Basic

Pipe Stress Analysis

Tutorial

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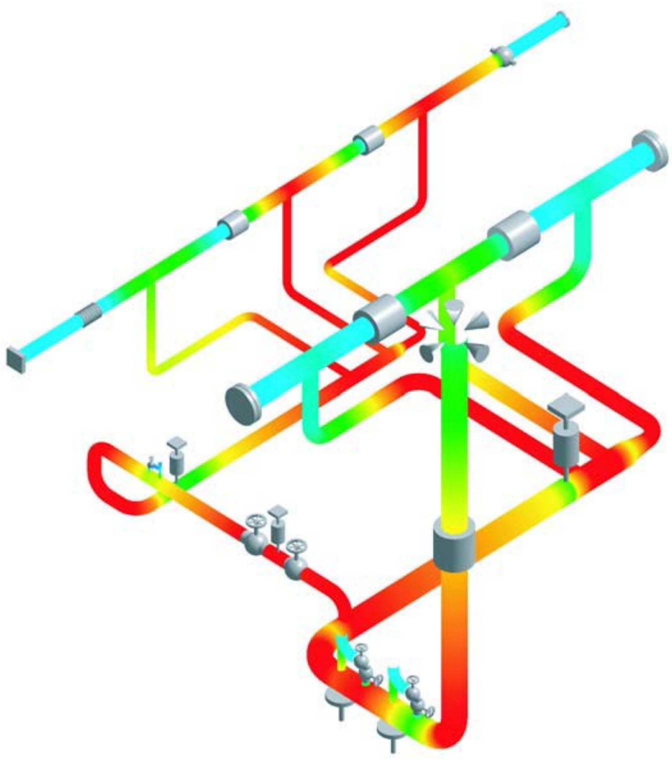

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Basic Pipe Stress Analysis Tutorial

Good, relevant and non-overwhelming technical information on pipe stress analysis is hard to come by. So, we decided to provide a simple tutorial on the basics of piping stress analysis. This tutorial is directed towards newcomers to Pipe Stress Analysis just as much as to engineers new to CAEPIPE.

To get the full benefit from this tutorial, you will need a working copy of CAEPIPE, pipe stress analysis software.

Download a Free Copy of CAEPIPE here
CAEPIPE - Features and Benefits

Useful learning resources:

CAEPIPE Tutorial 1
CAEPIPE Tutorial 2
CAEPIPE Users Manual
Pipe Stress Tips Archive
The Piping Journal Blog

You are welcome to use any other program if you choose to.

Tutorial: Table of Contents

Pipe Stress Analysis: Basic Concepts

Introduction

It is common practice worldwide for piping designers to route piping by considering mainly space, process and flow constraints (such as pressure drop) and other requirements arising from constructability, operability and reparability. Unfortunately, pipe stress analysis requirements are often not sufficiently considered while routing and supporting piping systems, especially in providing adequate flexibility to absorb expansion/contraction of pipes due to thermal loads. So, when “as designed” piping systems are handed-off to pipe stress engineers for detailed analysis, they soon realize that the systems are “stiff” and suggest routing changes to make the systems more flexible. The piping designers, in turn, make changes to routing and send the revised layout to the pipe stress engineers to check for compliance again.

Such “back and forth” design iterations between layout and stress departments continue until a suitable layout and support scheme is arrived at, resulting in significant increase in project execution time, which, in turn, increases project costs.

This delay in project execution is further worsened in recent years by increased operating pressures and temperatures in order to increase plant output; increased operating pressures increase pipe wall thicknesses, which, in turn, increase piping stiffnesses further. Such increased operating temperatures applied on “stiffer” systems increase pipe thermal stresses and support loads. So, it is all the more important to make the piping layout flexible at the time of routing. (CheckStress, SST’s add-on product for PDMS and Cadmatic directly addresses and solves this problem).

Types of Loads

Piping systems experience different types of loadings, categorized into three basic loading types — Sustained, Thermal and Occasional loads.

Sustained Loads

These mainly consist of internal pressure and dead-weight. Dead-weight is from the weight of pipes, fittings, components such as valves, operating fluid or test fluid, insulation, cladding, lining etc.

Internal design or operating pressure causes uniform circumferential stresses in the pipe wall, based on which a pipe wall thickness is determined during the process/P&ID stage of plant design. Additionally, internal pressure gives rise to axial stresses in the pipe wall. Since these axial pressure stresses vary only with pressure, pipe diameter and wall thickness (all three of which are preset at the P&ID stage), these stresses cannot be altered by changing the piping layout or the support scheme.

A pipe's deadweight causes it to bend (generally downward) between supports and nozzles, producing axial stresses in the pipe wall (also called "bending stresses") which vary linearly across the pipe cross-section, being tensile at either the top or bottom surface and compressive at the other surface. If the piping system is not supported in the vertical direction (i.e., in the gravity direction) excepting equipment nozzles, bending of the pipe due to deadweight may develop excessive stresses in the pipe and impose large loads on equipment nozzles, thereby increasing its susceptibility to "failure by collapse."

Various international piping standards/codes impose stress limits, also called "allowable stresses for sustained loads," on these axial stresses generated by deadweight and pressure in order to avoid "failure by collapse."

For the calculated actual stresses to be below such allowable stresses for sustained loads, it may be necessary to support the piping system vertically. Typical vertical supports to carry deadweight are:

- Variable spring hangers
- Constant support hangers
- Rod hangers
- Resting steel supports.

Rod hangers and resting steel supports fully restrain downward pipe movement but permit pipe to lift up.

A couple of examples are presented in this tutorial to illustrate how piping can be supported by spring hangers and resting steel supports to comply with the code requirements for sustained loads.

Thermal Loads (Expansion Loads)

These refer to the "cyclic" thermal expansion or contraction of piping as it goes from one thermal state to another (for example, from "shut-down" to "normal operation" and then back to "shut-down"). If the piping system is not restrained in the thermal growth/contraction directions (for example, in the axial direction of pipe), then, for such cyclic thermal load, the pipe expands/contracts freely; in this case, no internal forces, moments and resulting stresses and strains are generated in the piping system. If, on the other hand, the pipe is "restrained" in the directions it wants to thermally deform (such as at equipment nozzles and pipe supports), such constraint on free thermal deformation generates cyclic thermal stresses and strains throughout the system as the system goes from one thermal state to another. When such calculated thermal stress ranges exceed the "allowable thermal stress range" specified by various international piping standards/codes, then the system is susceptible to "failure by fatigue." So, in order to avoid "fatigue" failure due to cyclic thermal loads, the piping system should be made flexible (and not stiff).

This is normally accomplished as follows:

```
a) Introduce bends/elbows in the layout, as bends/ elbows “ovalize” when bent by end-
moments, which increases piping flexibility.

b) Introduce as much “offset” as possible between equipment nozzles (which are normally
modeled as anchors in pipe stress analyses).

For example, if two equipment nozzles (which are to be connected by  piping) are in line,
then the straight pipe connecting these nozzles will be “very stiff”. If, on the other
hand, the two equipment are located with an “offset,”  then their nozzles will have to be
connected by an “L-shaped” pipeline which includes a bend/elbow; such “L-shaped” pipeline
is much more flexible than the straight pipeline mentioned above.

c) Introduce  expansion loops (with  each loop  consisting of four  bends/elbows) to
absorb thermal growth/contraction.

d) Lastly, introduce expansion joints such as bellows, slip joints etc, if warranted.
```

In addition to generating thermal stress ranges in the piping system, cyclic thermal loads impose loads on static and rotating equipment nozzles. By following one or more of the steps from (a) to (d) given above and steps (e) and (f) given below, such nozzle loads can be reduced.

```
e) Introduce “axial restraints”  (which restrain pipe  in its axial direction) at
appropriate locations such that thermal growth/contraction is directed away from nozzles.

f) Introduce “intermediate anchors” (which restrain pipe movement in the three
translational and three rotational directions) at appropriate locations such that thermal
deformation is absorbed by regions (such as expansion loops) away from equipment nozzles.
```

A few example layouts are presented to illustrate how loops/offsets, axial restraints and intermediate anchors are used to reduce thermal stresses in piping (and resulting nozzle loads).

Occasional Loads

This third type of loads is imposed on piping systems by occasional events such as earthquake, wind or a fluid hammer. To protect piping from wind and/or earthquake (which normally occur in a horizontal plane), it is normal practice to attach “lateral supports” to piping systems (instead of “axial restraints”). On the other hand, to protect piping for water/steam hammer loads, both “lateral supports” and “axial restraints” may be required.

To carry sustained loads, normally vertical supports are required. For thermal loads, having no supports gives zero stresses. So, fewer the number of supports, lower the thermal stresses. Axial restraints and intermediate anchors are recommended only to direct thermal growth away from equipment nozzles.

Pipe Stress Analysis: Preliminary Procedure

Model the piping system in CAEPIPE (either directly inside CAEPIPE, or by using one of SST's data translators to import the piping model) and follow the steps shown in the CAEPIPE Tutorial to learn the basics of operating CAEPIPE to create and analyze a model and review its results. Once all the data is in, Analyze. Now, review Results.

General Procedure

From the thermal stress contour plot and the deflected shape for thermal load case, suitably route the pipe to make it more flexible and position axial restraints and/or intermediate anchors, if required, to direct thermal expansion/contraction away from critical locations such as equipment nozzles. Similarly, decide the types and locations of vertical supports based on the stress contour plot and deflected shape for sustained (= weight + pressure) load case as well as the deflected shape for operating load case (= sustained load + thermal load).

Here is a step-by-step procedure

Step 1

Review the thermal stress contour plot first. The plot is color-coded such that "blue" region denotes areas with the least stress ratios (where stress ratio equals to actual computed stress divided by material allowable stress), "green" region with higher stress ratios, "yellow" region with even higher stress ratios, and "red" region with the highest stress ratios. Intermediate areas between these distinct colors will be of "bluish-green", "greenish-yellow" and "orange" colors.

The goal will be to arrive at a layout that avoids "orange" and "red" zones in thermal stress plot so that there is sufficient thermal margin left for performing a detailed piping analysis when the layout is finalized at the 3D-design stage. You may wish to avoid even the "yellow" zone in the stress contour plot so as to provide additional thermal margin for future use. Since thermal stresses generated are directly dependent on how "stiff" or "flexible" the layout is, in order to reduce thermal stresses, it may be necessary to make the layout "flexible" (by including bends, offsets, loops etc.). So, the first step is to make sure thermal stress ratios remain within "blue to yellow' range and not get into "orange" and "red" zones. For more "flexible" layout, even "yellow" zone can be avoided.

