INTRODUCTION

Stress analysis is a science and an art performed behind the scenes of a project and invisible to the average observer; invisible unless something fails. Sure, there are pipe supports but they can be passed off as keeping the pipe off the ground in the battle with gravity. Anyone who ever put up a shelf has some idea how to counteract gravity. And for many applications, it is that simple.

But then we enter the realm of pipes containing chemicals or operating at high temperatures; sometimes both combined, and the simple anti-gravity approach isn't enough. Nor is it an obvious need in the perception of most people; in part because thermal growth is slow. But the benefits are readily apparent, especially if something bends or breaks. (See on page 5. The concrete column chipped but restricted the movement of the branch, thereby deforming the main connection and over stressing both pipes.)

In the United States, piping design, fabrication, installation, testing, and certification is governed by the ASME B31 Code for Pressure Piping series of Piping Codes. The Process Piping Code is ASME B31.3; the Power Piping Code is ASME B31.1. There are additional B31 code sections applying to underground fuel transmission lines, refrigeration piping, low temperature, low pressure building services piping, and Hydrogen piping. Pressure Piping codes provide strict formulas for calculating the minimum wall thickness of various pipe materials based on design pressures, design temperature and allowable stresses in the selected pipe material. The codes also provide general guidance on the type of acceptable pipe and fitting materials, as well as, on the need for specific considerations in the system design for support spacing, and corrosion resistance. The details of the piping design are left to the system engineer.

In spite of advanced finite element analysis tools, determining the optimal solution for a given problem is still very much dependent upon engineering judgement. Even when or if, stress analysis of a system is required depends on experienced engineering judgement. When is stress analysis necessary, perhaps required, and not required?

When To Do Pipe Stress Analysis

There are numerous "rules of thumb" for when to apply pipe stress analysis, and we have summarized a few of them. Note that these are NOT provided to allow an inexperienced person to make a decision that an experienced engineer should make. These "rules of thumb" are provided so an inexperienced person can appreciate some of the ways to look at a situation and converse with an experienced person.

Different industries may use stricter or simpler guidelines for performing stress analysis. Apart from the legal or contractual obligations that may exist, some general guidelines for when stress analysis should be done include:

- When system operating temperature exceeds 150F and the pipe diameter is 4 inch or above. If the temperature exceeds 300F, analyze lines smaller than 4 inch
- Any pipe above 12 inches diameter (some say 8 inches diameter).
- Any pipe 2 ½ inch and larger connected to rotating equipment or heat exchangers.
- Any pipe 6 inch and larger connected to pressure vessels.
- Cryogenic piping
- Hazardous chemicals
- Double wall pipe with a differential temperature between the inner and outer pipe of 40F or greater.
- Short hot runs of pipe anchored at both ends
- When professional review of the system shows the system to lack flexibility
- If the system is complex (branching)
- When seismic analysis is required

A general, less stringent guideline is sometimes referred to as "The 1500 rule":

- If the line size (nominal pipe size) times (x) the temperature (degrees F) is below 1500 then the line "may" not need formal stress analysis.
  Example 3' (x) 400 degrees (F) = 1200
- If the line size (nominal pipe size) times (x) the temperature (degrees F) is above1500 then the line "may" need formal stress analysis.
  Example 4" (x) 400 degrees (F) = 1600

Remember that thermal stress analysis works in both directions i.e. for hot or cold piping. The farther away the operating temperature of the pipe is from the ambient temperature during pipe installation, the more likely stress analysis is required.

When Pipe Stress Analysis May Not Be Required

- The system duplicates a successfully operating arrangement or can be judged adequate through comparison to a previously analyzed system. Comparison must be by a competent professional.
- No thermal growth (ambient temperature fluids), small diameter HVAC chilled water, and plumbing.

Why Perform Pipe Stress Analysis

- In order to keep stresses in the pipe and fittings within code allowables.
- In order to keep nozzle loadings on attached equipment within allowables set by manufactures or recognized standards (API 610, API 617, the Hydraulic Institute, ect.)
- In order to keep pressure vessel stresses at piping connections within the ASME Section VIII allowable levels.
- In order to calculate design loads for sizing supports and restraints.
- In order to determine piping displacements for interference checks.
- In order to help optimize piping design.

