Fatigue Analysis of District Heating Systems (1999: T4)

Introduction
This project is divided in two parts:

1. A practical part with temperature measurements
2. A theoretical part dealing with design model and calculations.

Practical part
The practical part was a continuation of a project under IEA District Heating and Cooling, Annex IV, named: Temperature Variations in Preinsulated DH Pipes, Low Cycle Fatigue. In that temperature variations were measured at 17 district heating sites in Denmark, Germany, Korea, The Netherlands and Sweden.

For the present Annex V the measurements were made by the Korean District Heating Corporation with the equipment used in the Annex IV project (4 units) at locations chosen by the Korean District Heating Corporation. The measurements at the four new locations lasted for one full year.

The data was sorted by the rain-flow method and matrixes of temperature variation and graphs are produced in accordance with the data processing done in the Annex IV project.

The data processing was done by Lund's Institute of Technology, Sweden.

Theoretical part
The discussion in the theoretical part is mainly based on the design model in a draft European standard prepared by joint working group JWG1 under CEN/TC107/TC267. This standard uses the hot-spot method for low cycle fatique analysis.

Based on this method a limited number of details of preinsulated bonded pipe systems are analysed. The details include:

- Some 90° bends
- Consumer connections, where the tee piece is the critical part
- Bevel welds (small changes of direction up to e.g. 5°)

Background
The development of preinsulated pipe systems for district heating has for quite some time been characterised by simplification of laying methods, thus employing cold-laying or prestressed systems instead of using expansion facilities like compensators and U-bends, giving more robust and cost-effective systems.

The simplified laying methods on the other hand give rise to higher stress and strain in the system, and therefore suitable calculation methods have been developed in order that the full potential of the systems can be utilised. This development has, e.g., taken place in an technical committee, TC 107 under the European Standardisation Organisation, CEN. The result, a Draft Standard for the Design and Installation of Preinsulated Bonded Pipes for District Heating, is presently being prepared for enquiry.

When the stress range is larger than twice the yield stress, the system is said to be in the low cycle fatigue range. When designing according to the draft standard, it is clear that the most important limit state for pre-insulated bounded pipes is low cycle fatigue. In this limit state, the temperature variations are the most decisive action.

On this background, the measuring project in Annex IV was implemented with the purpose to register the number of temperature variations (at 17 sites). In this project the measuring program was extended with 4 new sites in Korea. Furthermore, this project deals with the whole concept for calculation in the low cycle fatigue range to give a general view of the method and to give examples for fatique analysis.

Results

Temperature measurements

In this project temperature measurements were made on 4 points numbered 18 to 21 in continuation of the 17 points in Annex IV. Point 19 is a commercial building with district cooling, the other sites are blocks with apartments as follows:

- Number 18: 208 apartments
- Number 20: 408 apartments
- Number 21: 690 apartments

All measuring points are placed in substations on the primary side, which means on the district heating side of the installation and on top and underside of the pipes.

The temperature variations are transformed to full equivalent temperature cycles with a full temperature variation at ΔT_{ref} =110°C. The results for the 4 sites are shown in this report.

The results for point 19 and 21 are in the same range as the results in Annex IV while the results for point 18 and 20 for the return pipe gives much higher values than we have seen in Annex IV. The maximum value in Annex IV. The maximum value in Annex VI was about 400 cycles for b=4 (b is the slope of the SN-curve) for the return pipes by the consumer. For point 18 and 20 the corresponding values are about 730 cycles.

A new table for all the results in Annexes IV and V have been worked out. See table 1.1. There are no changes for production (main pipes), while all the new points are found at consumers (service pipe).