Step 2

In case thermal stress ratios exceed "yellow" zone (and are in "orange" and "red" zones in one or more areas of the piping system), it is important to study the thermal case deformed shape provided by CAEPIPE in order to understand how the piping responds to "pure thermal" load. By studying such deformed shape, it is possible to arrive at a layout with appropriate bends, offsets and loops and/or with appropriately located axial restraints/intermediate anchors such that thermal stress ratios do not exceed "yellow" zone. This process may require you to perform several layout and/or restraint scheme iterations.

Step 3

After finalizing piping layout under Steps 1 and 2 for thermal loading, the next task is to support the system vertically to carry its deadweight under operating condition. In this connection, first review sustained stress ratio contour plot generated by deadweight and pressure for the system without any vertical supports excepting those provided by equipment nozzles, shown in color codes from "blue" to "green" to "yellow" to "red" (as in Step 2 above).

Your goal is to arrive at a vertical support scheme consisting of

(a) resting steel supports (b) rod hangers © variable spring hangers and (d) constant support hangers

at appropriate locations (where such pipe supports can be attached to adjacent concrete/steel structures, platforms etc.) so that stress contour plot for sustained stress ratios avoids "orange" and "red" zones and remains within "blue to yellow" range.

Step 4

In case sustained stresses exceed "yellow" zone in one or more areas of the piping system, study the deformed shape for sustained load case in order to understand how the piping responds to its own deadweight: next, identify pipe locations in the 3D model where the pipe can be vertically supported by the support types listed above. Based on this information, it is possible to vertically support the piping such that sustained stresses do not exceed "yellow" zone. This step may require you to execute several iterations within CAEPIPE with several vertical support schemes.

In case, resting steel supports are selected to provide vertical support for piping under sustained load, it is to be made sure that piping continues to rest on such steel supports even during operating condition (= weight + pressure + thermal) and does not lift off from these supports. If pipe lifts up at any of these resting supports during operating condition, then that support does not carry any pipe weight and hence will not serve its purpose. Similarly, at rod hanger locations, the tendency of piping should be to deform downward for operating load case, so that the rod hangers carry the pipe weight under tension. On the other hand, if pipe lifts up at any of the rod hangers, then that rod hanger goes into compression thereby not carrying the weight of the piping during operating condition.

CAEPIPE displays the deflected shape of piping under operating load case too. By viewing this deflection from different directions, you can make sure that piping is resting on steel supports and/or piping is not deforming upward at rod hangers.

Step 5

You should perform Steps 1 to 4 for all piping systems of the project. Systems, for which the layout and support schemes are finalized, are ready for detailed analyses and stress report preparation.

Verification Step

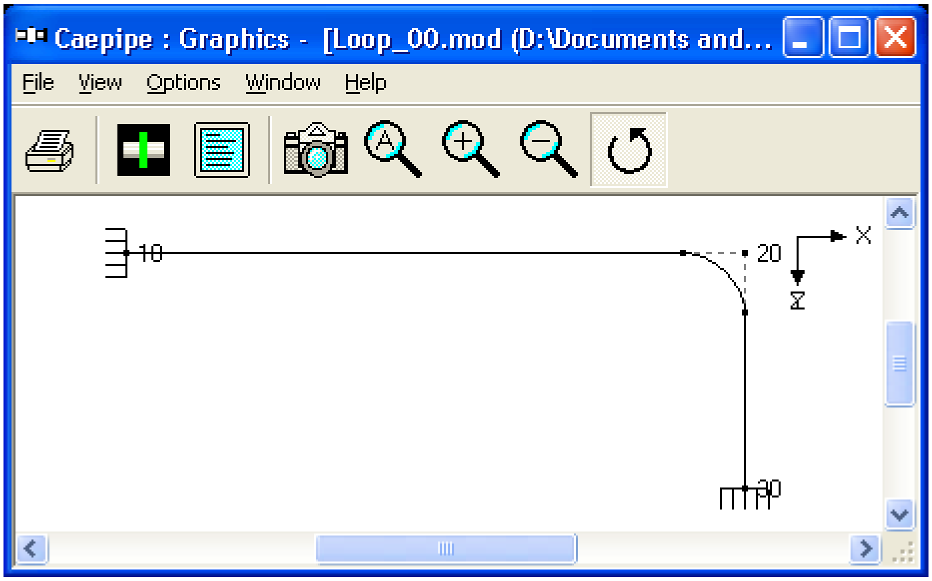
Provide all additional input data into the models such as insulation thickness and density, corrosion allowance and mill tolerance of pipe sections, thermal anchor movements, seismic anchor movements, support conditions such as friction and gap, other loads such as wind, seismic and water/fluid hammer, multiple thermal and pressure cases, etc. and perform detailed analyses. It is most likely that the layout and support schemes (finalized during steps 1–4) meet all other pipe stress requirements (such as meeting nozzle allowable loads) and hardly require any further iteration(s).

Example 1 - Using Expansion Loops

DATA: An 8" NB Schedule 80 pipe (see Fig. 1A) connects two equipment at nodes 10 and 30 with an offset of 4' (i.e., equal to distance between nodes 20 and 30). The pipe, made of A53 Grade A carbon steel, is heated to 300° F.

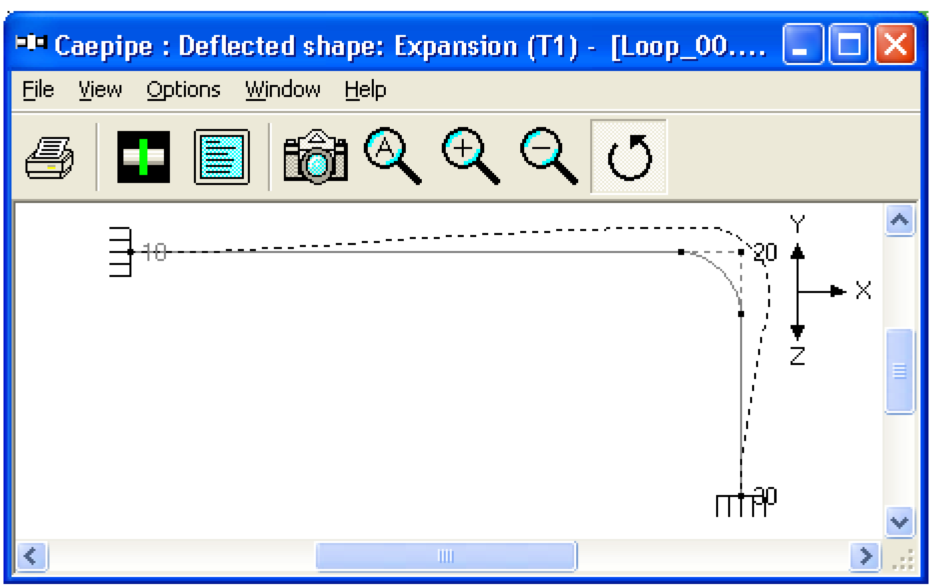
This problem illustrates the use of expansion loops to reduce thermal stresses.

Figure 1A – Layout



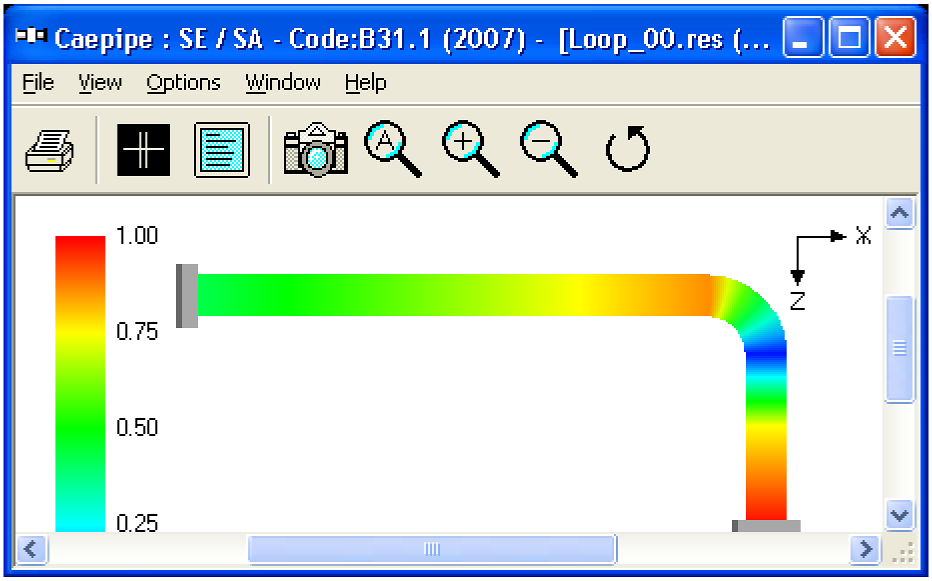
After modeling this layout in CAEPIPE, upon analysis, you will find that the pipe between nodes 10 and 20 grows thermally to the right towards node 20, while pipe between nodes 30 and 20 grows up towards node 20, as illustrated in Fig. 1B.

Figure 1B - Thermal Deflection



This thermal deformation generates large thermal stresses (orange and red zones) in the bend at node 20 and at anchor node 30, as shown in Fig. 1C.

Figure 1C - Non code-compliant (notice the reds)



The reds illustrate that the expansion stress is over the allowables, and fails code compliance. This layout will have to be rerouted. Let us try the rerouting as shown in Fig.1D.

Figure 1D - Rerouting

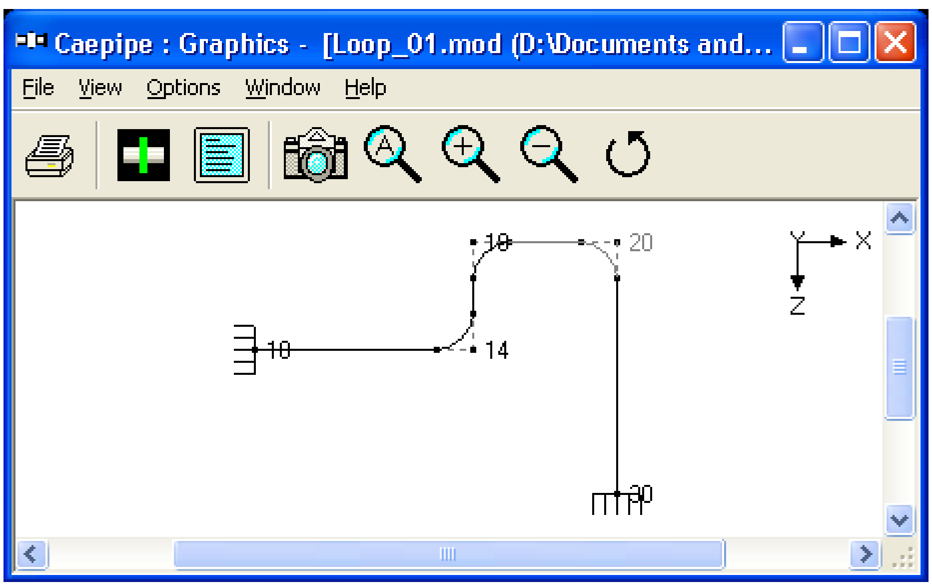


Fig. 1D shows a revised layout with a loop, introducing two additional bends at nodes 14 and 18, thereby making the layout more flexible. So, thermal growth of X-directional pipes between nodes 10 and 14 and then between 18 and 20 as well as the growth of Z-directional pipe between nodes 30 and 20 are absorbed by the three bends at nodes 14, 18 and 20. The corresponding stress contour plots for thermal and sustained load cases are shown in Fig.1E and Fig. 1F, confirming code compliance.