At Venture we typically focus on the effects of thermal expansion or contraction and the effects of seismic loading.

Thermal Expansion of Pipe

When temperature increases, so does the length of molecular bonds. As a result, solids typically expand in response to heating and contract on cooling; this dimensional response to temperature change is expressed by its coefficient of thermal expansion (CTE). Different coefficients of thermal expansion can be defined for a substance depending on whether the expansion is measured by:

- Linear thermal expansion
- Area thermal expansion
- Volumetric thermal expansion

Linear thermal expansion is the one-dimensional length change with temperature and is what affects this process most.

Coefficients of linear expansion are presented in the Table 1 below. While seemingly small, the expansion adds up. Accordingly, for comparison purposes, the amount of expansion in 100 feet of pipe for various changes in temperatures is included.

TABLE 1
IMPACT OF TEMPERATURE ON PIPE LENGTH FOR VARIOUS METALS

Type of Pipe	Coefficient of linear expansion *x 10^{-6} in/in °F*	Change in 100 ft at 100 °F ΔTemp (in)	Change in 100 ft at 200 °F ΔTemp (in)	Change in 100 ft at 300 °F ΔTemp (in)
Steel Stainless Austenitic (316)	8.9	1.07	2.14	3.20
Steel Stainless Austenitic (304)	9.6	1.15	2.30	3.46
Carbon Steel	6.7	0.80	1.6	2.41
Titanium	4.8	0.58	1.15	1.73

Ref: http://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.html

For comparison, the coefficient of linear expansion for HDPE plastic pipe is 90 x 10^{-6} in/in °F

To properly evaluate the stresses developed within a pipe, axial stresses, hoop stresses, and bending stresses must be considered. This requires multiple equations and factors more complicated than this introduction is intended to be. But an appreciation of how forces can develop can be seen in the very simple case of thermal expansion of a pipe that is prevented from bending. Consider the stresses for restrained expansion in 100 ft of pipe with a 100 F temperature increase, as shown in Table 2.

TABLE 2
IMPACT OF 100 F TEMPERATURE INCREASE
ON STRESS IN 100 FT OF STRAIGHT PIPE

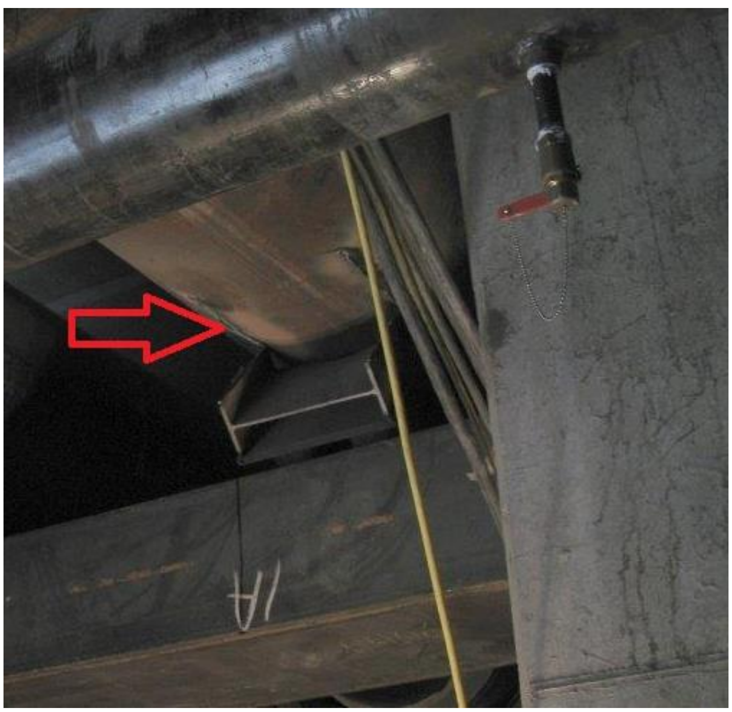
Type of Pipe	Modulus of Elasticity "Y" * ***(10^6 psi)***	Stress for 100 ft of restrained pipe (psi)	Yield stress (psi)
Steel Stainless Austenitic (316)	28	24,920	30,000
Steel Stainless Austenitic (304)	28-29	27,360	31,200
ASME A106 (Carbon Steel Pipe)	29.0	19,333	35,000
Titanium	15.5	7,440	141,000

