A SunCam online continuing education course

Piping Design Fundamentals – Avoid Pitfalls in Design and Analysis

by

Gerry May

1.0 INTRODUCTION

A pipe stress analysis should always reflect the actual physical pipe to an accurate enough level that there is great confidence that the pipe stresses are within acceptable limits, the pipe support loads are within acceptable tolerances and the pipe movements reflect what is observed in the installation. Perfection is not expected, but meaningful realistic results are required. The goal of this course is to provide guidance to create a piping design that will perform well in the field, and to create a pipe stress analysis that accurately predicts the field performance. With the guidance in this course, the user should know how to:

1. Plan a design analysis for various loading conditions
2. Initially locate supports
3. Judge the acceptable use of various piping components
4. Judge the acceptable use of linear and non-linear restraints
5. Properly interpret a computer-generated pipe stress analysis
6. Quickly spot the warning signs that a computer-generated pipe stress analysis answer may have exceeded the limits of its accuracy, and the results should not be trusted

All of these subjects are interrelated. Thus, this course is organized by topics of design and analysis recommendations for various stages of design and evaluation in Section 2. Section 3 combines guidelines for analysis and design of the pipe and pipe support system for static loading conditions. Section 4 combines guidelines for design and analysis for dynamic loading conditions.

Pipe stress analysis program input options are intentionally loaded with what seems to be limitless variations for pipe routing, branch connections, connecting nodes, stress intensification factors (SIF), combining loading conditions, and use of linear and non-linear restraints, including friction factors. All of these options will usually result in an output with calculated pipe stresses, pipe movements and support loads. Too often the author has seen the output blindly accepted or misinterpreted, leading to poor installations subject to "unexpected" failures.

The author recognizes that many of the recommendations in this course are not in most software instructions, or other documents. All of the recommendations are based upon years of analysis experience merged with years of observing piping systems in the field, and correcting damaged pipe and pipe supports.

Some of the recommendations may be controversial to some, and every effort has been made to point out the evidence for the author's viewpoint. If the reader disagrees with the recommendation, they should consider the issue from their experience, test their analysis program, and determine if a better recommendation exists.

Given the differences in analysis programs and the purpose(s) of analyzing a piping system, this class does not address the methods of modeling a piping system, except to note that the analyst should always understand the program and the assumptions it is making to properly interpret the results.

One general comment to always keep in mind: It is often easy to treat the analysis and modeling as a classroom exercise. Always remember that a design and analysis represents a real world in which fluids are going to be transported. Depending on the fluid, temperatures and pressures; people's lives may depend upon the design, analysis, fabrication, installation and operation being performed properly. It is fully expected that a well-designed piping system may operate for decades with little maintenance or inspection. Do your best to make it safe and reliable for everyone.

With these preliminaries out of the way, let's have a spirited discussion of the issues.

2.0 KNOW YOUR PROBLEM AND YOUR DATA

In order to properly model the piping system and eventually interpret the output properly, the standard process of analysis must be followed:

1. Know why this system is being analyzed – New design, modification, failure analysis or other reason. Is this a conceptual analysis that can be managed with a quick and conservative approach, or is this a detailed design in which all reasonable efforts should be made for accuracy?

2. What are ALL the possible loading conditions?

3. What loading conditions need to be analyzed? Numerous conditions may be negligible in relation to the total stress, or they may be regarded as subsets within the broader scope of the analysis. Take the time to discuss with at least the Process and Mechanical engineers to assure all the loading conditions are considered. A list is included later, but if there is a unique service, perhaps there are other possibilities not listed.

4. What information is available? Material specifications, pipe support proposed locations, equipment connections and process conditions are the minimum.

5. What are the stress intensification factors (SIF) of components? The SIF's in the ASME B31 codes are reliable. Most other components require validation by analysis or testing. If two components with an SIF are close together, such as a branch connection from an elbow, the interaction of the SIF of the combined components is unknown. If a reliable SIF is not available for components, then use a "standard" alternative, if at all possible.

6. Avoid using non-standard components such as dummy legs. See Figure 1. The flexibility of the elbow is affected in unknown ways, and the combined SIF of the elbow and dummy leg interaction is unknown. Yes, you can see these at all sorts of installations. If the operating temperatures are low enough, and the actual stresses are low enough, the engineer gets by with it. But from an analysis standpoint we do not know the SIF and flexibility, and this is an example of components to avoid.

7. Welded attachments for pipe supports should be avoided, particularly on high temperature lines. The weld is at a temperature near the fluid temperature but the end of the attachment is exposed to ambient air. This creates a differential thermal stress at the weld that is normally not calculated, but which can create failure. For piping systems that are inspected, each weld is another location to be inspected periodically, and another location of a potential failure. Virtually all piping failures occur at welds, not in the base metal, and that includes welded on pipe attachments.

Fig 1. A horizontal and vertical dummy leg installation that cannot be accurately analyzed due to unknown effect on the elbow flexibility, and the unknown interaction of the SIF's.

Fig. 2 Welded attachment is difficult to analyze due to localized thermal stresses. The red indicates weld cracks. All welded on pipe support attachments add another potential location for a pipe failure.

8. What information is reasonably assumed? Can there be ranges of answers based upon nominal versus upset conditions? Will multiple analyses be required to bracket the assumptions?

9. What analysis input information is unknown? Is there any way to research to turn unknowns into knowns? How will the unknowns be addressed in the analysis and design?

The analyst may be in the position of performing analysis for a new system that is being designed, modifying an existing system with new branch lines or other major modifications, or analyzing an existing system to solve a particular problem. The general approach is similar in each case, but the knowns, unknowns and exact modeling techniques may be different.