Figure 1E - Code-compliant thermal case

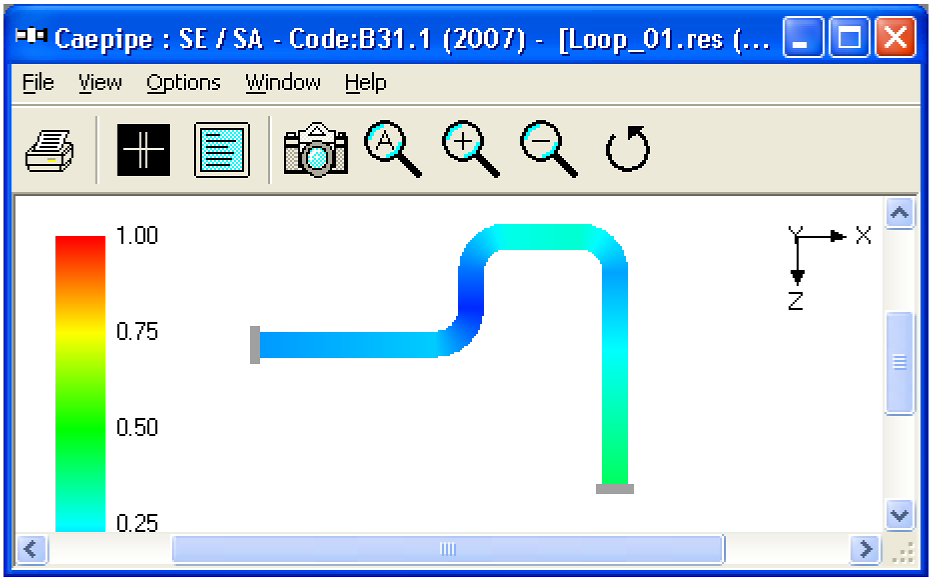
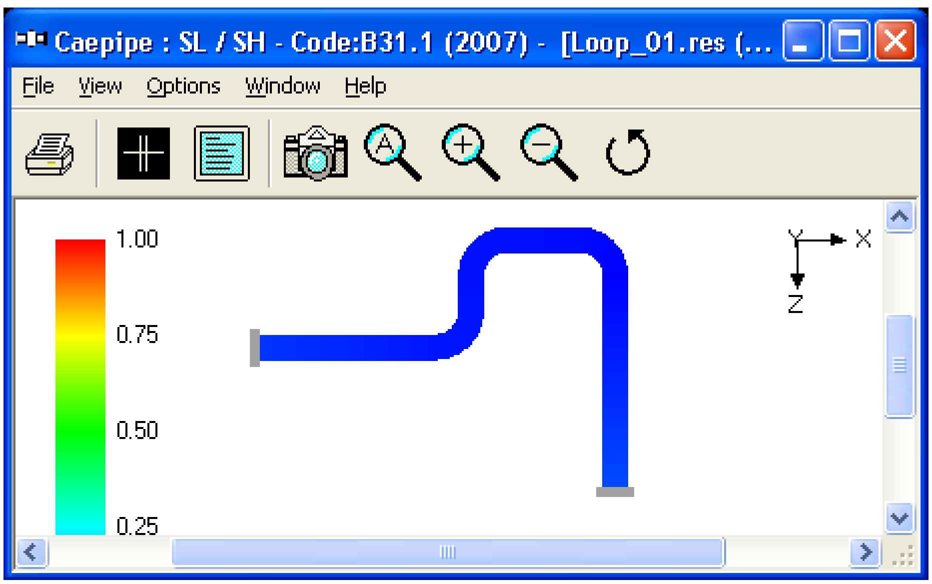


Figure 1F - Code-compliant sustained case

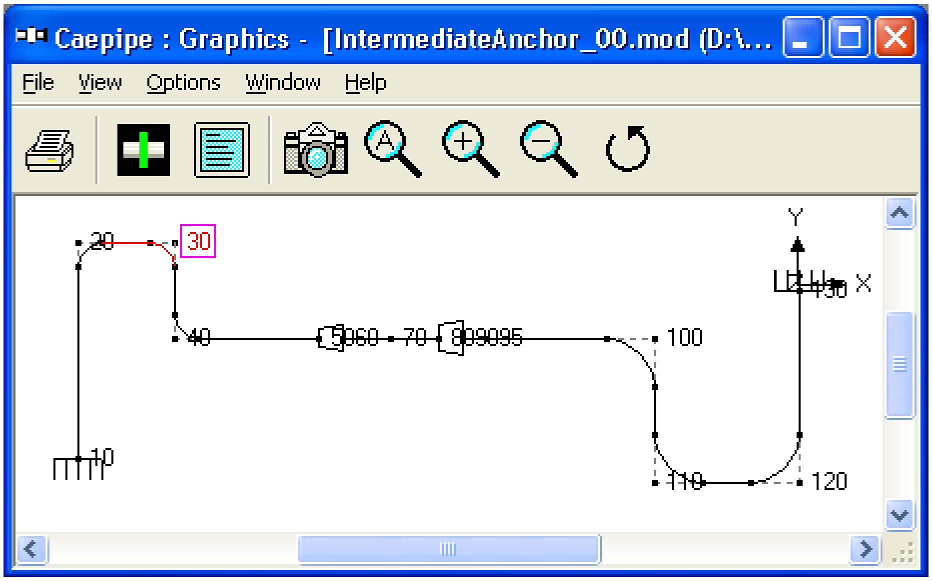


Example 2 - Splitting Thermal Growth

DATA: This system shown in Fig. 2A is made of three pipe sizes:

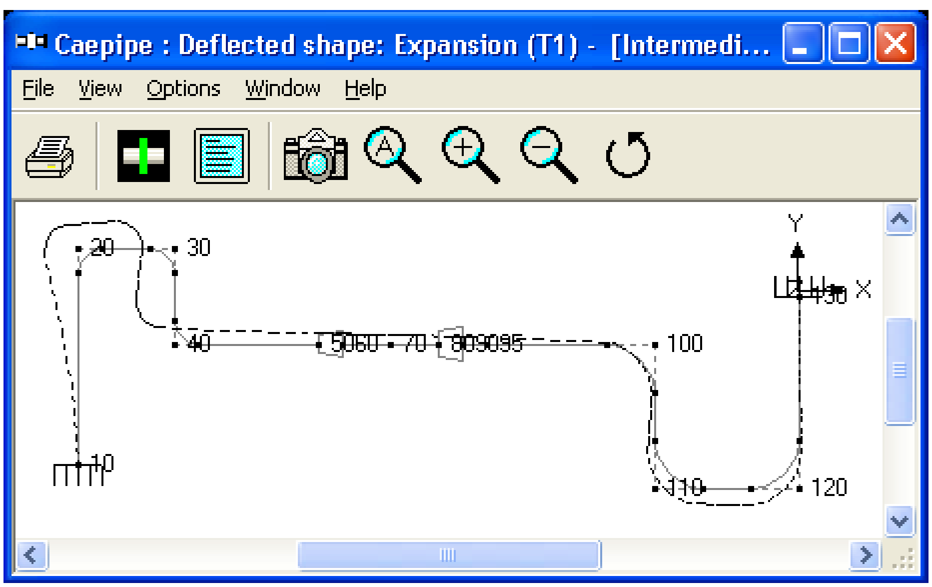
- 4" NB/Sch. 40: Between nodes 10 and the first reducer
- 6" NB/Sch. 40: Between the first reducer and the second reducer and ending at node 90
- 8" NB/Sch. 40: Between nodes 90 and anchor node 130
- T=470°F

Figure 2A – Layout



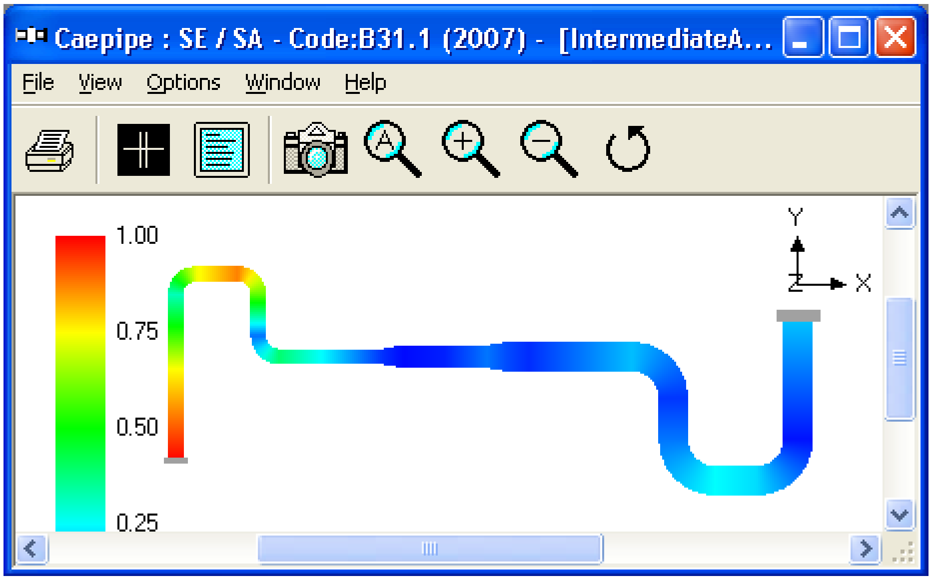
Since the loop between nodes 10 and 40 is *much more flexible (4" pipe)* than the loop between nodes 100 and 130 (8" pipe), the straight pipe between nodes 40 and 100 will thermally grow mostly towards the 4" loop, as shown in Fig. 2B, straining the pipe between nodes 10 and 40.

Figure 2B - Thermal Deformation Plot



This, in turn, produces large thermal stresses (i.e., orange and red zones) in the 4" loop and at anchor node 10, as observed in Fig. 2C. In other words, the thermal growth of pipe between nodes 40 and 100 is mostly absorbed by the 4" loop and very little by the 8" loop, defeating the very purpose of the 8" loop.

