Sustained Stresses and Nonlinear Restraints

The proper computation of sustained stresses has been an issue since the late 1970s, when computerized pipe stress analysis programs first attempted to address the problem of non-linear restraints. The existing piping codes offered little guidance on the subject, since their criteria were developed during the era when all analyses were considered to behave in a strictly linear fashion. The problem arises because the codes require that a piping system be analyzed separately for sustained loadings — the engineer must determine which stresses are caused by which loadings. Sustained loads are force loadings which are assumed not to change, while expansion loadings are displacement loadings which vary with the system operating conditions. Determination of the sustained loads is the simple part — most everybody agrees that those forces consist of weight, pressure, and spring preloads — these forces remain relatively constant as the piping system goes through its thermal growth. However, confusion occurs when the status of nonlinear restraints change (pipes lift off of supports, gaps close, etc.) as the pipe goes from its hot to cold state — in this case, which boundary conditions should be used when evaluating the applied forces? Or in other words, what portion of the stress in the operating case is caused by weight loads, and what portion is caused by expansion effects? (Note that there is no corresponding confusion on the question of calculating expansion stresses, since the codes are explicit in their instructions that the *expansion stress range* is the difference between the operating and cold stress distributions, both of which are known.)

The obvious answer to this question, to the developers of some pipe stress programs, was that the sustained stress calculation should be done using the operating, or hot boundary condition. This compounded the problem, in that the laws of superposition no longer held — in other words, the results of sustained (W+P) and thermal (T) cases, when added together, did not equal the results of the operating (W+P+T) case! One pioneering program, DYNAFLEX, attempted to resolve this by introducing the concept of the “thermal component of weight” — an oxymoron, in our opinion. Other programs, notably those which came from the mainframe/linear analysis world, had to approximate the behavior of these non-linear restraints. Their approach to the problem is to run an operating case, obtain the restraint status, and modify the model according to these results. All subsequent load cases analyzed use this restraint configuration. The fact that the laws of *static superposition* didn't hold was hopefully not noticed by the user. CAESAR II, on the other hand, represents new technology, developed expressly for operation on the PC, and therefore incorporates directly the effects of non-linear restraints. This is done by considering each load case independently — the restraint configuration is determined for each load case by the program as it runs, based upon the actual loads which are considered to be present.

Some users have asserted that there are actually two sustained load cases. In fact, there has been a B31.3 code interpretation that indicates that the sustained stress may also be checked with the operating restraint configuration. Calculating the sustained stresses using the operating restraint status raises several other issues; what modulus of elasticity should be used, and which sustained stresses should be used for occasional cases.

It is COADE’s assertion that there is only one sustained case (otherwise it is not “sustained”) — there can be, however, multiple sustained stress distributions. The two most apparent are those associated with the cold (installed) and hot (operating) configurations, however, there are also numerous in-between, as the piping system load steps from cold to hot. Whether the “true” sustained load case occurs during the installed or operating case is a matter of the frame of reference. If an engineer first sees a system in its cold condition, and watches it expand to its operating condition, it appears that the first case (since weight and pressure — primary loads — are present) is the sustained case, and the changes he viewed are thermal effects (due to heat up) — secondary loads due to displacements. If a second engineer first sees the same system in the operating case and watches it cool down to the cold case, he may believe that the first case he saw (the operating case) is the sustained case, and changes experienced from hot to cold are the thermal expansion effects (the thermal stress ranges are the same in both cases). Consider the further implications of cryogenic systems — where changes from installed to operating are the same as those experienced by hot systems when going from operating to installed. Once elastic shakedown has occurred, the question becomes clouded even further, due to the presence of thermally induced pre-stresses in the pipe during both the cold and hot conditions. We feel either the operating or installed case (or some other one in-between) could justifiably be selected for analysis as the sustained case, as long as the program is consistent.

We have selected the installed case (less the effect of cold spring) as our reference sustained case, since thermal effects can be completely omitted from the solution (as intended by the code), and this best represents the support configuration when the sustained loads are initially applied. If the pipe lifts off of a support when going from installed to operating, we view this as a thermal effect — consistent with the piping codes' view of thermal effects as the variation of stress distribution as the piping system goes from cold to hot (this view is explicitly corroborated by one code — the *French petrochemical code*, which states that weight stress distributions due to thermal growth of the pipe should be considered as expansion stresses). For example, we feel that a change in a rigid support load from 2,000 lbs to zero should be treated no differently than would be a variable spring load changing from 6,000 lbs to 4,000 lbs (or another rigid support load going 2,000 lbs to 1 lb). In the former case, if the pipe became "overstressed", it would yield, and sag back to the support, relieving the stress. This process is identical to the way that all other expansion stresses are relieved in a piping system.