2.1 NEW DESIGNS

This should be the easiest analysis to perform, as in theory, the locations of supports, pipe routing and types of supports are not specified. The analyst can help develop the optimum routing for minimal thermal stresses, optimum support locations and types of supports. This is possible if the analyst is involved as the plant and piping systems are laid out and structures are defined.

If the analyst is only brought in to analyze a piping system after decisions have been made, and the analysis is only being performed to verify everything is fine, three potential major problems occur:

1. The potential benefit of the analysis has been lost. The analysis should be used early in the design to optimize the piping system, particularly on critical systems. Large critical systems may dictate the shape of the plant and a large amount of the costs. Failure to optimize these systems through analysis and coordination with process, structural and mechanical equipment design during the conceptual phase may force a higher expense on the installation and operation of the plant than is necessary.

2. If the initial analysis does not produce an acceptable output, the analyst may be put in the position of modeling until the program produces an acceptable result – not the correct result. This situation can lead to misinterpretation of results, discussed later.

3. The piping system as designed is truly unacceptable and must be re-designed creating cost overruns and delays.

Loading conditions and acceptance criteria need to be set during the conceptual phase. All piping systems will have requirements for thermal, dead weight and pressure loads set by process calculations and code requirements. There should be safety margins set for potential over pressure and over temperature conditions. Owners or the design team should have specifications for the types of components that will be used from types of branch connections, materials of construction, and use of specialty equipment such as expansion joints.

When analyses are being made in the conceptual stage, it is strongly recommended that the maximum allowable stress criteria should be less than or equal to 50% of the Code allowable stress for the weight + pressure and thermal loading conditions. This is typically not a difficult criteria to meet. There are three major reasons for this conservatism:

1. As detailed design is performed, the details often result in increased calculated pipe stresses. This early-in-the-design conservatism allows for some changes without causing a major re-design of the entire system.

2. Particularly on high temperature lines that may be subject to creep degradation, keeping the stress at 50% of the allowable stress greatly increases the life of the pipe. Code allowable stress for materials operating in the creep range is based upon 100,000 hours of operation. If the system is likely to operate for decades, the calculated stress needs to be at or below 50% of the Code allowable to minimize creep degradation.

3. If the piping system is subject to significant corrosion or erosion (internal or external), the lower calculated stress shall provide more time between inspections and possibly longer life.

Equipment suppliers may have limitations such as allowable piping loads. Are they reasonable? Sometimes the vendors specify allowable loads that are so ridiculous that we have embarrassed them by questioning, "The allowable loads at the nozzle convert to less than 1% of the allowable pipe stress. We cannot be that accurate. Get realistic with the nozzle allowable loads." **Recommendation: If at all possible, provide minimum acceptable allowable nozzle loads in purchased equipment specifications that the pipe will not exceed. Part of the selection process should include whether the supplier is willing to accept those values.**

Special loading conditions need to be specified early. Is seismic design any concern on any of the pipes? What is the loading criteria? What is the acceptance criteria? How are we going to analyze this? Note that **if seismic or other dynamic loading conditions are a consideration, they may be significant drivers for optimum pipe routing and pipe support concepts. If dynamic loading conditions are to be analyzed they should be incorporated in the conceptual analysis.**

Are there other special loading conditions, such as:

- wind,
- surge (during start-up or shutdown),
- safety valve thrust,
- steam hammer by fast acting valves,
- equipment vibrations that could damage the pipe,
- flow that may be liquid at times and gaseous at times (effecting weight and support calculations,
- Is a gaseous or steam system to be hydrotested in the field? Special analysis may be necessary to size pipe supports for a one time loading condition.
- Special maintenance requirements such as safe access for clean-out ,
- Special venting or draining considerations, note that water hammer caused by superheated steam suddenly hitting entrapped water can create damaging loads. Water hammer cannot be designed or analyzed for but must be avoided by proper design and operation.
- Other unusual situations?

Pipe Support Locations

Pipe support location is a significant topic alone. As described in Section 3, a good goal is to assure the pipe does not sag more than 0.1” between supports due to weight loading. A second rule should also meet the recommended maximum weight only bending stress of 2000 psi. Obviously, the analyst must include analysis nodes between the supports to confirm this. The guidelines below are a starting point to locate supports. The pipe stress analysis will confirm or deny if they are appropriate for your particular case.

1. There are standard spacing rules for straight carbon steel pipe that many companies have developed based upon the pipe diameter. Know the assumptions in the rules and adjust spacing as necessary, for the pipe material, operating temperature, density of the fluid, insulation and thickness of the pipe. If the analyst is not sure about the spacing guidelines for a specific situation, it would not take long to develop a few test cases to calculate recommended pipe spacings.

2. On horizontal straight pipe, support locations should be reasonably evenly spaced, with exceptions described in the following guidelines.

3. At horizontal and vertical elbows, a support should be within 50% of the standard straight line spacing measured from the tangent intersection point of the elbow. For long sweeping 3D or 5D bends the support may have to be located on the bend.

4. On risers greater in height of 10 feet for pipes up to 6 inch diameter, and 20 feet for larger pipes, there should be at least one support in the top 1/3 of the riser.

5. For risers of 50-foot height or more, include at least one more vertical support lower in the riser.

6. At locations near equipment nozzles with low allowable loads, a spring support very near the nozzle is the most reliable approach to ensure the nozzle loads are as low as possible. It also provides an assist to craft personnel if the pipe must be disconnected for maintenance.

7. At heavy wall rigid bodies, such as valves and unusual fittings, install a support within 3 pipe diameters of the end of the component. Some vendors include a location for the support directly on the valve body. If a flanged valve, the support can be incorporated into a special flange design.