Figure 2C - Thermal Stress Contour Plot



In order to alleviate thermal stresses in the 4" loop, introduce an intermediate anchor at node 95 immediately after the second reducer, so that the thermal growth of straight pipe from node 95 to node 100 is absorbed by the 8" loop, while the thermal expansion of straight pipe between nodes 40 and 95 is absorbed by the 4" loop, thereby making both loops achieve their intended purpose. The corresponding thermal displacement and thermal stress contour plots are given in Fig. 2D and Fig. 2E respectively.

Figure 2D - Thermal Deformation Plot for Layout with Intermediate Anchor

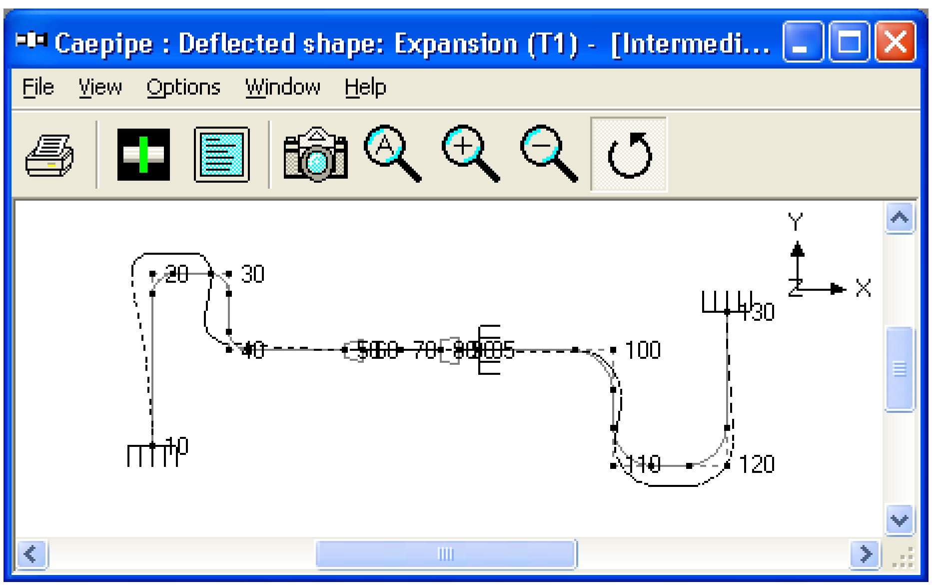


Figure 2E - Thermal Stress Contour Plot for Layout with Intermediate Anchor

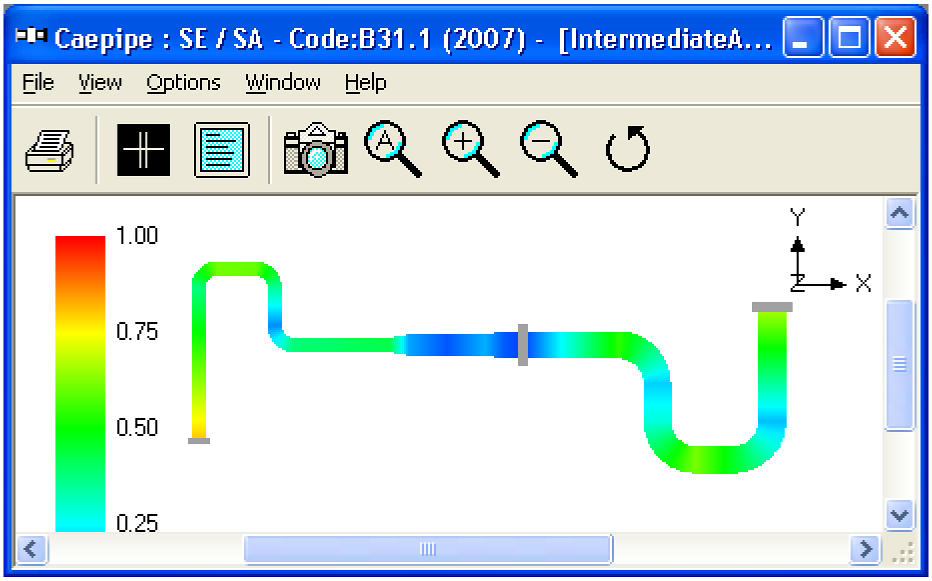
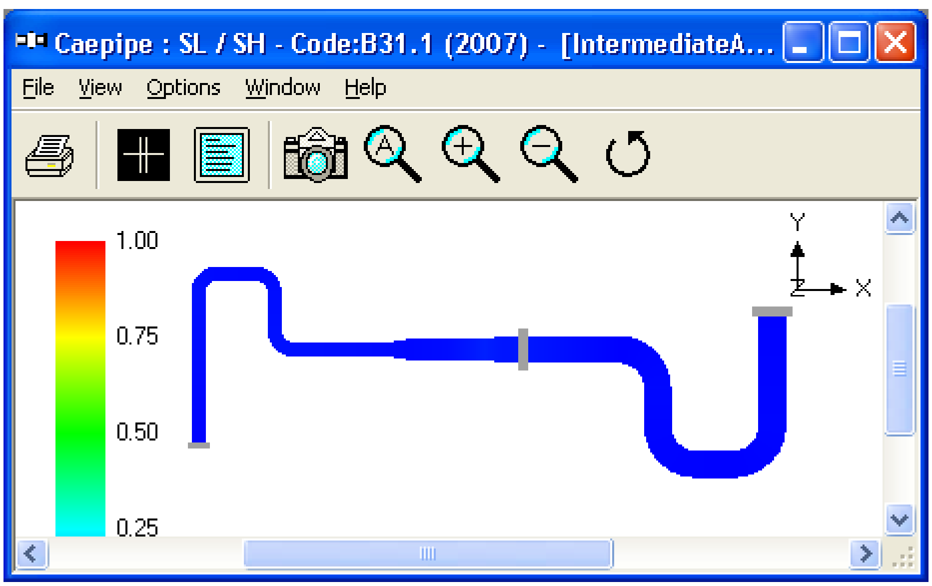


Fig. 2F confirms that the present configuration with only two equipment nozzles at nodes 10 and 130 and an intermediate anchor at node 95 safely meets the code stress requirement for sustained load.

Figure 2F - Sustained Stress Contour Plot for Layout with Intermediate Anchor



Example 3 - Axial Restraints to Direct Thermal Growth

This problem shows how axial restraints (i.e., pipe supports that prevent movement along a pipe's axis) can be effectively used to direct thermal growth towards expansion loops and split thermal growth in a line such that the two piping portions grow in opposite directions.

Figure 3A - Layout with Intermediate Anchor at Node 95

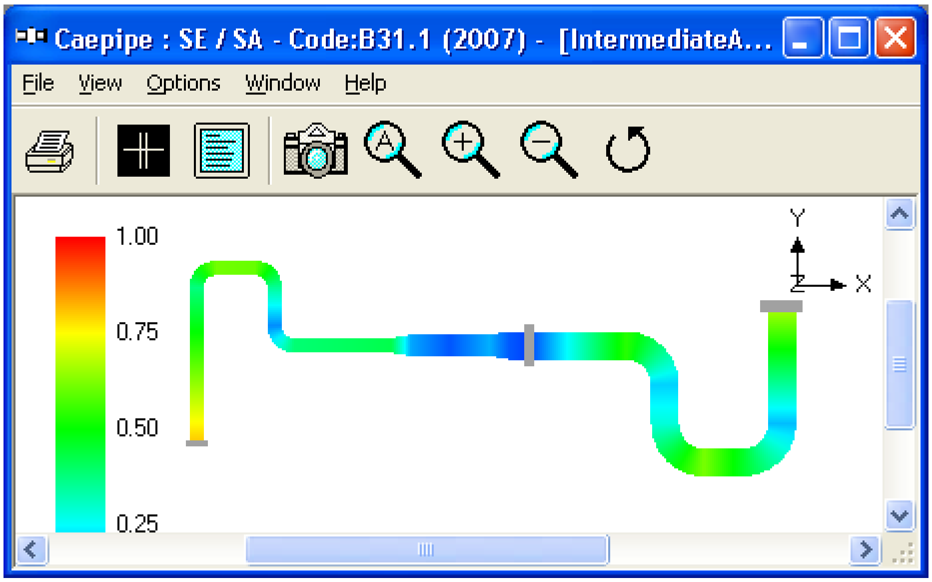
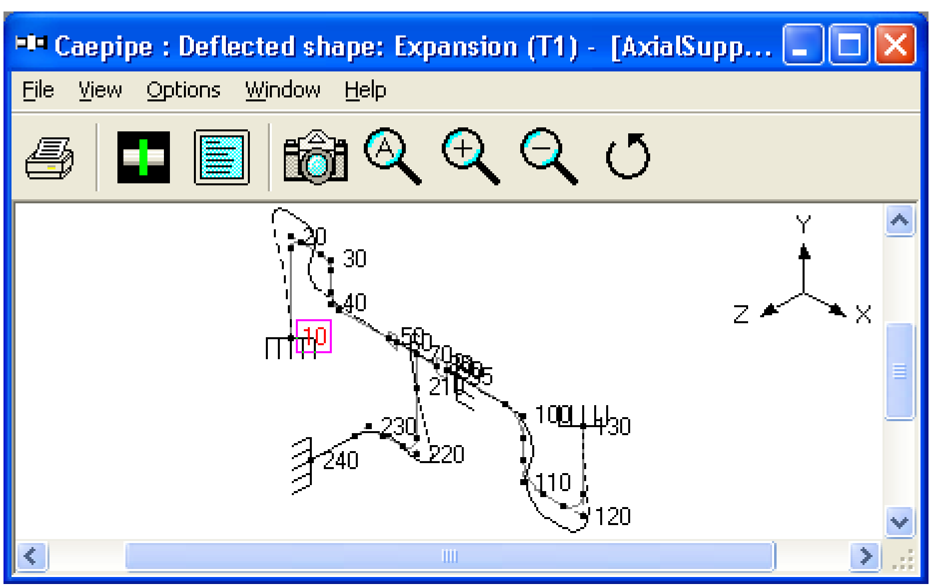


Fig. 3A shows the same problem as in Example 2 but with a 6" NB branch line added at the welding tee at node 70 (i.e., from node 70 to node 240).

The deformed geometry, due to the thermal load (Fig. 3B), shows that the tee at node 70 does not move up in +Y-direction. The intermediate anchor at node 95 restrains the vertical riser (between nodes 220 and 70) from thermally growing upward towards node 70. As a result, this riser grows downward producing large bending moments and stresses at and around equipment nozzle at node 240.

