PERIODICA POLYTECHNICA SER. MECH. ENG. VOL. 1, NO. 2, PP. 157–164 (2001)

A REMARK ON THE APPLICATION OF COLD SPRING

Ferenc KOLONITS

Hungarian Atomic Energy Authority
H-1539 Budapest 114, P.O.B. 676, Hungary
fax: +36 1 356 4856, e-mail: kolonf@helka.iif.hu

Received: November 24, 1999

Abstract

The reactions and stresses in a piping subject to cyclic temperature changes are customarily redistributed between cold and hot states by a suitable cold pull-up. For the measure of that, in general, only the thermal expansion is considered and the resulting reactions are controlled. However, if the process aimed at making stresses more favourable, other loads, foremost the internal pressure, have also to be taken into account.

Keywords: piping, flexibility, pull-up, prestress, cold spring, shakedown.

List of Symbols

i	Stress index in the sense of ANSI B31.1
d	Pipe diameter
p	Internal pressure
s	Sign pointer, ± 1
E	Modulus of elasticity
R	Material constant
S	Stress
Y	Guess of ideal (reduced) stress according to Distortion Energy Theory
Z	Section modulus
$\mathbf{c}$	Cold pull-up vector
$\mathbf{e}$	Expansion vector
$\mathbf{m}$	Moment vector acting on a cross-section of pipe
$\mathbf{M}$	Matrix transforming constrained displacement into cross-sectional moment

Indices

a	Axial component
b	Bending
c	Cold (out-of-work) state
e	From restrained (thermal) expansion
eH	Elasticity-plasticity limit (yield stress)
h	Hot (working) state
i	internal
o	outside
p	From internal pressure
r	Radial component
t	Tangential component
w	From weight
DE	Refers to Distortion Energy Theory

1. Introduction

Pulling up warm-going piping in cold state is a widely accepted construction measure. Generally, it is applied in order to lessen reaction forces/moments and stresses, respectively, under working (hot) conditions, at the cost of introducing loads in cold (erection and/or out-of-work) state. The measure of the application is customarily given in percentage of the total thermal expansion restrained on the pipe section in concern.

Earlier, the cold spring was considered as an effective measure in handling expansion stresses. However, as stress range concept prevailed, it fell back in a rather secondary role. If the amplitude of stress cycles is not high enough to force a repeated plastic deformation at the extremes, a shakedown will be effected. The piping itself produces the pull-up necessary and sufficient by some initial yielding to remain elastic during the cycles to follow. The cold spring went out of factors of stress analysis. With respect to uncertainties, codes may even limit how many per cent of applied pull-up shall be trusted as taking effect, while the benefits of a judicious cold spring are remaining appreciated.

This paper is aimed at some aspects of the above ‘judicious’ solution. As it is widely known, for a piping working in the creep temperature range the only benefit of a cold spring is mitigating the initial reactions in working state. With progressive creep and relaxation, both stresses and reactions tend to vanish in hot conditions, appearing, however, in the cold state as if 100% cold spring had been applied. In high-pressure, high-temperature piping, the limiting factor is typically the allowable level of reactions at the connected equipment rather than the stresses in the piping itself. These allowable limits are set often in both hot and (fully relaxed) cold conditions. The limits usually do not give too much leeway between even for a transitory pull-up. The one viable solution is to develop a trace flexible enough and satisfying requirements without any resort to cold spring.

2. Pull-up of Piping Working under Creep Range

In contrast to that, a piping working under creep limit might be permanently influenced concerning both reactions and stresses. If reactions are concerned as to be reduced under a certain limit, a proportional distribution of the total expansion between cold and hot state and superposition to other loads can be made in a known and easy way. However, if reactions were of not too much importance, pull-up might be aimed at improving stress relations.