8. Consider maintenance of equipment when locating supports if it is likely pipe will be disconnected routinely. Supports located at the end of the pipe to be left in place is appreciated by the field personnel.

9. Expansion joints should be used sparingly, but if they are required, the rules for support are rigorous. It is often best to work with an expansion joint vendor or other specialist to assure the joint is supported properly to avoid squirm or other movements that will cause premature failure.

10. The inclusion of guides, anchors and other specialty supports must be coordinated with at least the structural group, as the loads may be high in a non-vertical direction and structural may have to make special accommodations.

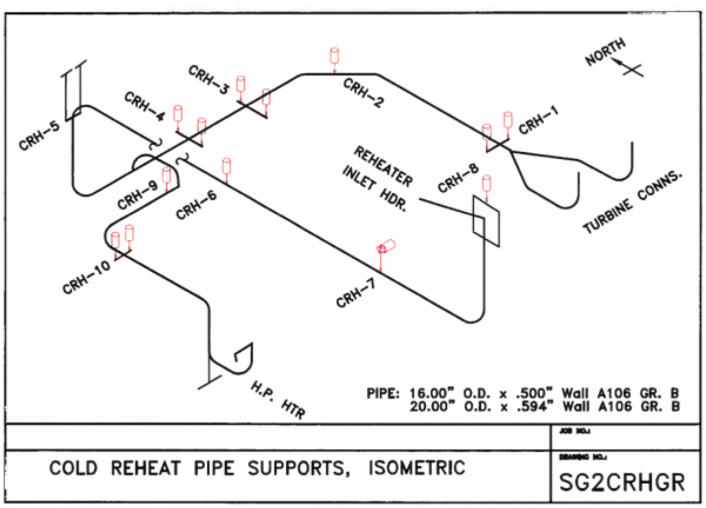


Figure 3. The use of a rigid vertical support at CRH-5 limits the vertical movement and stabilizes the system. Note that the support is near the top of the riser for stability. If located in the lower half of the riser, the top of the riser would be unstable.
All of the other supports are spring supports except for the unlabeled base support near the H.P. Htr. While the location is not ideal because it is a stanchion support, it is acceptable at this location because it is on a short riser, CRH-10 is within a few feet of the riser and the H.P Htr provides additional stability.

2.2 POST ANALYSIS DESIGN ISSUES

Once the analysis is performed and the systems optimized, the analyst provides results to structural for design loads, mechanical for equipment nozzle loads, and pipe support locations and types to the pipe support design group. These groups, including pipe support vendors create the detail design drawings, specifications for purchase, detail pipe spool drawings, and pipe support details. **The stress analysis needs to be reviewed as the design drawings are being finalized to ensure that the final design is a reflection of the analysis.**

If there are any significant differences between design drawings and the analysis model, re-analysis or re-design of the anomalies is necessary.

THE ANALYSIS MUST MATCH THE FINAL DESIGN.

Unfortunately, this step has been missed in many projects. To save money, pipe support design is sent to another group without review by the piping analyst. These disconnects have caused substantial errors and should not be tolerated by an engineering company or client.

> **An historical reference to the Hyatt Regency walkway collapse in 1981 that killed 114 people:** The major issue was that the walkway detail support design was modified in the field without the Engineer of Record being involved, as was common at that time. Structural design at U.S. engineering firms now requires approval by the Engineer of Record of the detailed designs. Given the potential for catastrophic failures of some piping systems, the same attention to detail is strongly recommended by the author for piping systems. (If you are not familiar with the Hyatt Regency failure, there are numerous references and some engineering ethics classes available on the internet discussing this engineering disaster.)

Assuming the design has been performed well, proper materials purchased and fabricated, then there is still the field installation. Field modifications are expected. Equipment does not always arrive per the drawings, steel and concrete is not exactly at the design locations, pipe is thicker than nominal and pipe supports don't fit in the space envelopes. These and other issues are common and can usually be dealt with minimal impact to the pipe design.

Pipe installation requires welding pipe together over hundreds of feet with great accuracy at each weld. Good pipe fitters are often able to minimize errors by carefully planning ahead, chamfering weld end preps and rotating pipe to make weldable fit-ups. Invariably there are welds that the pipe is “cold pulled” to make the fit-ups. In all but the most extreme cases, the design team never knows about this and rarely is there any documentation in the construction field reports. However, with some equipment such as rotating equipment and critical pressure vessels, these loads could be significant. QA inspectors should be alerted by the design team to review final fit-ups for critical piping systems to minimize overloading of equipment nozzles. If there is any concern, the pipe stress analyst should be consulted to evaluate the ramifications of the “cold pull”.

To summarize the pipe stress analyst/s role on a project, should include the following:

- Optimization of critical piping systems during the conceptual phase
- Calculations to confirm the pipe routing and support system are acceptable
- Providing loads and other information that is required by Structural, Mechanical, and Pipe Support Design groups.
- Review of final design drawings, including pipe support drawings to assure the final design is accurately reflected in the final analysis.
- Review and analysis of any proposed changes at vendors or the field to pipe and pipe supports.

2.3 ANALYZING EXISTING PIPING SYSTEMS

Analysis of existing piping systems is usually performed because there is a problem that has occurred and it needs to be understood to properly correct. Some possibilities include

- Broken support
- Failed component
- Spring hangers not functioning within their travel ranges
- Unusual loading conditions that were not anticipated

Or the analysis might be performed because inspections are to be prioritized and there is no design stress analysis available to provide guidance.