Supply			
Production	Min.	Average	Max.
b=3	17	136	365
b=4	4	42	102
b=5	1	18	37

Return			
Production	Min.	Average	Max.
b=3	2	7	14
b=4	0	1	1
b=5	0	0	1

Supply			
Consumer	Min.	Average	Max.
b=3	7	130	578
b=4	2	51	308
b=5	1	28	197

Return			
Consumer	Min.	Average	Max.
b=3	35	667	3262
b=4	4	174	819
b=5	1	55	245

Table 1
Numbers of full temperature cycles for ΔT_{ref}=110°C and b=3, 4 and 5 based on results in this project and in the project in Annex IV, ref. [2].

By analysing the results from measuring on top and bottom of the pipes, it can be concluded, that there are only small differences on the supply pipe. On the return pipe there are differences, which go up to 25°C and with some single values of 40°C. Especially one consumer has big differences in the summertime. The differences mean very little for the fatigue analyses, but the differences may have effect on temperature measuring in connection with operation and energy measuring systems.

The commercial building with district cooling has an average number of temperature cycles, but the level for the return temperature is in the range from 60°C to 100°C with an average of about 80°C. This level is 10-20°C higher than the other consumers.

Results theoratical part

In this project a proposal for 'design lines' has been developed for temperature historic. The lines are shown in this report. The formulas for the curves are as follows:

- For all Supply pipes and return pipes production :
  $n_i = 2x10^6 \left(\frac{1}{\Delta T_i}\right)^{2,6}$
- Return pipes:
  $n_i = 2x10^6 \left(\frac{1}{\Delta T_i}\right)^{2,2}$

n_i is number of cycles during 30 years for $\Delta T = 1, 2, 3 .... °C$.

where

n_1 ($\Delta T = 1$) means all cycles for $0 < \Delta T \leq 1°C$
n_2 ($\Delta T = 2$) means all cycles for $1°C < \Delta T \leq 2°C$
etc.

Example:

If we set in 50 in the formula for return pipes, we get n = 347, this means that over 30 years we can expect 347 temperature variations in the range from 50-51°C. If we use the formula for supply pipes, instead we get 77 expected temperature variations.

Conclusions, Design model
A conservative conclusion based on the result of the present project would be:

1. The present design method as suggested by the draft European standard is maintained:
   - The Palmgren-Miner rule applies
   - The number of full temperature cycles, N_0, is calculated from temperature history presuming a SN curve and a reference temperature, ΔTref
   - The stress variations are proportional to the temperature variations, $\Delta\sigma = c\ \Delta T$
   - Von Mises or Tresca for multi-axial stress/strain state
   - SN-curve is used for lifetime estimation
2. Further improvement of design methods must be based on fracture mechanics and stress history.
3. Fatigue life must be characterised by temperature history, not by full temperature cycles.
4. Small temperature cycles e.g. $\Delta T < 20°C$ can be ignored.
5. Modelling of pipe-soil interaction must be improved, specially p-y diagrams in areas with road surface.
6. Stress intensification factors should be based on "hot-spot" stresses. It should be investigated if the difference between "hot-spot" stresses and the "experimental" method (Mark) applies to other components than bends.
7. The calculation examples might suggest that a higher SN-curve could be applied for un-welded material. However, insufficient modelling of soil reactions, the transformation from multi-axial stress state to the reference stress and the lack of reduction factor for electro chemical environmental actions indicate that the designer should be cautious applying a higher limit.
8. Concerning multi –axial stress-strain state: A "flat" SN-curve ($b \geq 4$) is more likely to represent the true conditions rather than a "steep" SN-curve ($b \leq 3$)

Alternative conclusion
The uncertainties in the present design methods are large concerning:

1. Actions (temperature history and p-y diagrams)
2. Modelling
3. Stress concentration factors
4. Choice of SN-curves including the effect of electro-chemical environment.

Alternative design approaches could be:

Temperature variations must be monitored (specially at the consumers) and controlled at a low level (N_0 < ??). If N0 is chosen sufficiently low, low cycle fatigue design will be unnecessary. This approach will be possible in systems equipped with “intelligent” heat meters presently under development.