* Modulus of Elasticity assumed to hold constant across the temperature range. Modulus of elasticity actually decreases as temperature increases, which modestly mitigates the impact of thermal expansion on pipe stress.
Stress = Y * (elongation in inches/length of pipe in inches)
For example: Stress Carbon Steel = $29\text{x}10^6(0.8/1200)$=19,333 psi
Force = Stress x Area of the metal
Force = 19,333 x 2.3 sqin = 44,467 lbs

Table 2 shows that a relatively modest temperature increase can lead to conditions near failure. Typically stress is not allowed to exceed 50% of yield strength.

Consider the case of a pipe fabricated from A106 above. If the ends are not allowed to grow, a pipe with a metal cross sectional area of 2.3 square inches will develop a force at both end of 45,000 lbs, and a pipe with a cross sectional area of 15.77 square inches will develop a force at either end of 305,000 lbs; loading can get formidable. (These two areas correspond to the cross sectional areas of 3" and 12" Schedule 40 A1016 pipe.) So it is not much of a stretch to see that forces from thermal expansion can get dangerous even with a relatively modest temperature increase.

The photo below depicts a pipe restraint failure, because expansion forces were not considered in the design of the support.



Thermal stress analysis is a static analysis, and compares weight and pressure (sustained load case) with weight, pressure and temperature (operating load case). The difference is the impact of temperature (Expansion load case).

Occasional Loads

Occasional loads occur "sometimes" during normal operation, and may require modelling. They may include:

- Seismic loads
- Wind loads
- Occasional uniform forces, such as Snow loads
- Hypothetical accidental event, such as pressure relief valve discharging,

Seismic Loads

Seismic loads are a type of occasional load and are typically modelled using a series of factors which have been tabulated by ASCE for various regions of the USA, various materials, and various life safety considerations. The USGS has a web site which will provide appropriate factors for a location.
http://earthquake.usgs.gov/designmaps/us/application.php

Factors include:

- Importance factor, typically 1, or 1.5 if there are life safety considerations (e.g., chlorine line) or the facility
- Acceleration factor, which is applied in the X, Y, and Z directions
- Response factor, which is a measure of joint strength
- Site class, which corresponds to soil type
- Component amplification factor, which reflects the relationship of the piping system response to the structural response of the event.

Seismic loads are imposed in addition to expected operating conditions. There is not a requirement to evaluate the design seismic event simultaneously with other occasional load conditions, such as wind.

Stress Mitigation Measures

The tools used now for stress relief have not changed much over the years. To accommodate thermal expansion, consider the following design best practices:

- Use loops and other 3 dimensional direction changes in the pipe routing.
- For hot pipe, avoid the shortest line between two points. Allow for bends.
- Use expansion joints or ball joints where space constraints preclude the use of loops
- Perform stress analysis before buying and installing the pipe.
- Don't outsmart yourself by creating a tight footprint. Allow space in a layout for bends and 3 dimensional changes in direction.

Loops versus Expansion Joints

Pipe expansion can be absorbed by the piping configuration if piping loops, swing joints, or Z-Bends are incorporated into the design. Piping loops can require extra pipe supports and can take up plant "real estate." Loops are best for the long-term performance of a system, but require supports that allow for movement and restraints such as custom sized spring hangers. In some cases rigid structures must be added to limit movement in one direction.

Piping expansion joints can be used in tight areas, where there is not enough real-estate to install loops or Z-Bends to absorb thermal expansion. In high temperature or high pressure applications expansion joints must be metal bellows or slip type joints to allow for axial thermal expansion. The metal bellows are usually stainless steel with a liner, and these require special design and control measures to allow axial compression or extension, with usually limited lateral movement and no torsional movement. Slip type expansion joints are typically carbon steel construction, and are used to allow for axial expansion only.

Some of the additional advantages of expansion joints include: vibration isolation, and allowing for limited lateral movements to reduce nozzle loads on equipment. Joints used in this manner are typically bellows with tie rods. These types of joints are typically custom designed, and are sized by the manufacture based on the designer's restraints.