For the analyst there are often challenges to obtaining the necessary information for the analysis model. **Never assume that the design drawings are 100% accurate. Field confirmation should be made of routing, pipe diameter, pipe thickness, branch connections, pipe support locations and pipe support types. Even the material of construction needs to be confirmed, particularly if it is an alloy.** Due to limitations, spot checks only may be made and it is assumed that the other material and pipe sizes are similar.

But keep an open mind as analyses are performed. If the analysis results do not match the field observations for pipe movement or hanger loads, one of the causes of the discrepancies may be the assumptions. It can be amazing what fabricators and constructors might "hide" during the fabrication and construction process. Some actual findings in verifying installed pipe:

- A six foot long piece of XXS pipe installed in a standard wall installation because they ran out of the correct pipe.
- Pipe supports placed in the wrong location.
- Pipe supports switched between locations.
- Pipe supports never installed.
- Branch connections not installed per specifications, i.e. stub-in connections where TEE's or weldolets are specified.
- Travel stops left in constant support and variable spring hangers during operation
- Incorrect welding materials such as carbon steel filler material in an alloy pipe
- Branch connections that are not on the design drawings
- Numerous other willful or accidental mistakes

Analysis of existing systems often lacks the design criteria that is commonly available in new designs. That can include allowable nozzle loads, spring rates and actual hanger loads. Old spring hangers can wear out and corrode making the readings from the scale (if still attached) a rough guideline at best.

Depending upon the question the analysis is supposed to answer, creative analysis may be required. Multiple analyses may be appropriate to bracket assumptions and find an answer or set of answers to questions. For example, if pipe supports are acting erratically, some analyses might assume some of the hangers are acting properly, and then having the program size other hangers to see what the effect would be. Or perhaps in the analysis one or two hangers are assumed to have failed, and calculate the effect is on the remaining supports. With today's analysis tools, a lot of scenarios can be tested quickly once a model is built.

Based upon the author's personal experiences, take the time to document each attempt and keep the model and results for reference. Sometimes you head up blind alleys and have to backtrack to an earlier analysis to get to the correct answer to your unique question. If the previous analyses were not saved and documented properly, there is a lot of wasted time trying to get back on track.

2.4 ANALYSIS OF PIPE MODIFICATIONS

Sometimes there are reasons for pipe modifications for process, such as a new branch line, or process conditions being modified. This can turn into a combination of analyzing new and existing pipe. For the existing pipe, it is appropriate to build a model and optimize it until it reflects what is observed in the field. Once that it done, the new pipe and other modifications can be inserted into the model with more assurance that the pipe analysis will accurately reflect the modified pipe.

Assure the existing pipe is properly sized for the new conditions. It is not unusual that modification creates an over temperature or over pressure condition in part of the existing pipe. OSHA 1910 .119 requires a Management of Change (MOC) procedure to review all aspects of a modification to avoid these types of problems for certain chemicals. A similar approach should be used even if not required by management or law. When MOC was introduced in the 1990's, existing piping and mechanical systems were reviewed. Some of the common mistakes in field modifications that had been made over the previoys years included:

- Some portions of pipe being subjected to temperatures or pressures they were not designed for.
- Some portions of existing pipe carrying a chemical they were not designed for.
- Safety valves being blocked from protecting the equipment they were installed to protect. (New valves installed, or even the pipe disconnected and re-routed away from the safety valves.)
- A significant change in fluid density perhaps causing problems with the pipe support designs.
- Equipment nozzle loads increased to unacceptable levels.
- Inadequate separation of two chemicals that should never be allowed to mix.

- Drains for modified piping need to be re-routed to different tanks or other dumping areas.

Use the opportunity to look at the analysis results to see if there are any improvements identified that could significantly improve the existing pipe and supports when the modifications are made. The goals should always include assuring a piping system is safe and operable in all expected operating modes. A planned modification is a perfect opportunity to identify correctable deficiencies. It will be the owner's decision whether to implement the improvement recommendations, and it would be a rare owner that doesn't appreciate the service of recommending improvements.

3.0 STATIC ANALYSIS EVALUATION

This portion of the instruction is split into static analysis with linear, non-linear and friction supports. For our discussion, a linear restraint is always active in both directions of force or rotation in the analysis. If a rigid vertical support is modeled as a linear restraint, it restricts any movement up or down and loads will be calculated that can push the support downward or upward. This definition applies in any direction or rotation that is included in the model restraint.

A non-linear restraint may be a restraint that acts in only one direction. If a base support, the model could be a restraint that restricts any downward movement but allows upward movement without restraint. A rigid rod could be modeled as a non-linear restraint. However, if the movement is up, it implies the rod would be put into compression.

Another version of a non-linear restraint would be a limit stop or gapped guide that allows movement until the gap is closed.

In all of these cases of linear or non-linear restraint there can be spring rates of the force or rotation per inches of movement or degrees of rotation. They can even be mixed together with one spring rate for the first x inches, a different spring rate form x to y movement and so on

Fig. 4. A gapped guide or limit stop, with 3" between the bumper plate and the steel. This type of non-linear support is usually installed to restrict thermal movement. If intended to limit movement in dynamic cases, it is difficult to analyze since non-linear devices are not supported in dynamic analysis.

Friction is a special non-linear force dependent on the perpendicular force and the frictional constant. In a real installation the friction force may be a variable based upon the accuracy of the construction installation, the temperature of the pipe, condition of the slide plates, rotation of the slide plates and other factors. The frictional constant is usually provided by the supplier based upon the type of material used, such as fluorogold of other sliding surfaces. Some of these plates lose adhesive and wrinkle or are damaged by wear, varying the frictional "constant". The effect on the analysis will be discussed in more detail in the friction section.