In this respect, 'judicious' might mean that with a cold spring, while shifting the loads in the temperature cycle from hot to cold state, one keeps his piping elastic without spontaneous (i.e. uncontrolled and uncertain) plastic yielding. Taking into account the unavoidable uncertainties, an equal ratio of summarized (reduced) stresses in both cold and hot state to the respective yielding stresses shall be strived for. Were the yielding stress and Young's modulus of the piping material identical in hot and cold conditions and stresses were produced only by restrained thermal expansion, the above ideal state would be produced most simply by a uniform 50% pull-up along all three spatial directions. If reduced stresses were composed on the base of maximum shear and stress intensity factors affecting uniformly all moment components as B31.1 supposes it, the above cold spring is even optimal, the produced equal cold/hot stresses being less than by any equal ones produced by other composition of pull-ups (details will be shown later). The general concept of applying cold spring is like that, making some additional allowance for material parameters decreasing with temperature by shifting more than half of the loads from hot state to cold.

The incipient yielding, however, is effected not only by stresses from restrained thermal expansion but by the sum of all kinds of stresses, from internal pressure and primary loads, respectively. The former is even changing in cyclic manner from hot to cold while the latter are mostly constant but might change if e.g. a feedwater line becomes emptied. Let a guess of summarized/reduced stresses be made in conformity with some simplifying assumptions generally accepted (i.e. in piping codes).

3. An Index for Total Stress with Respect to Plastification

The internal pressure will be taken with the stresses of greatest value (on the internal side of the pipe wall) into account as shown in *Table 1*, where $S_{ap} = pd_i^2 / \left(d_o^2 - d_i^2\right)$, the axial stress being constant along the cross-section.

The stresses due to external loads are to be calculated from the moments acting on a cross-section of the piping. The acting forces shall be taken into account for special layouts only, e.g. for a sort of straight district heating pipes without dedicated compensating elements, the thermal expansion being taken up by (high)

Table 1. Stresses in a pipe cross-section

Direction	Stress from internal pressure	Stress from bending
axial	S_{ap}	$i\,S_b$
tangential	$2S_{ap} + p$	$2i\,S_b$
radial	$-p$	0
torsional shear	–	$0.5S_t$

axial compression and without any bending – there the task of optimal cold spring had been investigated in detail for several constructions in respective manuals.

Let us follow the general case and consider the moments. The Cartesian components lying in the plane of a cross-section produce bending, the one perpendicular to that, pointing along the pipe axis, results torsion. The resultant bending moment generates stresses which might be derived from the stresses in a bent straight pipe by stress indices. The stress index is defined primarily for pipe bends showing what a manifold of stress calculated from so-called reduced moment (a SQRSS of moment components) shall be taken into account as checking against allowable stress. This is a rough estimation, however, one might trace down the original assumptions: i represented the intensification of the axial bending stress, while showing about the half of the stress originated by crosswise bending of the pipe wall due to flattening, approximately for both in- and out-of-plane bending of elbow. The latter is a practical approach relating the stresses causing fatigue to those in a butt-welded pipe with an inherent stress index of 2, instead of a theoretical pipe without any stress raiser (as interpreted by MARKL [1], for the '55 ANSI B31.1 proposals). Thus, the stress index compatible with that of the axial bending, will be $2i$, as related to (longitudinal) bending stresses in straight pipe. These stresses, as shown also in *Table 1*, will be superposed in every possible sign combination around the cross-section of the pipe. Here the S-s are the nominal values calculated from the moment components uniformly by the known cross-section modulus (for bending). The torsional modulus is two-fold with respect to the bending one, therefore stands the 0.5 multiplier there. This all is derived originally to pipe bends, however, the B31.1 calculates with i-s for other piping components in the same manner.

The summarized stress components will be composed into a 'reduced stress' able to show the distance from an incipient yielding according to Huber–Mises–Hencky Distortion Energy Theory. With that, the formulae to get will be more simple. It is true that almost all codes for design calculations use the Maximum Shear Theory, which is more conservative. For the present purpose, however, the resulting stresses are not to be checked against a certain limit but to ensure equal per cent reserve with respect to yielding in hot and cold state, and for this the DE might be fit even better.

