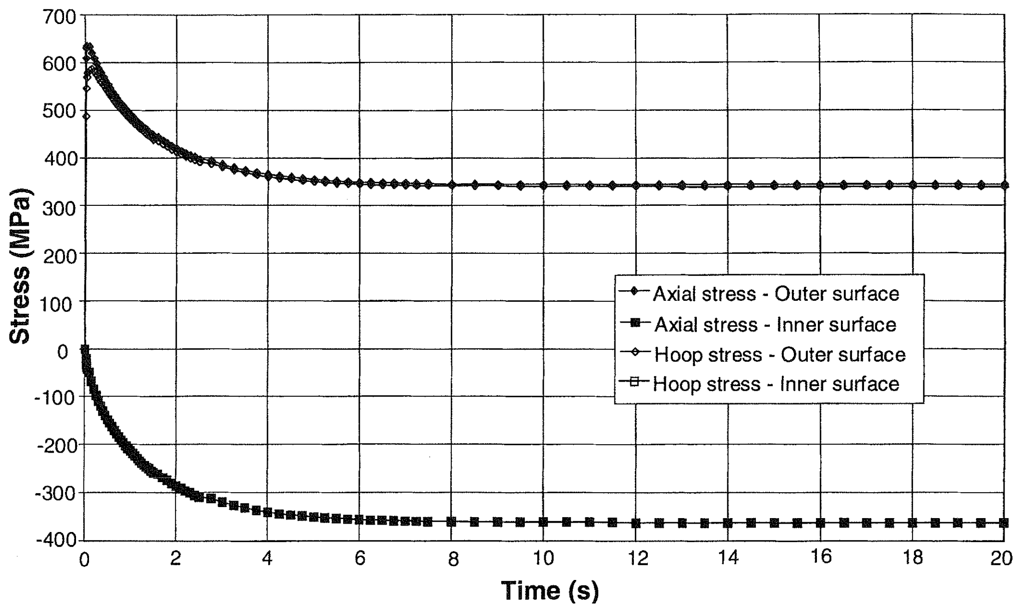

Fig. 7 Time history of transient 'shock cooling' stresses

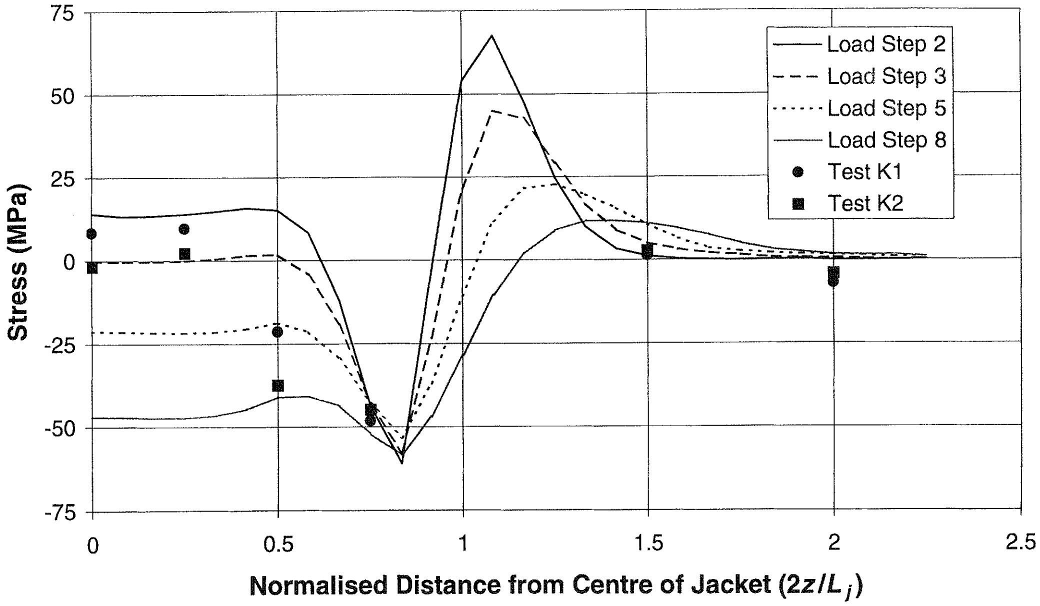

Fig. 8 Predicted longitudinal stress variation and test data obtained by Keary *et al.*

growth of the plug. As shown in Figs 8 and 9, stresses at the ends of the jacket are also affected by the prevailing axial temperature gradients. For this reason, the correlation between CPT stresses and pipe dimensions was only attempted within the middle 60 per cent of the jacket. The stresses towards the ends of the jacket were examined separately.

5.2.1 *Stresses within the jacket*

The finite element model was used to predict the effect of changing the pipe geometry, namely the mean diameter D_m and the diameter–thickness ratio D_m/t, which were chosen as the independently varying parameters. A series of 16 analyses were performed, combining the values of D_m and D_m/t from the four experimental programmes. The range of parameters used is given in Table 3. The sizes of pipes used in the experiments are identifiable from the respective designations given in parentheses. In all simulations, the jacket length was set at twice the pipe diameter, which coincides with that used by Keary *et al.* and Fugro