3.1 STATIC ANALYSIS WITH LINEAR RESTRAINTS

Once there is a working analysis model and the loading conditions properly identified, there are a number of output evaluations that need to be made. The first and universally performed static evaluations are:

- Calculated pipe stresses are less than maximum allowable stress, usually defined by ASME codes.
- Thermal movements are acceptable to keep the pipe within the acceptable space envelope.
- Pipe supports can be designed to properly support the calculated loads and thermal movements.
- Equipment nozzle loads are acceptable to equipment suppliers, such as pumps, vessels, tanks, compressors, etc.

3.2 IS THE ANALYSIS ACCURATE - ADDITIONAL STATIC EVALUATIONS

Small Displacement Requirements

The commercially available pipe stress analysis programs are based upon the same set of beam equations that engineers learn in statics and dynamics courses. Those equations all have limitations for "small displacements". There is no universal number for this limitation, but there are warning signs.

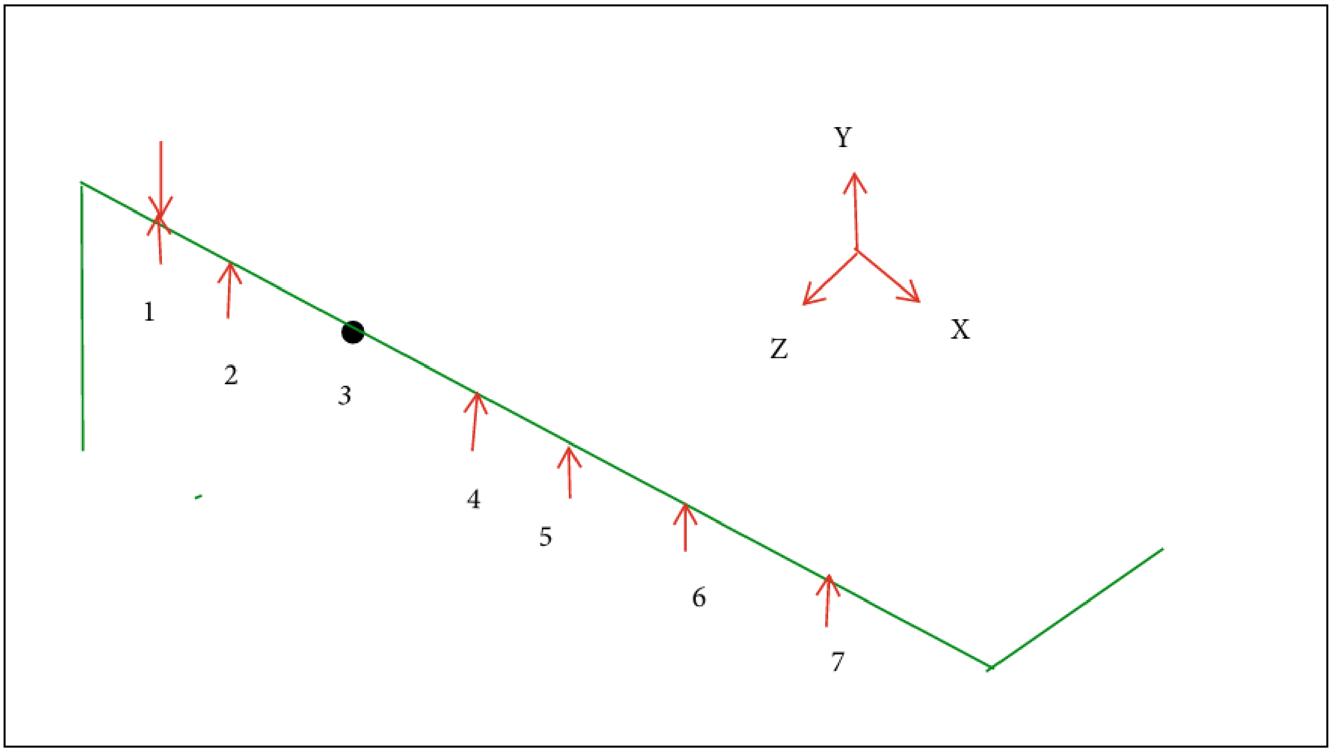
When a weight + pressure analysis is performed, the following evaluations should be made:

1. Assure all weight loads are downward in all operating and ambient conditions. (Sounds obvious but the author has seen many supports designed for a downward load when the analysis says the pipe is trying to lift up at that location.) If this situation exists, determine the cause(s) and develop solutions. Pipe supports need to be moved to assure a downward load at each support.

2. Assure the maximum vertical sag due to weight between pipe supports is acceptable. **0.10" sag is always acceptable. 0.50" sag is a red flag that one or more additional supports should be added. Between 0.10" and 0.50" is a cautionary area that may need to be evaluated.** This may be the same problem as No. 1, just a different symptom of the same issue. See Figure 5.

3. If there are variable springs included in the analysis, determine if the analysis reflects the loads at ambient or operating condition. It may be appropriate to run a separate analysis of weight only loads at operating condition to determine the actual pipe stresses and sag during operation.

4. If there are constant support hangers included in the analysis, a special situation exists that may require evaluation of vendors. Per MSS standards, a constant support load can very plus or minus 6% through its full range of motion. 12% variation in load is a lot. Some vendors provide much tighter load control and it may be required for certain piping systems.