Figure 3B - Thermal Deformation Plot



Since the intermediate anchor effectively restrains upward growth of this vertical riser node 70, we see large localized thermal stress at the welding tee. See thermal stress contour plot shown in Fig. 3C.

Figure 3C - Thermal Stress Contour Plot

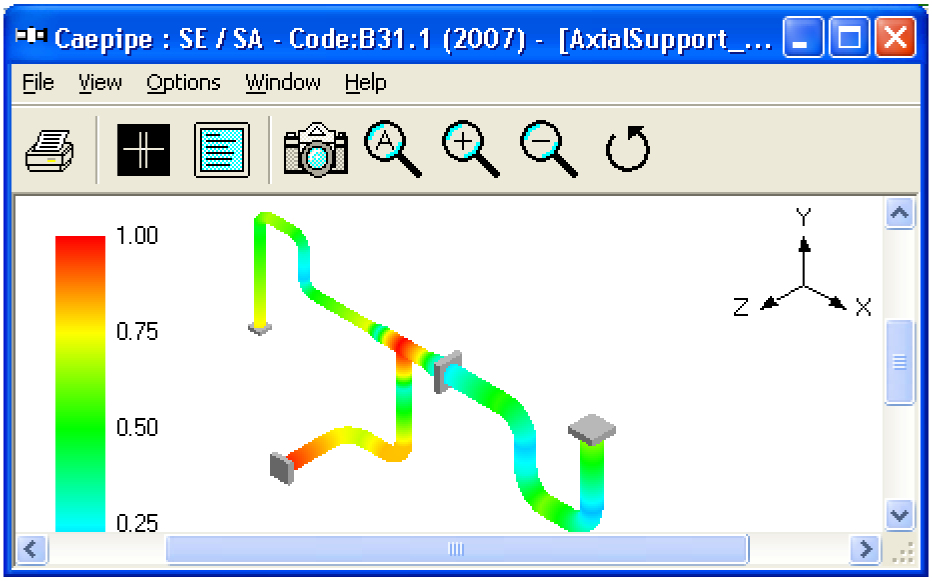


Figure 3D - Layout with Axial Restraints at Node 95 and 210

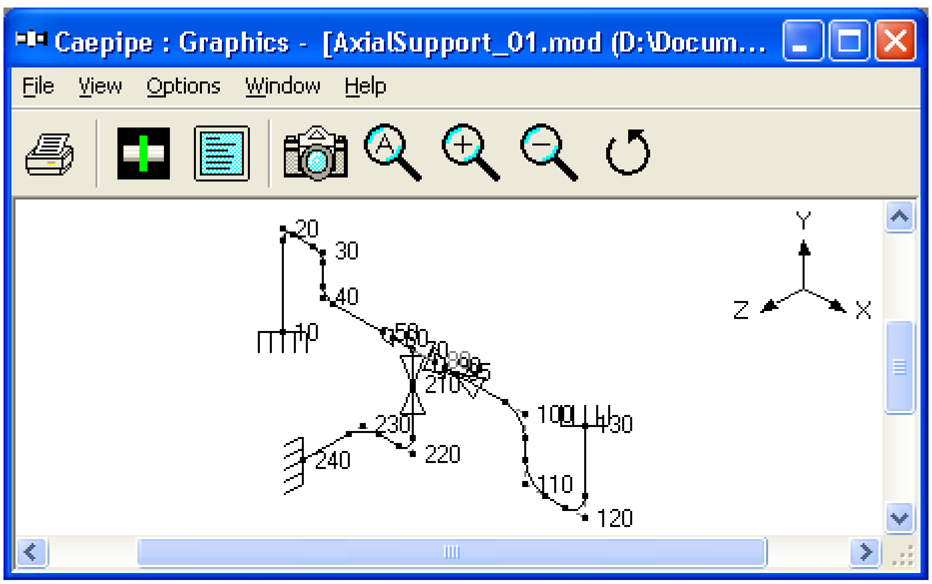
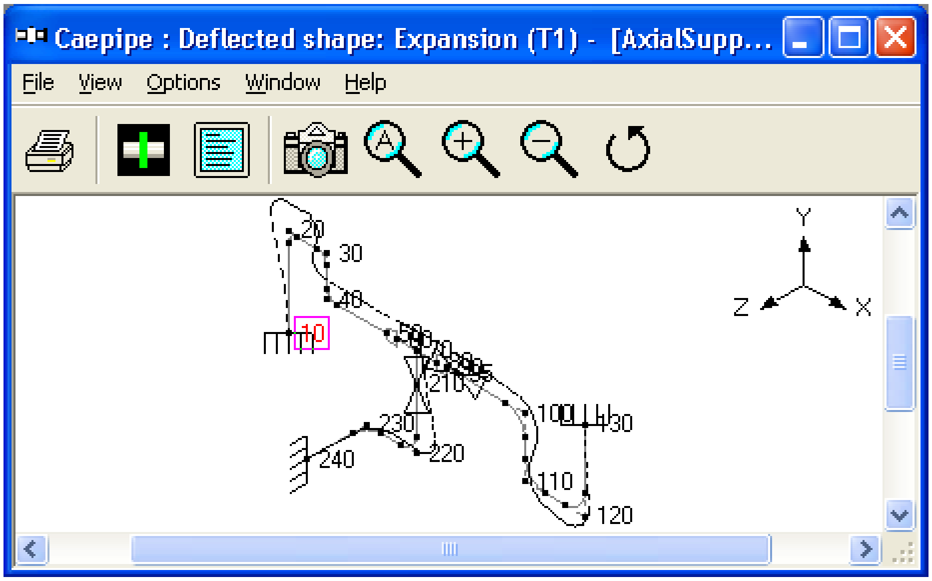


Fig. 3D shows the same piping system with one axial restraint at 95 (replacing the intermediate anchor at node 95) and another at node 210 — the one at node 95 splits and directs thermal growth towards the 4" and 8" loops and permits the horizontal line to move up in +Y-direction at node 70; the second one at node 210 splits the thermal growth of the vertical riser (between nodes 220 and 70). The resulting deformed geometry plot in Fig. 3E shows a more flexible system, which produces smaller forces and moments, and hence stresses at the equipment nozzle node 240 and welding tee node 70.

Figure 3E - Thermal Deformation Plot for Layout with Axial Restraints



Figures 3F and 3G show the thermal and sustained stress contour plots (in this case sustained stress is due to only deadweight as pressure is zero), confirming a code-compliant system for both load cases.

Figure 3F - Thermal Stress Contour Plot for Layout with Axial Restraints

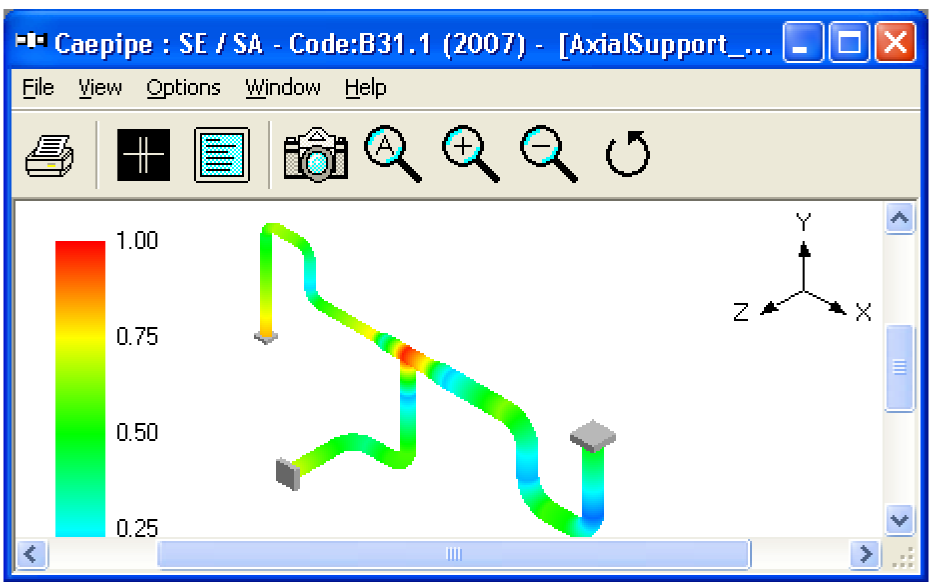
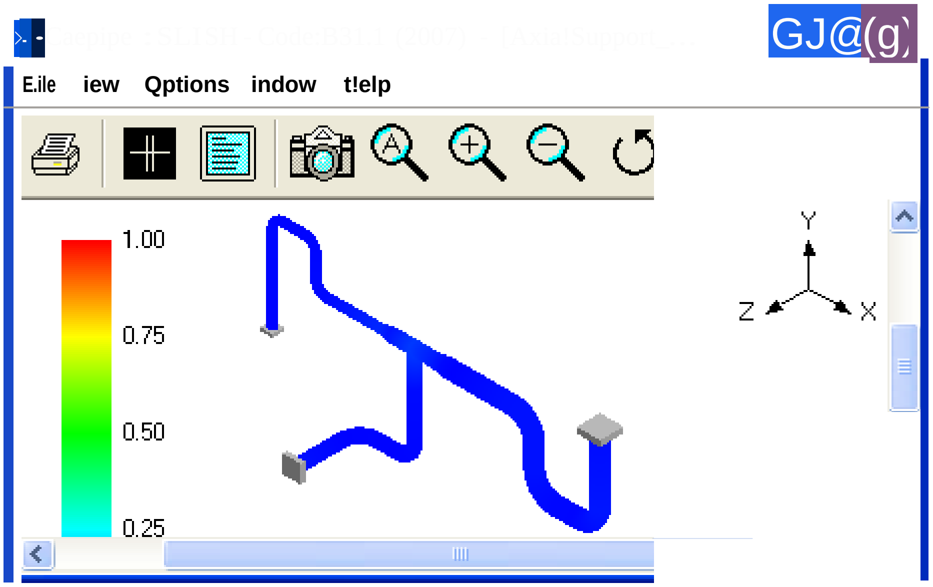


Figure 3G. SUslaine::l Stress Contour Plot for layout Wth .Axial Restraints

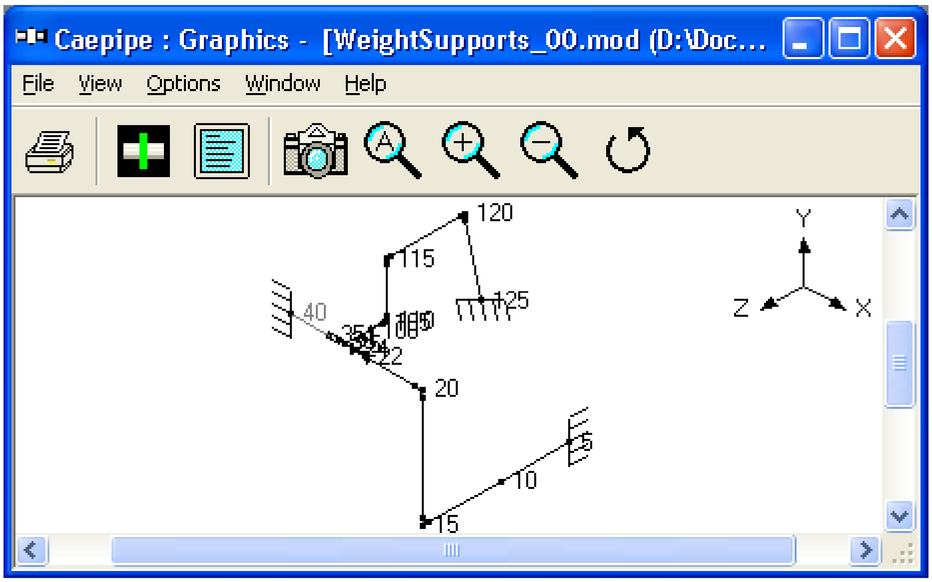


EXAMPLE 4 - Locating Supports For Deadweight Analysis

This example illustrates how to select and locate vertical supports to carry piping deadweight in the operating condition.