The stress differences appearing in the DE formula are listed in *Table 2*, where (s_a), (s_t) stand for signs chosen for axial and tangential intensified bending stresses, respectively, and the last column shows the differences as resulting a maximal reduced stress with suitable choice of those signs. The DE reduced stress will be

$$S_{DE} = \sqrt{4\,(i\,S_b)^2 + 3\left(i\,S_b + S_{ap} + p\right)^2 + 0.75 S_t^2} = Y\,(p, \mathbf{m}_w + \mathbf{m}_e)\,, \tag{1}$$

representing a test function, a kind of index for incipient yielding in function of internal pressure and stresses induced by cross-sectional moments, respectively. The latter consist of ones by weight and other primary loads (w) and of those from restrained thermal expansion (e).

Table 2. Assessing components of maximal reduced stress

Components	Difference	for max. red. stress
$S_a - S_t$	$(s_a)\,i\,S_b + S_{ap} - (s_t)\,2i\,S_b - 2S_{ap} - p$	$3i\,S_b + S_{ap} + p$
$S_t - S_r$	$(s_t)\,2i\,S_b + 2S_{ap} + p + p$	$2\left(i\,S_b + S_{ap} + p\right)$
$S_r - S_a$	$-p - (s_a)\,i\,S_b - S_{ap}$	$i\,S_b - S_{ap} - p$

4. Evaluation

With a flexibility calculation, the cross-sectional moments along the piping are obtained. These moments can be calculated also separately for unit values of restrained thermal expansion along each co-ordinate direction and the results suitably arranged form a 3×3 matrix $\mathbf{M}$ transforming the 3 components of restrained expansion $\mathbf{e}$ into those of cross-sectional moments $\mathbf{m}$. With a rotation, if necessary, the components can be arranged in such a way that the one torsion and two bending moments were separated and identified. From those the corresponding stress components for calculation according (1) might be obtained. Let the cold spring by which the restrained expansion diminished be $\mathbf{c}$. The piping flexibility calculation is usually performed with an elasticity modulus E for cold state. The above test function for a certain cross-section in cold state, out of work and without pressure will be

$$Y_c = Y\,(0, \quad \mathbf{m}_w - \mathbf{Mc})\,, \tag{2}$$

while in hot state on a compatible base

$$Y_h = (R_{eHc}/R_{eHh})\,Y\,(p, \mathbf{m}_w + (E_h/E_c)\,\mathbf{M}(\mathbf{e} - \mathbf{c}))\,, \tag{3}$$

because of R_{eH} elasticity limit diminishing at working temperature.

If there are substantial expansion stresses, i.e. as the present studies might be of interest, the suitable cold spring is characterized by yielding the same Y in hot and cold state. This is advisable to seek at least nearly an identically proportional part of the restrained expansion in all components, although no strict proof can be given for its being optimum like in the simplified approach mentioned already and detailed below. Doing so, the maximal Y-s are obtained mostly at the same-cross section in both hot and cold state.

5. Conclusion

The cold prestress may be considered as a tool for modifying the distribution of both reactions and stresses between cold and hot state, respectively. These two objectives, however, could be reached on different paths, with different reasoning. A near-equalization of reactions does not mean the same for stresses and might not exclude spontaneous local yielding.

Appendices

1. Optimal Pull-up Considering expansion Only

The simplified approach of B31.1 operates with the 'reduced moment' of the Maximum Shear Theory, i.e. the absolute value of the moment vector acting on a cross-section is calculated and the expansion stresses derived from the state as if this were a simple bending moment:

$$S_e = i\sqrt{\mathbf{e}^T \mathbf{M}^T \mathbf{M}\mathbf{e}}/Z, \tag{4}$$

where the superscript T means transpose and Z the section modulus. If expansion is considered as a space vector, the surfaces pertaining to constant S are tri-axial ellipsoids in a general position depending on eigenvalues of the central matrix product (for a spatial piping being normally positive definite). Applying $-\mathbf{c}$ cold spring, this vector (from the origo) will end at a point of the ellipsoid pertaining to the S_c in cold state. The **e** vector of the thermal expansion will be added and the end will be situated on another concentric ellipsoid pertaining to S_h, hot state. If the variation of Young modulus and allowable stress, respectively, are omitted (they can be included by simple similarity considerations), the task will be equivalent to that how to place the **e** vector inside a minimum-size ellipsoid. One may see directly that for this end, the vector shall be placed symmetrically through the origo and the cold spring shall be the half of that.