Node	1	2	3	4	5	6	7
Fy lbs.	300	-1000	na	-900	0	0	-500
X in.	0.3	0.3	0.02	-0.25	-0.2	-0.1	0.01
Y in.	0.0	0.0	-0.6	0.0	0.4	0.3	0.0
Z in.	0.003	0.006	0.01	0.03	0.01	0.005	0.002

Fig.5. An illustration of the forces and displacements at supports if there is excessive sag due to weight in a horizontal pipe. The span between Nodes 2 and 4 is excessive, resulting in a .6" sag at node 3. Node 1 is a linear vertical support and thus the movement is held at 0.0" but the pivoting of the pipe at node 2 results in an upward force at Node 1. The pipe pivots also at node 4, resulting in no force in the non-linear support and an upward movement at node 5. At node 6 the pipe is still above the 0 point, but is supported at node 7. Note that the horizontal movements indicate instability also.

5. Review horizontal movements of all dead weight analyses. **Usually, calculated horizontal movement values are less than .01" in a well-supported system. If the horizontal movements are greater than 0.1", then it is an indication that the "small displacement" limitations of the calculations are being exceeded.** The piping system is unstable due to weight and the entire analysis is suspect. This usually happens when there is significant sag between supports or a significant cantilevered load, such as a 20' riser that is not supported directly on the riser. If the analysis is suspect, then the pipe installation will be unstable. Look back at the isometric drawing Figure 4. If there were no support in the riser, a force of only a few pounds would cause the pipe to move horizontally.

Thermal Analysis

When a thermal loading condition is analyzed, the following evaluations should be performed.

1. As a first attempt, run a baseline thermal analysis with no rigid pipe supports or restraints.
    a. This will probably calculate the lowest possible overall thermal stress that can be obtained.
    b. This analysis also provides the locations of the natural 0" of movement in the X, Y and Z directions that will help locate preferred locations for any rigid vertical or horizontal supports.
    c. Calculated loads at equipment nozzles will provide a first review of likely problems in meeting vendor allowable load requirements. If the equipment nozzle loads are high, reducing the loads at the nozzles with restraints or other devices will probably increase the calculated stresses at other locations.

2. Run a thermal case with rigid vertical supports at preferred locations and optimize. If any movement is up, or there are upward forces at a rigid vertical support, the support needs to be moved or modified to a spring or constant support.

3. Integrate in any necessary horizontal supports for particular loading conditions.

   a. As restraints are added, thermal stresses usually increase.
   b. Add restraints sparingly. Most piping systems are best supported from above with minimal horizontal restraints. There is more discussion of this issue in Section 4.

4. Assure all rigid restraint loads are reasonable, and acceptable.

5. Assure that one large stress is not concentrated at one location. This happens when there is a significant change in section modulus between pipes and components such as straight pipe and a heavy wall fabricated fitting. While the maximum calculated stress may be less than allowable, it may not be accurate. Stress analysis programs do not accurately handle large changes in section modulus, both due to the SIF and the over influence of the stiffer component. If the section modulus differential is greater than or equal to three at any location, use extreme caution in evaluating the results.

   a. Fig. 6 shows a large thick fabricated branch connection, which has a large calculated stress at the transition to the branch pipes. The SIF is difficult to ascertain. The thick fabricated branch will not bend and rotate, so that the stress is concentrated in the branch pipes. **Depending on the modeling technique and program assumptions, the calculated branch pipe stress may be much lower than will exist in operation.** In this situation, a finite element analysis of the branch connection may be required. Or perhaps, a stronger branch pipe should be installed to minimize the SIF and discontinuity between the two components.

   b. The lesson in all of this is that if something is designed that is difficult to properly analyze, change the design to something that there is great confidence in analyzing, if at all possible. Connecting virtually rigid pieces to very flexible pieces concentrates all of the stresses in the flexible pieces. Large differences in the section modulus are not handled well in pipe stress programs and the results should be viewed with extreme caution.

Fig. 6. A major heavy wall component tends to force all the thermal stresses into the pipe. Analysis tends to undercalculate the stress in the flexible pipe. Use extra conservatism.

The discussion on weight analysis focused on assuring the analysis has not exceeded the small displacement limitations of the analysis program. An obvious question would be, "The program calculates several inches of thermal movement, why is that not an indication of exceeding small displacements?" The answer is that the thermal displacements are actually a quasi-static cyclic loading condition, not the result of a primary pipe stress of weight or pressure.

However, there is another issue of "stability" that is important in the thermal case. There are times that an analysis has severe rotations in the thermal case, but the output indicates acceptable pipe stresses, movements and restraint loads. With significant rotations, moving a restraint a couple of feet may cause a large difference in loads and pipe movement.

Instability in a thermal analysis is difficult to recognize and is often caught by accident as different runs are performed. It may be recognized when rotations of 0.5^0 or more are seen in the output, particularly near rigid vertical or horizontal restraints. If there is any question whether a thermal analysis is stable or not, one approach is to do the following:

1. Run a case with no rigid supports in the area of interest.

2. Look at the results to evaluate the movements and rotations compared with the case with rigid restraints.

3. If the rotations are significantly greater with the rigid restraints, re-run the rigid case twice with the restraint moved two feet in both directions

4. Evaluate the results of the new analyses and judge if the installation is too sensitive for probable field installation tolerances. This is a difficult judgement

but recognize that if the field installers must push and pull the pipe for the final weld or to align a restraint to match the analysis, it is doubtful that it will be installed exactly the same way that the analysis is modeling.

5. Consider a different routing or support scheme to make the piping system more stable, and easy to install in the field.

Whether the analysis is being performed for a new installation, modification, or evaluation of damage, **an over-restrained piping system often has high restraint loads and high stresses. Lightly-restrained piping with well-spaced pipe supports is rarely a problem for the thermal and weight analysis criteria.**

SOMETHING DOESN'T SEEM RIGHT

Invariably the analyst will come across an analysis output that just doesn't seem quite right. The input is checked and seems correct, but perhaps the pipe movements are surprising, or a restraint has a high load, or some pipe stresses in a certain area are surprisingly high. When in this situation, do not ignore your concern.