Fig. 4A shows a practical problem with 10” NB Standard schedule pipe from equipment nozzle at node 5 up to the reducer at node 30, 8” NB Standard schedule pipe from this reducer to the pump nozzle at node 40, and a 6” NB Standard schedule branch line from the welding tee at node 25 to the equipment nozzle at node 125.

Figure 4A - Layout with Node Numbers



The thermal stress contour plot given in Fig. 4B confirms that the piping system is highly flexible and hence meets the code requirement for thermal load.

Figure 4B - Thermal Stress Contour Plot

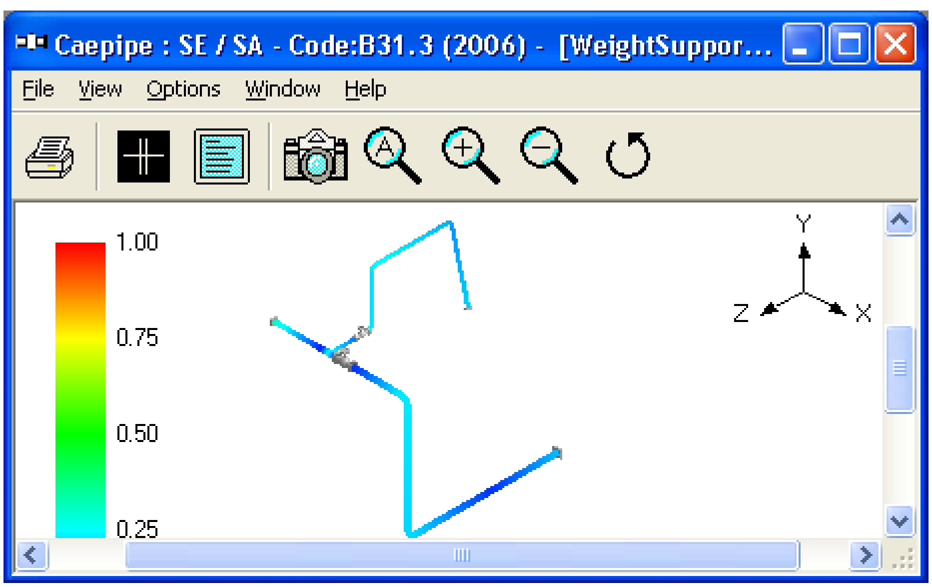
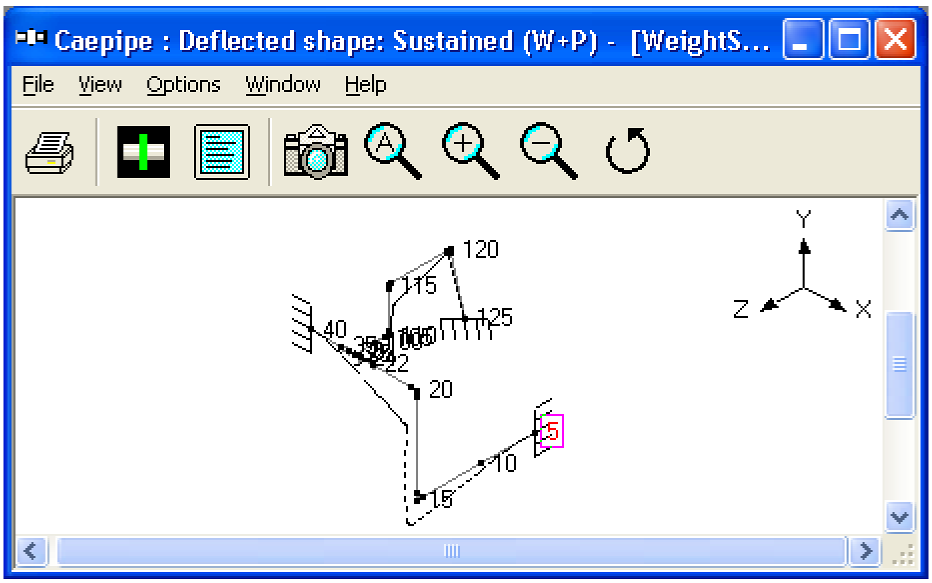


Fig. 4C shows the deflected shape for sustained load (i.e., mainly deadweight). It is observed that the weight of

- (i) the horizontal line from node 5 to node 15 and
- (ii) a major portion of the vertical riser from node 15 to node 20 is carried by the equipment nozzle at node 5. On the other hand, the pump nozzle at node 40 carries the weight of

- (i) the horizontal line from node 20 to node 40,
- (ii) the valve portion of the branch line from node 25 to node 125 and
- (iii) a small portion of the vertical riser from node 15 to node 20.

Figure 4C - Sustained Load Deflected Shape



The deformation response for deadweight, in turn, generates large forces and moments and hence large sustained stresses at nozzle nodes 5 and 40 as shown in Fig. 4D for sustained stress contour plot.

Figure 4D - Sustained Stress Contour Plot

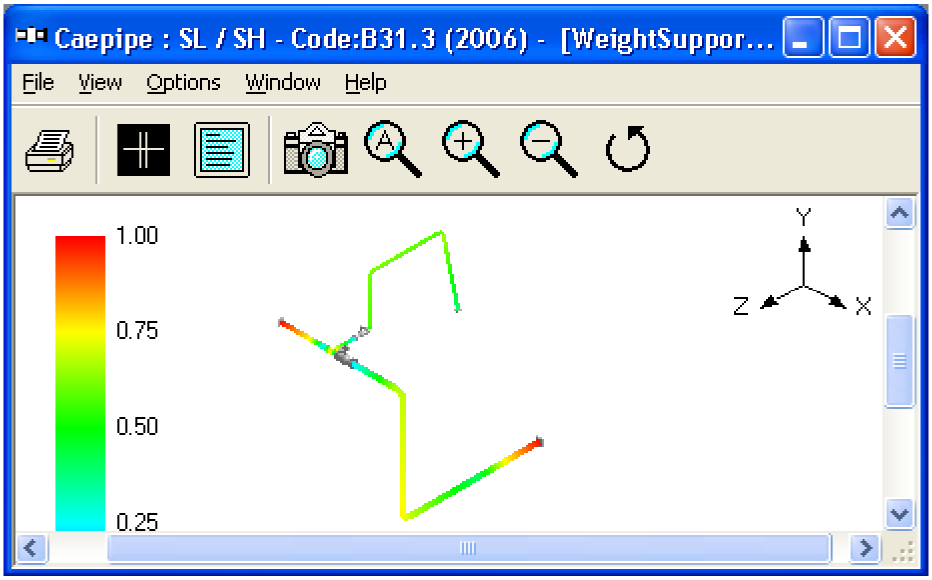
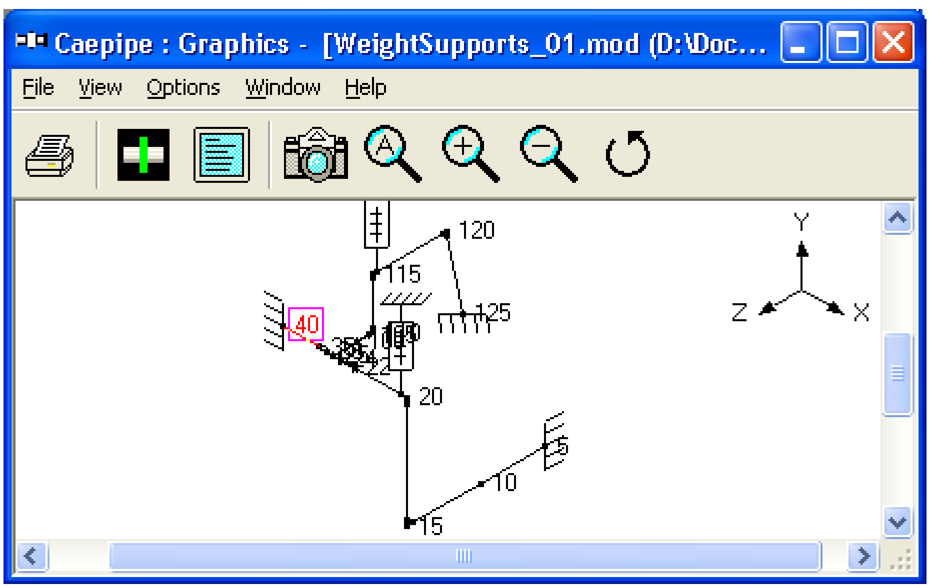


Fig. 4E shows the same layout with variable spring hangers at the bends at nodes 20 and 115, which carry piping deadweight and provide negligible restraint to thermal movement from cold to hot condition and vice versa.

Figure 4E - Layout with Hangers



The thermal and sustained stress contour plots given in Fig. 4F and Fig. 4G confirm that the piping system with hangers is code-complaint for both sustained and thermal load cases.