Or

For T_{design} < e.g. 90°C design is done according to company standards and low cycle fatigue design is unnecessary.
For T_{design} > e.g. 90°C cavities are established at all expansions and all tees are chosen according to DIN 2615 Reihe 4. With this approach it might also be possible to develop standardised solutions in order that low cycle fatigue design becomes unnecessary.

Or

For T_{design} < e.g. 120°C and preheating design is done according to company standards. Stress reducing measures must be taken for bends and tees.
It is presupposed that the above mentioned company standards are developed in accordance with the European standard or other generally recognised methodology for piping systems taking the large axial forces in pre-insulated pipes into account.

Calculation examples
In the report calculations are made on bends, tees and bevel welds. The calculations are based on the draft European standard.

The calculations in this report show that modelling with beam-element programmes with bi-linear soil springs is very sensitive to the placing of springs.

A number of stress reducing measures have been examined. It is well known that increasing the bend radius reduces the stresses and thus increases the fatigue life. Increasing the wall thickness of the bend gives a moderate increase of the fatigue life in some cases. The most consistent way to increase the fatigue life for bends is to increase the flexibility locally by creating cavities. Foam cushions can also be used, but they have their own limitations.
The results for bends are demonstrated in this report. It also presents calculations that concerns tee at branch connection to consumers.. Again it is shown that minor changes in the modelling give large variations in the results.

The calculations on tees show that choosing the right type of a tee can give a considerable increase in fatigue life. For example an extruded T-piece DN 200/DN 80 with standard pipe wall thickness and axial stress 150 N/mm2 in the main pipe can only allow 58 load cycles without safety factor. If instead a DIN2605 Teil 1, Reihe 4 weld in tee is chosen, the cycles will be added to 7469 cycle
(ΔT_{ref} = 110°C, b = 4).

The calculations in this report confirm that problems with the fatigue life of tees always can be handled by increasing the wall thickness.
The calculations on bevel welds show that there are no problems with respect to the calculations in the report. But bevel welds can give problems with buckling by cold laid systems where the second order effects (local buckling) can be a decisive action.

Further studies
1. At measuring sites R12, R18 and R20 fatigue failures have been recorded. However, none of these sites have had a life time of 30 years in spite of the fact that the number of full temperature cycles have been calculated to be in range normally assumed by design. For these sites it might be interes-

ting to establish the actual stress history. Alternatively it could be considered if the rather large number of temperature cycles can have caused micro cracking, which due to the electro-chemical environment (the pH-value of the water) causes stress crack corrosion (SCC) earlier than expected by the usual design approach.

2. Calculating the reference stress at a multi-axial stress state by using von Mises or Tresca. The possible error thus introduced might explain the difference in the SN-curves used and the lower experimental curve established by Markl.
3. Improved modelling of the pipe-soil interaction under road surfaces.
4. The present study deals mainly with the lifetime of steel pipes. However increased stress levels in the steel will also give increased stresses in the PUR-foam. The limit state for compression and shear stresses in the PUR-foam are insufficiently well known and should be elaborated further.
5. There are still some uncertainties concerning stress concentration factors mainly due to the difference between stress concentration factors based “hot-spot stresses” and factors based experiments. However the way the stress concentration factors are applied when modelling the pipe-systems can give large differences. For example the two methods for calculating stresses in the draft European Standard give much different results.

6 The calculations in this report have confirmed what often has been observed when making comparative studies with different edp-programmes: Beam-element programmes with elastic-plastic soil springs are very sensitive to even small changes in the model. Minor changes in the modelling can give large differences in the calculated lifetime. It would therefor be suitable if minimum requirements for modelling were set up.

7. Further assessment of the influence of the electro-chemical environment on the fatigue life of pre-insulated district heating pipes. In principle this could be done by making fatigue tests on relevant steel qualities embedded in hot district heating water. Especially it should be examined what influence the pH-value has. Only very limited research has been done in this field because the effect of corrosion of low cycle fatigue cracking cannot be accelerated.