2. A Numerical Example

Let a 324 × 8 mm pipe (isolation 100 mm, 200 kg/m^3) with $R = 600$ mm bends be considered as sketched in *Fig. 1,* both ends clamped and hanged on a constant effort device, internal pressure 4 MPa in working conditions. For a temperature difference from cold to hot state of 300°C, with characteristics of a rather low-grade carbon steel – Young modulus in cold state 200 GPa, expansion coefficient $12 \cdot 10^{-6}$, the most stressed cross-section was found at the indicated point, adjacent to a bend.

The moment on this cross-section from weight is:

$$\mathbf{m}_w = [0.28 \quad 1.04 \quad 0.75]\text{kNm}, \tag{5}$$

the first being torsion, the others bending. The moment from a constrained displacement **c** applied at the origo:

$$\mathbf{m}_e = \mathbf{Mc}, \tag{6}$$

where

$$\mathbf{M} = \begin{bmatrix} 150.5 & 450.2 & 84.1 \\ 22.8 & -153.9 & -11.11 \\ 242.5 & 222.7 & -69.0 \end{bmatrix} \text{kN}. \tag{7}$$

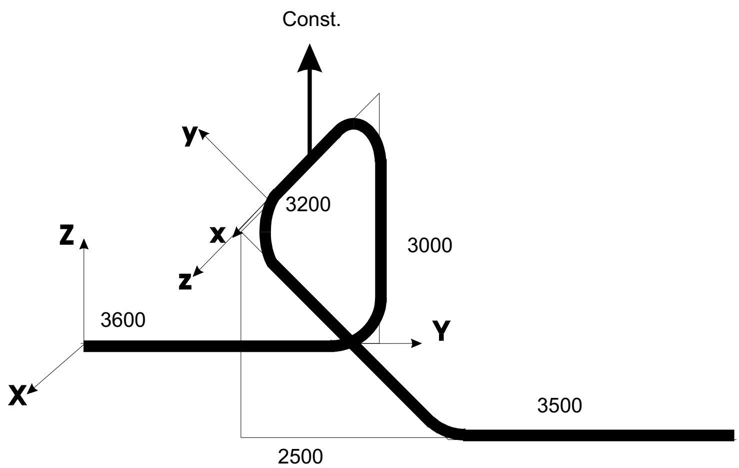

Fig. 1. Pipe considered in Appendix 2

With these, the stress components for arbitrary $-\mathbf{c}$ cold pull-up and $\mathbf{e} - \mathbf{c}$ total restrained expansion under working conditions, respectively, can be calculated. In order to consider results for cold and hot conditions on an equal base, the **M** matrix has to be reduced in proportion with E_h/E_c (taken to 0.881) and the resultant stresses to be multiplied by the quotient of yield stresses R_{pc}/R_{ph} (taken to 1.714). The total restrained thermal expansion:

$$\mathbf{e} = [11.52 \quad 34.56 \quad 1.8] \text{ mm}. \tag{8}$$

Omitting numerical details (might be suitably arranged in an Excel Worksheet), there were obtained

– if only the thermal expansion was considered, a 60.2% pull-up were necessary, producing 82.7 MPa,

– including the moments from weight, 61.6% of the total thermal expansion in consequence of being 83.7 MPa,
– considering expansion, weight and pressure, 95.9%, i.e. [11.05 33.14 1.7] should be applied for obtaining 130.7 MPa cold-base equivalent stresses in both cold and hot state.

The first two cases are, however, 'nominal' ones because the weight is present by all means and pressure in working condition. Therefore, in working condition a 171.9 MPa and 169.8 MPa, respectively, shall appear (in cold equivalent) and the yield stress limit is far more approached than in cold state and than in the correctly equalized third case as well. Practically, by round-off, the cold pull-up to be applied is

$$\mathbf{e} = [11 \quad 33 \quad 0]\ \text{mm}. \tag{9}$$

By this, although no more in 'perfect' balance, the stresses are even a bit reduced.

References

[1] MARKL, A. R. C.: Piping-Flexibility Analysis, *ASME Trans.*, **77**, (1955) pp. 127–149.