Figure 4F - Thermal Stress Contour Plot for Layout with Hangers

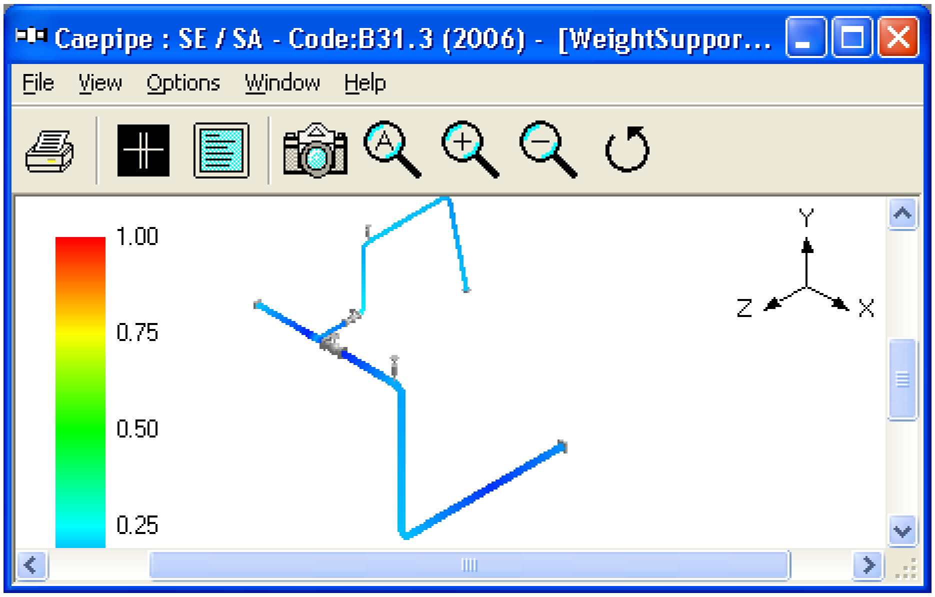
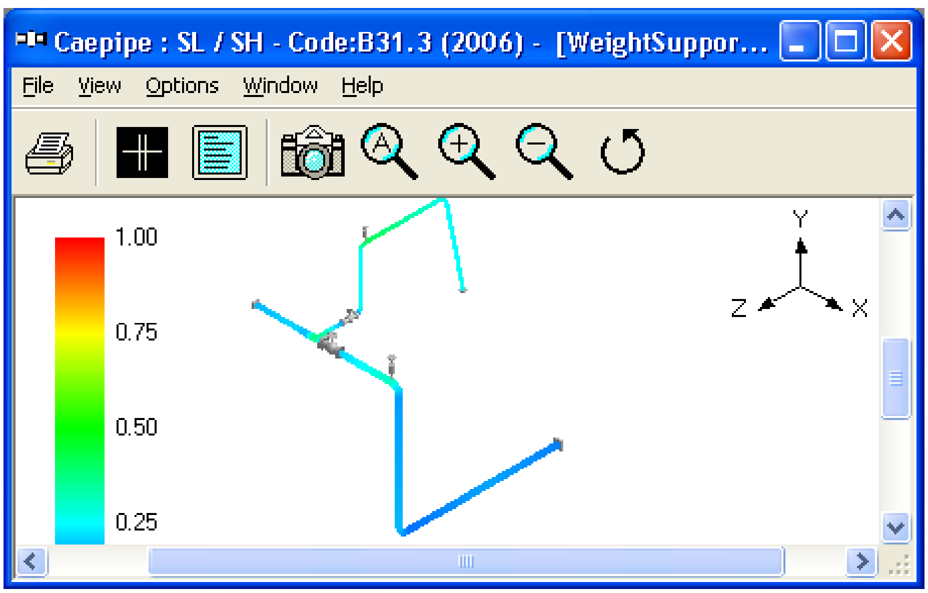


Figure 4G - Sustained Stress Contour Plot for Layout with Hangers

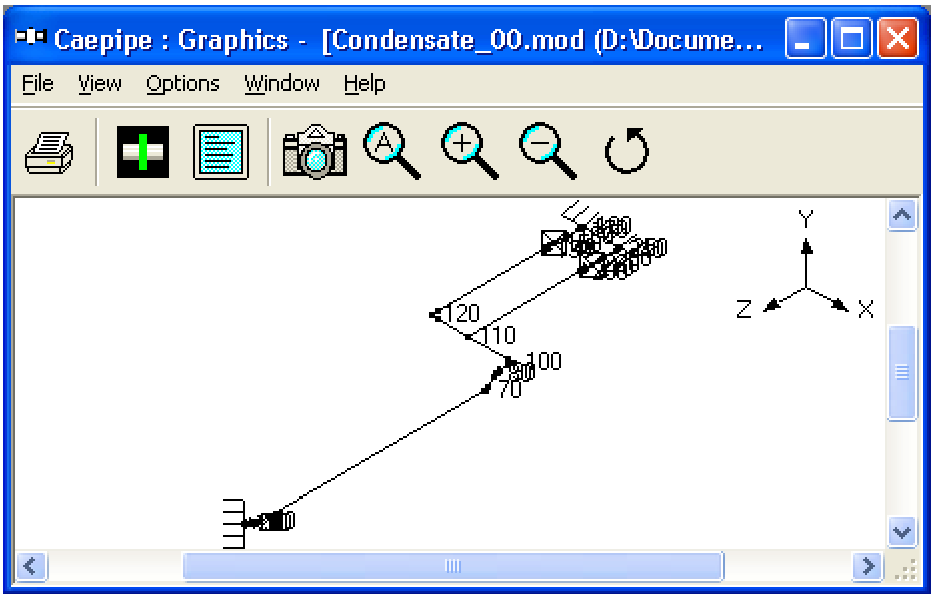


EXAMPLE 5 - Making Layout Changes to Reduce Thermal Stresses

This practical example illustrates how to place resting steel supports to carry the system weight with operating fluid and modify the layout in order to re-direct thermal growth to comply with code stress requirements.

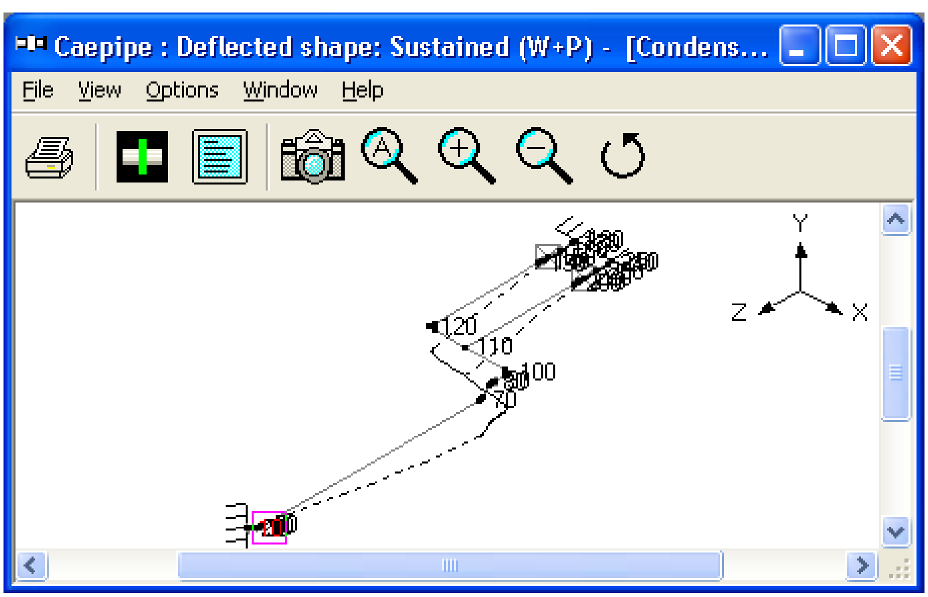
Fig. 5A shows the initial layout where condensate from a tank (node 10) is extracted by the pump suction lines. When one pump is operating, the other one is on standby.

Figure 5A - Layout with Node Numbers



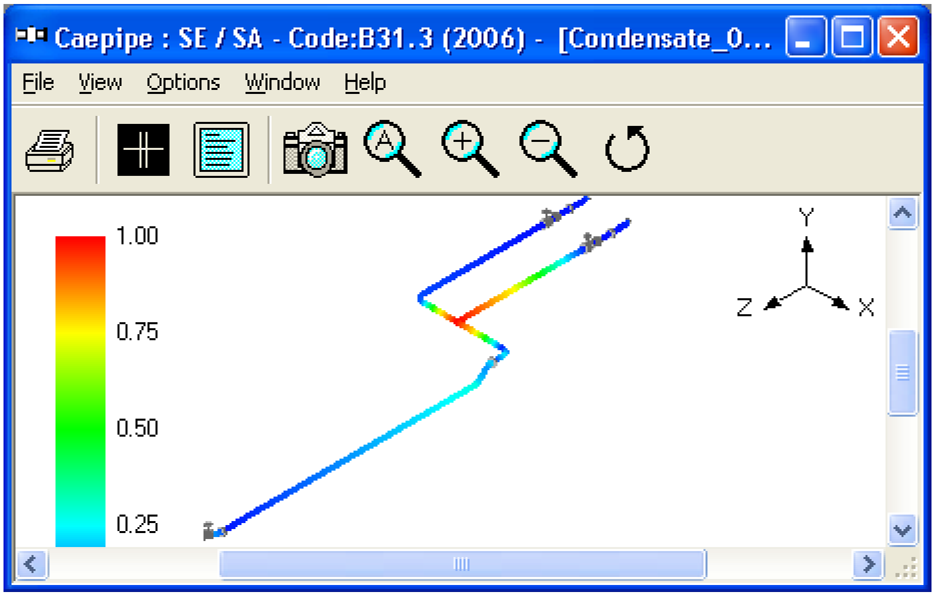
From Fig. 5B, we see that the pipeline from nodes 10 to 100 grows thermally in the –Z direction (towards the pumps), whereas the two pump suction lines, one from nodes 120 to 180 and the other from nodes 110 to 250, grows in the opposite direction towards the tank (+Z direction). So, the straight pipe between nodes 100 and 120 (with a welding tee at node 110) experiences two opposing deflection patterns - the pipe portion between nodes 110 and 120 is being deflected in the +Z direction like a rigid stick while the portion from nodes 10 to 100 deflects in the –Z direction.