There is one last check that the author has used many times on his own work or in checking someone else's analysis. Review the internal load tables for each node. These tables provide the forces and moments at each node for each case. It is surprising how fast an anomaly is spotted at a particular node. Usually, a branch line or restraint has a much different load than the nearby nodes and it is obvious when reviewed.

Often it is a fairly simple task to identify why the load changes so radically. Sometimes there is a subtle error in the input, maybe the program assumes something the analyst didn't understand, or you have found an anomaly in the program. If after research you think it might be the program or a misunderstanding of the program, do not hesitate to call the program help line. They have always been helpful to the author and should be to anyone who asks a question after researching it as best you can. It is always to their benefit to fix any problems, and that may include describing the program assumptions better.

3.3 NON-LINEAR RESTRAINTS

Over the years, one of the improvements to pipe stress analysis programs has been the inclusion of non-linear restraints.

All of these programs assume that a restraint is active or inactive to start, then determines if the results support that assumption. Does a limit stop close the gap or not? Then based upon the answer, it runs another analysis to determine how the limit stop hitting the restraint changes the movements and loads, especially to all of the other non-linear restraints. If there are a lot of non-linear restraints, there may be dozens of analyses performed in a few seconds with different assumptions.

Sometimes the program converges on a solution and results are displayed of movement, loads and stresses. It may not be the only possible solution, just the first solution the program finds. **Non-linear restraints create the possibility that the solution is not unique. Sometimes the analyses never converge on a solution.** The program keeps trying solutions until the analyst stops the run. What now?

The preferred suggestion is to change the restraint system that can be realistically changed in the design. If pipe base supports need to be changed to rods or springs, that is fine.

If gap dimensions need to be modified, that would be reasonable to attempt. However, this could be a warning sign. If a small change to a gap results in a significant change in the analysis results, is it reasonable to expect that the gap will be installed and maintained in the installation to that level of accuracy? Perhaps the location of the gapped guide needs to be moved to a location where the restraint in that direction can be a linear restraint.

Depending on the design and model there may be other reasonable modifications to make to obtain an acceptable analysis. But assure that a different design is something that can be designed and installed to the accuracy necessary. There have been analyses that have been tested by moving a support less than 1 foot and results have gone from easily acceptable to unacceptable. If the model is close to that sensitive, modify the design until it is stable. Moving a support two feet in a well-supported and stable piping system should create a minor change in pipe stress and movements.

When using non-linear restraints make sure how the program decides if a restraint is active or inactive. Does it decide based upon a particular loading case and apply the decision to all loading cases, or does it decide based upon each loading case as an independent situation? In either method, the results must be carefully checked to assure consistency.

If the program decides in the operating case that a support is always active, then gapped restraints may be modeled as active in the ambient weight case, when they really aren't. Load directions and pipe movements must be checked at each support to assure consistency. If there is inconsistency, such as an upward load or movement at a base support, then special analyses are necessary to model each loading condition.

On the other hand, if the program evaluates if a non-linear restraint is active or inactive in each loading case anomalies can still arise. Assume in the example that a gapped restraint is active in the ambient weight + pressure case but the gap is opened in the operating weight + pressure + thermal case. The system may appear to be stable in both cases and calculated stresses are acceptable. But perhaps the gapped restraint is making the horizontal movement small in the ambient weight case. Try a weight case with the restraint inactive as calculated in the operating case. It may be that the system is unstable due to weight and the results are unreliable.

Other anomalies can develop in which the loads appear to be the wrong direction for the movement calculated. Non-linear restraints must be reviewed for load direction and movement in all loading conditions to determine if the results are consistent and predictable. If not, modify the restraint system until it is stable and the design can match the analysis.

3.3 NON-LINEAR FRICTION FACTORS

When frictional loads were first introduced into the pipe stress analysis programs, they were primarily used to provide a force to the structural group for their design. But clearly including any frictional force in the pipe stress analysis effects pipe movement and stresses.

Virtually all of us who have modeled friction factors have reached a point that the analysis does not converge to a solution. A first attempt is often to modify friction factors or maybe remove the friction option completely from one or more supports. We try this enough and get an answer, but what does it mean?

There is really only one conclusion to make. The piping system with the support system as proposed is unpredictable for loads,

movement and stress. If a support system cannot be analyzed successfully with idealized friction factors, it seems guaranteed that the system will move in an unpredictable manner with all of the variables in friction loading.

Figure 7. When sliding supports rotate off of flat on flat, there is no data for the friction factor. While the left two photos are dramatic, the right photo is typical in the field of a slight rotation in which only part of the slide plates are touching. The perpendicular forces are concentrated in a small area leading to possible gouging of the slide plates. Analysis would miss this problem completely.

Fig. 8 This base support has low friction slide plates. On the left side there is a buildup of dirt that will get between the slide plates and adversely affect the friction factor.

Fig. 9. This base support has uplifted off of the steel due to nearby base supports not sliding and causing the pipe to bow up. Bowing of this type would not be calculated in a typical pipe stress program.

WHEN THE USE OF FRICTION RESULTS IN AN UNPREDICTABLE RESULT, A DIFFERENT TYPE OF SUPPORT IS NEEDED, PROBABLY ROD TYPE SUPPORTS. THIS RECOMMENDATION IS NOT THE INDUSTRY NORM.