Allowing pipe expansion or contraction to be absorbed by the piping configuration is preferable to incorporating expansion joints into the piping system to absorb thermal pipe expansion or contraction. Expansion joints, whether slip or bellows, can potentially develop leaks. In addition expansion joints cause the piping to exert high forces into the restraints required to force the pipe to axially grow into the joint. This is particularly true in higher pressure systems. The force required to restrain the pipe so that it grows into the expansion joint is equal to:

F = Psys (psig).AJT thrust area (sq-in.) +FJT friction (slip,- lbs) or spring rate (lbs/in.) x expansion (in.)(bellows)

As stated before, there are many equations, requiring more explanation, necessary for stress analysis.

Design with Stress Analysis

At Venture, we perform pipe stress analysis using Caesar II, and prepare design drawings in AutoCAD.

The process of locating and modelling loops, spring hangers, and restraints still relies largely on the designer's and stress analysist's experience, and require multiple iterations to get to a solution. The program does not offer suggestions on how to route the pipe or choose a support. A more experienced operator can get a good solution faster, as can a more cautious operator. A fast solution by a cautious operator will be more expensive than a slower solution by an experienced operator.

For a typical output see Figure 1 & 2 at the end of this article.

Conclusion

Although pipe stress analysis is often critical in design of industrial systems, many users don't see the value. But it protects people, equipment, and reliability. Pipe stress analysis is performed as part of responsible professional design to insure a safe installation of high energy piping in industrial facilities such as chemical process plants, refineries, and power generating stations. A safe installation is intended to include protection of personnel, and protection of equipment and property. A "by-product" of safe design is system reliability and longevity.

Want more? There is a lot of information in the web. For example…
http://www.pipingguide.net/2010/10/stress-analysis-of-piping.html
http://www.pipestress.com/papers/quickflex.pdf