Figure 5B - Thermal Deformation Plot



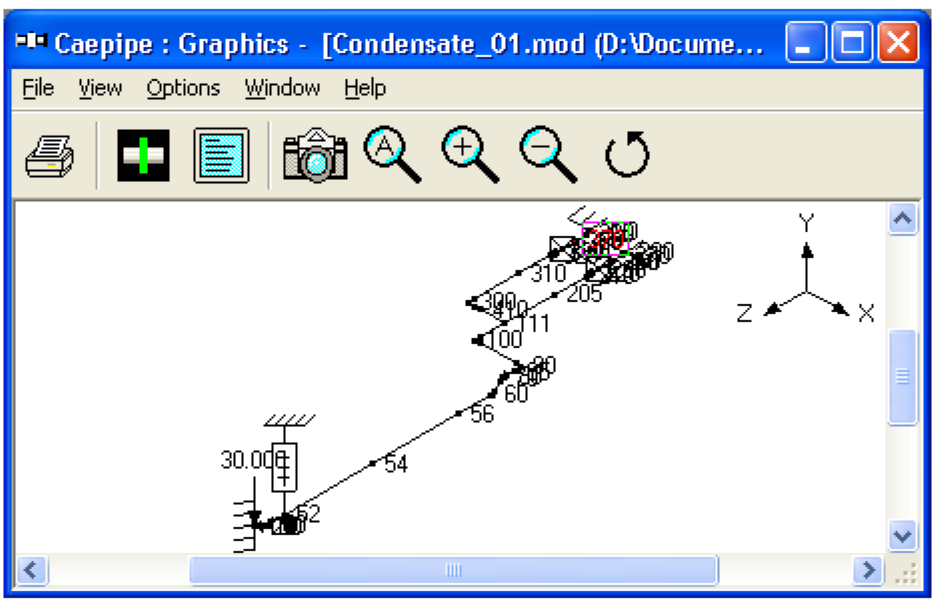
This causes the pipe between nodes 100 and 110 to bend at the tee producing high strains and hence thermal stresses locally at the tee node 110, as shown in Fig. 5C.

Figure 5C - Thermal Stress Contour Plot



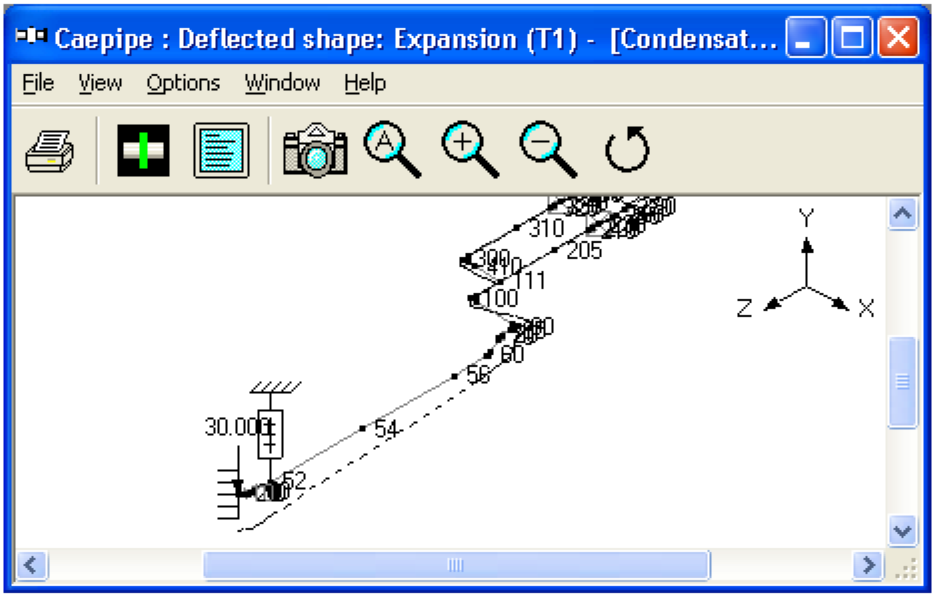
In order to reduce these thermal stresses at node 110, we cut the straight pipe between nodes 100 and 120 into two parts – one part is the pipe from nodes 100 to 110 and the second part is from nodes 111 to 410 to 300. We then shift the second part downstream towards the two pumps, resulting in the modified layout shown in Fig. 5D.

Figure 5D - Revised Layout with Node Numbers



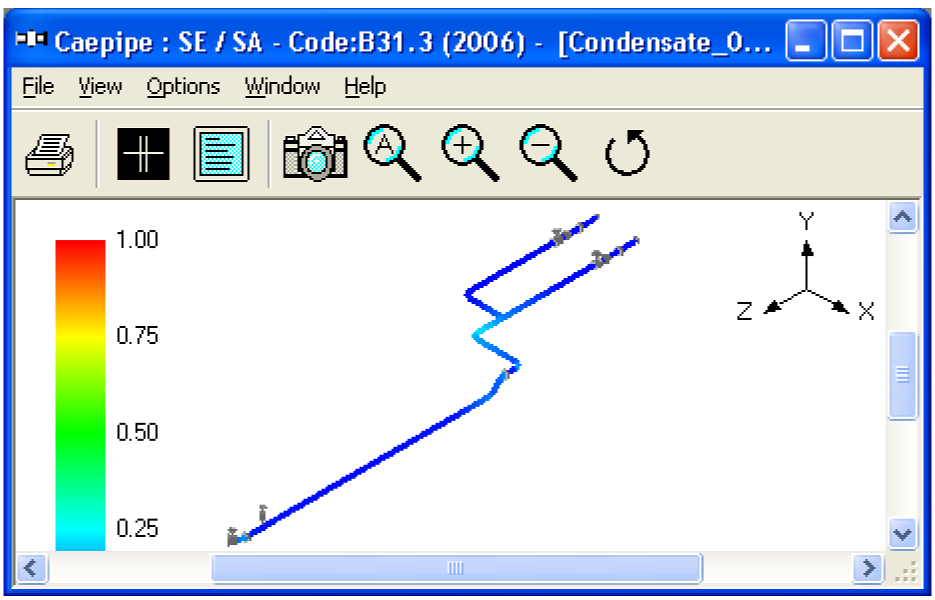
This shift of pipe downstream does not adversely increase the pressure drop between the tank at node 10 and the pumps at nodes 180 and 250. From the thermal deformation plot for this revised layout shown in Fig. 5E, we can see that the two pump suction lines from the suction nozzles to the welding tee at node 111 have almost equal thermal growth in the +Z direction.

Figure 5E - Thermal Deformation Plot for Revised Layout



Moving the branch pipe between nodes 111 and 300 as a rigid stick results in lower thermal stresses in that branch pipe as seen in Fig. 5F.

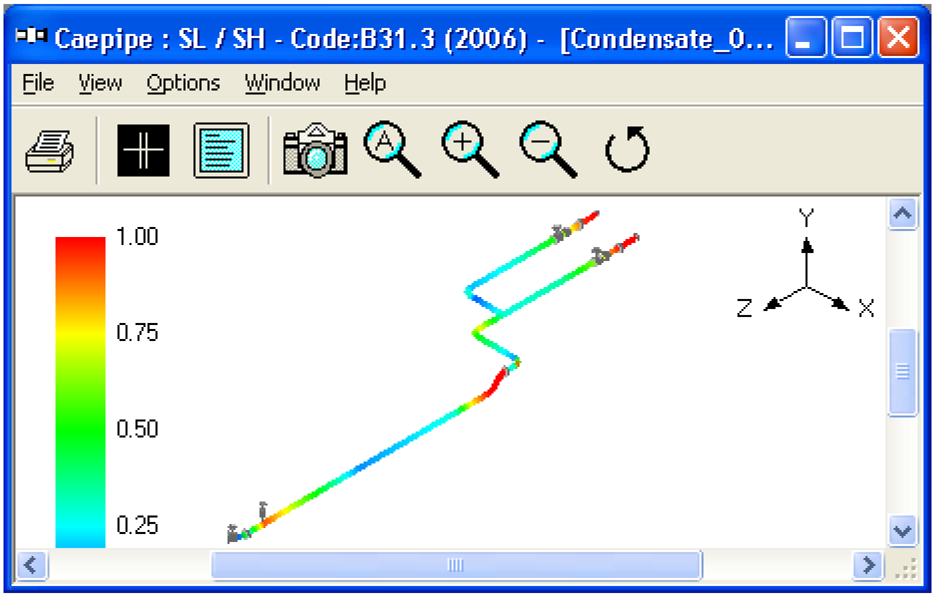
Figure 5F - Thermal Stress Contour Plot for Revised Layout



In addition, we see that the two pump suction lines make the bend node 100 grow thermally in the +Z direction, whereas the pipe from the tank node 10 to the bend node 90 grows in the –Z direction. These opposing deflections rotate the interconnecting pipe between nodes 90 and 100 like a (horizontal) "see-saw" in the horizontal XZ plane, resulting in lower thermal stresses in this region, as observed in Fig. 5F.

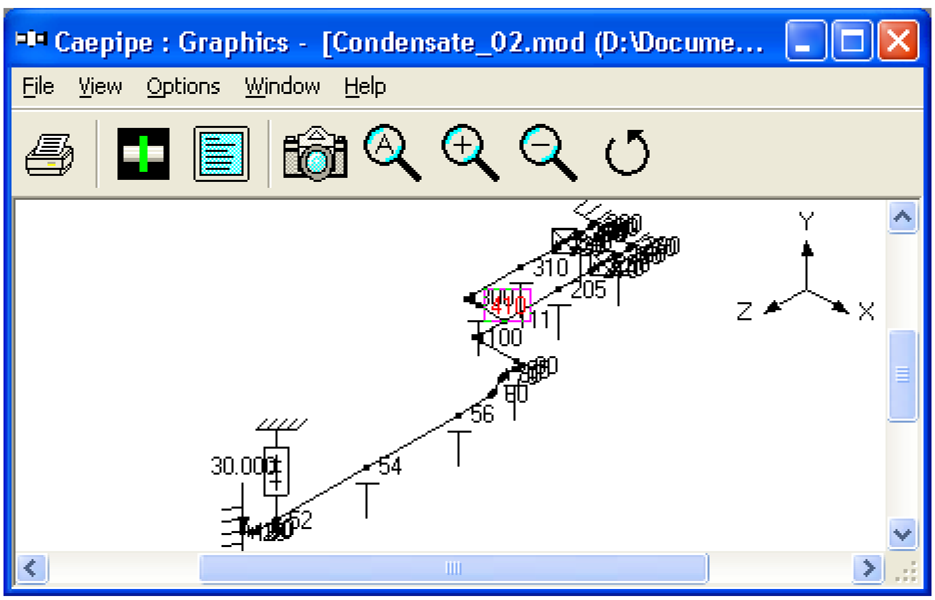
Although the thermal stress criterion has been met, the weight stresses exceed the sustained stress allowables, as illustrated by many red and orange areas in the sustained stress contour plot given in Fig 5G.

Figure 5G - Sustained Stress Contour Plot for Revised Layout



This is because there are no vertical supports (excluding the three nozzles and a variable spring hanger at node 52) to carry the weight of the system. Vertical resting supports are therefore introduced as shown in Fig. 5H.

Figure 5H - Revised Layout with Resting Supports



The recalculated sustained stress (i.e., weight + pressure) contour plot (with most areas in blue) shown in Fig. 5I are now well below the allowable stress values, and hence code-compliant.

Figure 51· 9Jslaine::l Stress Contour Plot for Re-.tse::l layout Wth Resting SUpports