This recommendation is made from experience of seeing failed sliding supports, bowed pipe, sliding supports literally sliding off of their support steel, failed pipe due to malfunctioning sliding supports, and non-maintained slide plates in the field. At two power plants, sliding supports were re-designed into rod supports, and in both cases the results in predictable movement, and elimination of pipe support and piping failures have justified the changes.

Where friction supports are identified in the conceptual design, this is the sort of situation referred to when analysis should be performed in the conceptual stage on critical piping systems. If an unworkable solution is baked in during the conceptual stage, it is very difficult to get it changed during the detailed design phase. The analyst will probably feel pressure to produce a result that shows the pipe design is satisfactory, but it probably does not represent reality. Problems may not be obvious in the installation immediately, but premature failures and re-design are very likely to be in the owner's future.

As a starting point for friction sliding supports, rod supports should be used instead of friction supports if the expected thermal ambient to operating movement is greater than 0.5 inches in any sliding direction. This may seem radical to many experienced people, but field data indicate that sliding supports usually do not work as intended. Rod supports very rarely fail. Pipe racks with multiple pipes laid out in a limited space may appear the least expensive option, but the cost of repair, and the safety issues of critical system pipe failures is not worth the risk.

4.0 ANALYSIS OF DYNAMIC LOADS

Dynamic loads can be caused by a variety of sources and are not analyzed nearly as often as static weight and pressure loads, or quasi-static thermal loading conditions. But when dynamic loads are considered important, they should be evaluated carefully in concert with the static and quasi-static loading conditions.

In 1991, Evans Goodling published a paper evaluating the effect of seismic loading conditions on piping systems. "Effects of Support Stiffness Variations on Seismic Inertia Stresses in Pipe" at the ASME 1990 PV&P Conference, PVP Vol. 198). The paper was based on world-wide assessments of installed piping systems that had experienced earthquakes, analysis models, and test piping subjected to vibrations. The result was that they could not find a single instance of a piping system failing due to swaying during a seismic event with two important exceptions:

1. If the pipe moved so far as to move into another pipe or equipment, it could be damaged by the impact.
2. Overloaded pipe supports could fail, causing the pipe to fail. Overloaded supports could be caused by extreme movement of the pipe.

Pipe is flexible and can sway and move to relieve stress far more effectively than to restrain the pipe and transferring the loads to the structural steel, that is already being unusually stressed by the seismic event. Pipe movement and restraint loads become the primary criteria in most dynamic analyses. Pipe stress is a secondary criteria since the stress is very short term. This criteria should be followed in virtually all dynamic evaluations, not just seismic. If reasonable, allow the pipe to move during a dynamic event. Avoid friction supports and non-linear supports since they are unpredictable and not capable of being analyzed in a dynamic event.

Safety valve thrust forces should be calculated and applied to assure the nozzles are adequate and the pipe is properly supported. If at all possible, it is best to locate rigid supports near all safety valves that have significant vertical thrust forces.

For special situations such as fast acting valve openings and closings that are designed to protect turbines and other equipment from overspeed conditions, use a time history analysis to calculate the pipe stresses and movements. Pipe stress is not a primary consideration as the loading is so short term that the pipe really doesn't have time to build up pipe stresses to the "hammering effect of a steam hammer. The pipe will move, and the criteria to assure pipe supports are not overloaded, spring hangers are not topped out or overloaded, or the pipe moves into other equipment should be the primary acceptance criteria.

If the support concept is to use non-linear restraints, including friction supports, and dynamic loading conditions are to be analyzed, then the analyst is in an almost no-win position. Non-linear restraints are not appropriate in dynamic analyses. The support must be either active or inactive. Selecting active or inactive would be almost impossible to do accurately. One possible solution would be to model snubbers in appropriate locations and directions to limit dynamic movement. But snubbers are expensive and maintenance intensive. In most cases it would more cost effective to develop a design using linear restraints only.

5.0 SUMMARY

We can all learn to model the pipe per the computer program manual in a minimal amount of time. **Interpretation of the results requires an understanding of the program limitations, a feel for when the results may appear acceptable but are unstable, and an understanding of the necessary safety and reliability that should be expected for each piping system.**

1. Always understand why a piping system is being analyzed and all the loading conditions that are likely to occur. Maybe all loading conditions or even all piping systems do not need to be analyzed, but make those decisions on a rational basis.

2. Insist on components for which there are recommended SIF's in the applicable Codes.

3. Do not include components, such as dummy legs on elbows which effect the flexibility and SIF of the elbows.

4. If calculated stress is greater than 50% of the allowable stress, particularly in the conceptual design phase, attempt to optimize the pipe routing and support scheme to reduce the maximum stress.

5. If non-linear supports are being used, assure the thermal movements of the pipe are predictable.

6. Friction supports should not be considered if the sliding movement is expected to be greater than 0.5”.

7. On new designs, assure the final pipe routing, components and pipe supports match the final analysis. Significant modifications in the shop and field should be evaluated.

8. If there is concern that the analysis has exceeded the limitations of the program due to large differences in section modulus, or calculated sag or horizontal movement in weight + pressure analyses, change the components, support types, support locations or routing until the analysis is acceptable.

9. An over restrained pipe may be unstable in analysis and difficult to install. A well-supported system from above that is minimally restrained is usually the most stable with the lowest possible thermal stresses and rotations. Add horizontal restraints sparingly, as necessary, for particular loading conditions.

10. Dynamic loadings may be a significant driver for location of supports and support types. Most dynamic loading conditions are supported best by allowing the pipe to sway as long as the pipe does not hit other equipment, or overload supports.

11. If after reviewing an analysis, “Something doesn’t seem right” even after checking the input, the analyst should review the table of internal forces and moments at each node to see if that provides a clue as to where the anomaly is developing in the system.