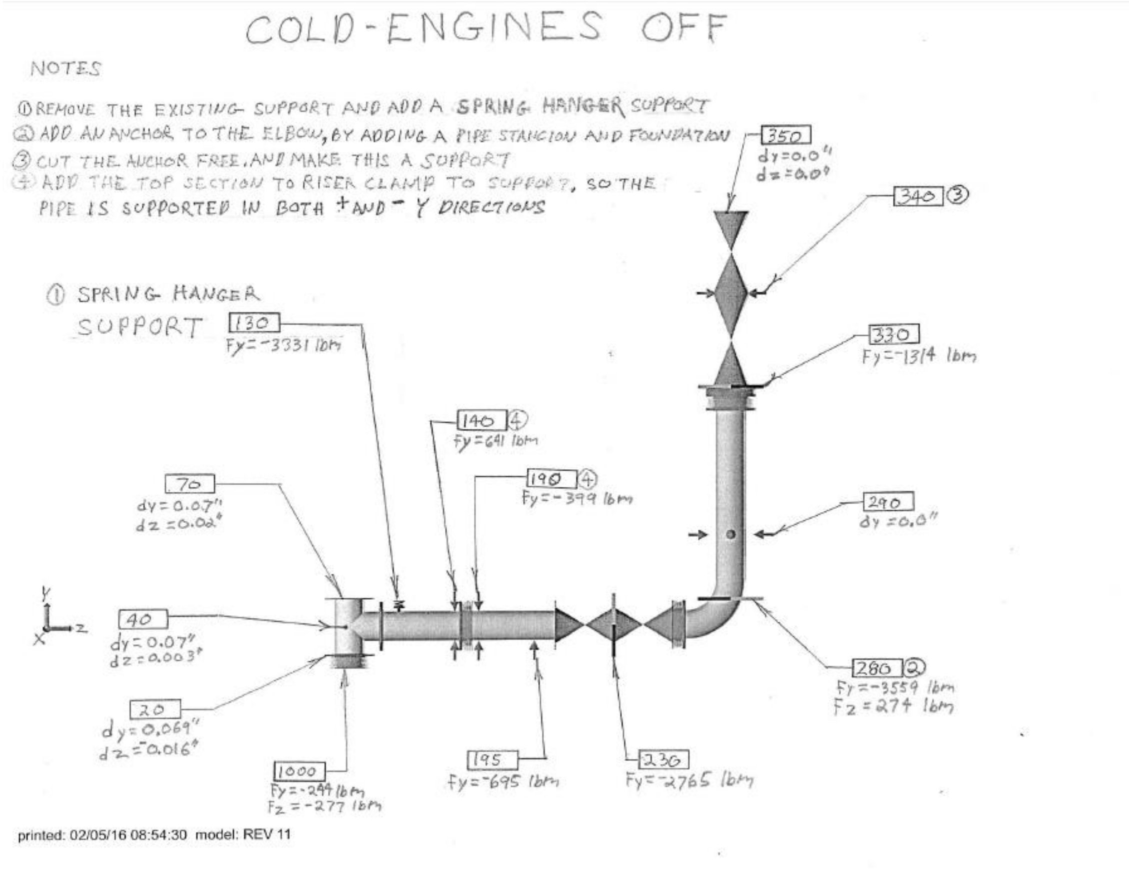


Figure 1: Analysis of an engine exhaust system under cold conditions.

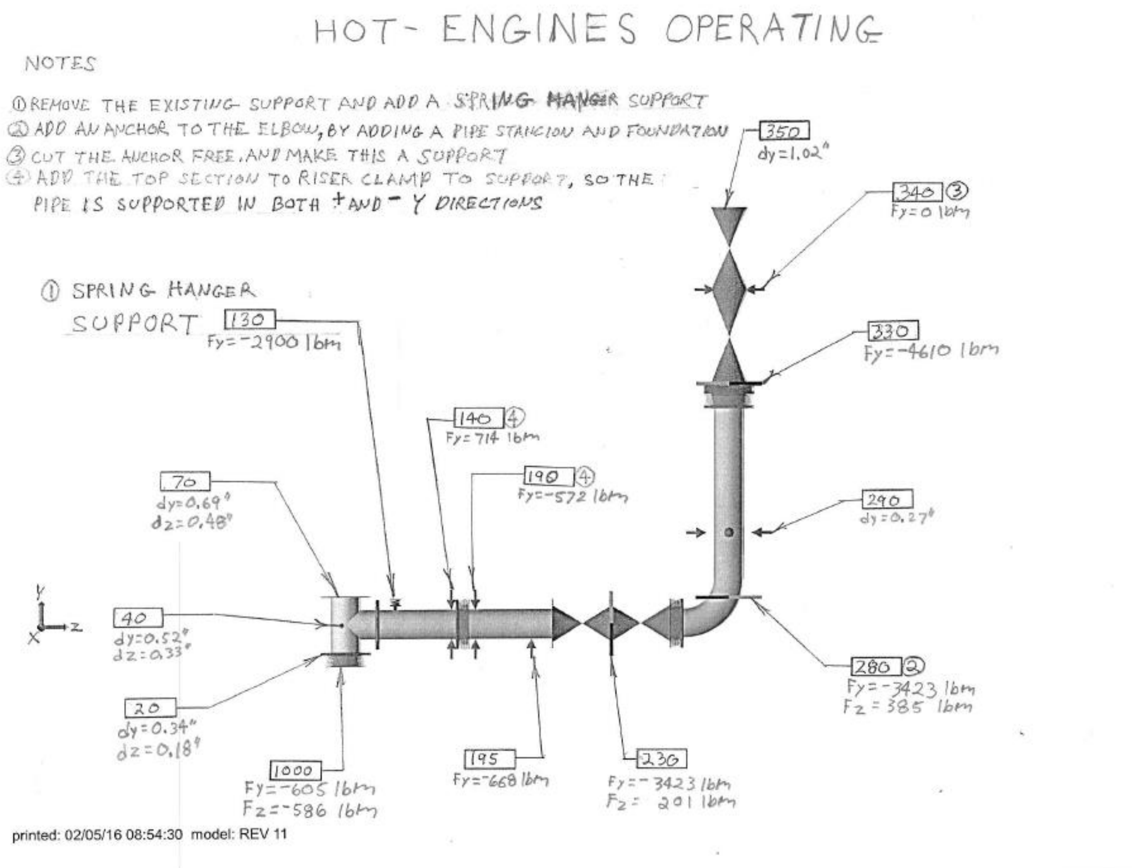


Figure 2: Analysis of an engine exhaust system under hot conditions.