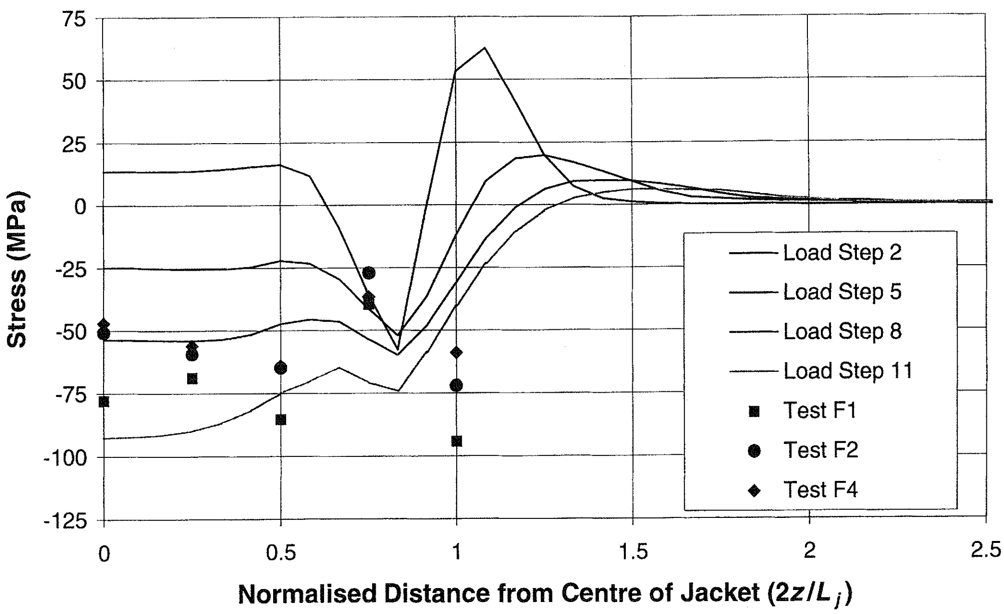

Fig. 9 Predicted longitudinal stress variation and test data obtained by Fugro

even higher if the transient phase is accounted for (see Fig. 7) but this phase lasts only for a few seconds. As Table 2 indicates, the predicted steady state maximum values show negligible dependence on the diameter–thickness ratio while their respective experimentally determined values vary widely. It appears that their magnitude is greatly affected in practice by the way that liquid nitrogen is applied. It is therefore advisable that, in the absence of any clearly defined procedures, the predicted value, obtained from Fig. 5 as a function of freezing temperature, be considered for design purposes.

During the CTP, the measured stresses within the jacket remained more or less constant at each location but their time-averaged values showed a longitudinal variation. These stresses were found to be mainly compressive and of moderate magnitude. There was a degree of repeatability in the experimental results but they were still widely scattered and therefore reveal rather weak dependence trends. The difference between the stresses on the inlet side of the pipe and the side opposite was more or less the same at various longitudinal locations; it was also found to be consistent with the expectation that, the shorter the jacket filling times, the closer the conditions are to axisymmetric.

The more clearly identifiable dependence was that on the D_m/t ratio according to which stresses increase non-linearly with increasing D_m/t. This trend was confirmed by the numerical solution although the predicted relation was in this case linear. The numerical simulation appears to have provided reasonable upper bounds for the stresses which reflect the likely overestimate of ice tensile strength assumed in the model. It also showed that, with D_m/t kept constant, there is almost no dependence of stresses on either D_m or t. Because of the spread of experimental data (see Fig. 11), this conclusion is not strongly contradicted. It is proposed that Fig. 10 summarizes very comprehensively the current knowledge and can be considered as the basis for design calculations in the case of liquid nitrogen freezes on straight pipes.

There are important quantitative and qualitative differences between experimental measurements and theoretical predictions but it is worth pointing out the uncertainty and scarcity of data as well as the simplicity of the adopted material model for ice behaviour which undermines the validity of the numerical model. Geometry, support and loading conditions were simulated with a greater degree of confidence; they were therefore not expected to have a major effect on the accuracy of the predictions. A fuller, more accurate description of the behaviour of ice should improve the quality of the predictions. It is hoped that, through further research, it will be possible to account for these factors more precisely in the future.

There are fewer experimental stress data from the end of the jacket location but those available clearly indicated that the axial stress, still compressive, can be substantially greater in magnitude than the corresponding average within the jacket. In contrast, the hoop stress is generally less compressive and, in some instances, has been observed to turn tensile up to the magnitude of 20 MPa. Obviously the production of a graph similar to that of Fig. 10 would require the same breadth of data from the end of the jacket as that available from within the jacket. It is also worth noting that there were no data available for investigating the stresses just outside the jacket, which were found tensile by both testing [**1**] and analysis [**6**].

The experimental data confirmed expectations of tensile stress development during the thawing phase. A wide variation in measured stresses was identified although a degree of uncertainty arose in the cases when the gauges' output does not return to zero at the end of the freezing cycle. The most reliable estimates of maximum tensile stresses developing during thawing are given in Table 4. Again absence of systematic data and a relevant numerical model prevented this study from producing a comprehensive representation of stress magnitude during the thawing phase as a function of geometric parameters.

It is hoped that the results of this investigation will provide a sound and comprehensive basis for bringing up to date the industry guidelines for safe pipe-freezing procedures. On the other hand, the presented review of experimental and analytical work on pipe freezing provides a wide scope for further research into improving the breadth, reliability, accessibility and applicability of stress data. Regarding testing, uncertainties arise from the scarcity of data, especially over certain ranges of geometric and freezing parameters as well as the performance of strain gauges. Regarding modelling, questions remain about ice adhesion and tensile behaviour, dependence of its properties on the pressure, the combined thermal and pressure stresses and the effect of thawing and asymmetric freezing. The development of predictive models would be greatly assisted by additional test data, particularly in the case of the combined thermal–pressure stress problem.

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