We are confident that our interpretation is correct. However, we understand that our users may not always agree with us — that is why CAESAR II provides the greatest ability to custom tailor the analysis to one's individual specifications. If desired, a "*hot sustained*" case can be analyzed by adding two load cases to those normally recommended by CAESAR II. This would be done by assuming that the pipe expands first, and then the sustained loads are applied (this is of course an idealized concept, but the stresses can only be segregated by segregating the applied loads, so the sustained loads can only be applied either before, or after, the expansion loads). Following are the default load cases, as well as those required for a "hot sustained."

Default	New
W+P1+T1(OPE)	W+P1+T1(OPE)
W+P1(SUS)	W+P1(SUS)
L1-L2(EXP)	T1 (EXP)
	L1-L2(EXP)
	L1-L3(SUS)

In the new load case list, the second case still represents the *cold sustained*, while the fourth case represents the expansion case (note that L1-L2, or W+P1+T1-W-P1, equals T1, with non-linear effects taken into account). The third case represents the thermal growth of the "weightless," non-pressurized pipe, against the non-linear restraints.

The fifth case (L1-L3, or W+P1+T1-T1, equals W+P1) represents the application of weight and pressure to that expanded case, or the "hot sustained" case. Note that when the piping system is analyzed as above, the actual effects of the non-linear restraints are considered (they are not arbitrarily removed from the model), and the laws of superposition still hold.

An alternative school of thought believes that a "hot sustained" is only valid if (1) the sustained, primary loads are applied, (2) all springs are showing their **Hot Load** settings, and (3) any supports that lift off (or otherwise become non-active) have been removed from the model. An analysis such as this is achievable by setting the "Keep/Discard" status of the Restrained Weight case (the first hanger design load case) to "Keep", thus permitting the results of that case to be viewable as for any other load case. The Restrained Weight case automatically removes restraints that become non-active during the designated operating case, and apply the Hot Load at each of the hanger locations.

Notes on Occasional Load Cases

Several piping codes require that the stresses from occasional loads (such as wind or earthquake) be added to the sustained stresses (due to weight, pressure, and other constant loads) before comparing them to their allowables. This combination is easily created in CAESAR II:

CASE #

1.	W+P+F1	(SUS):	Sustained stresses
2.	WIND	(OCC):	Wind load set
3.	U1	(OCC):	Uniform (g) load set for earthquake
4.	L1+L2	(OCC):	Code stresses for wind *
5.	L1+L3	(OCC):	Code stresses for earthquake*

*** Scalar Summation Method required**

If nonlinear effects are modeled in the system these combinations may not be so straight forward. Friction, one-direction restraints and double-acting restraints with gaps are the nonlinear items which present this complication. Wind loading on a long vertical run of pipe with a guide will serve as an example. Assume there is a one inch gap between the pipe and guide. Under normal operation, the pipe moves 3/4 inch towards the stop leaving a gap of 1-3/4 inch on either side of the pipe and a 1/4 inch gap on the other side. If wind loads are analyzed alone, the pipe is allowed to move 1 inch from its center point in the guide to the guide stop. Since occasional loads are usually analyzed with the system in operation, the pipe may be limited to a 1/4 inch motion as the gap is closed in one direction, and 1-3/4 inch if the gap is closed in the opposite direction. With nonlinear effects modeled in the system, the occasional deflections (and stresses) are influenced by the operating position of the piping.

The following list of CAESAR II load cases takes this point into consideration. Note that the load cases shown below are only for wind acting in one direction, i.e., +X. Depending on the system, the most critical loads could occur in any direction, i.e., +/-X, +/-Z or skewed in an XZ direction.

The intention of the following load case construction is to find the occasional load's effect on the piping system in the operating condition. The stress due to the moment change from the operating to the operating plus wind case is added to the stress from the sustained case.

The isolated wind effect on the piping system in the operating condition in is computed in Case 5. Case 6 adds the stresses from Case 5 to the sustained stresses from Case 2.

CASE #

1.	W+T+P	(OPE):	Operation analysis
2.	W+P	(SUS):	Sustained stresses
3.	W+T+P+WIND	(OPE):	Operating analysis with wind
4.	L1-L2	(EXP):	Expansion stresses (Algebraic summation)
5.	L3-L1	(OCC):	Wind's net deflection (Algebraic summation)
6.	L2+L5	(OCC):	Code stresses for wind (Scalar summation)