A Recommended Approach to Piping Flexibility Studies to Avoid Compressor System Integrity Risk

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Abstract:

Reciprocating compressors are often packaged on a skid including the piping, vessels, and other equipment necessary for the particular application. The company packaging the compressor must interface the package pipe connections with the plant yard piping. The plant yard piping is often designed by, and the responsibility of, a different engineering company. The interface, or skid edge connection, is the point at which the engineering company and compressor packager define their limit of responsibility. A common industry practice for piping flexibility studies is for the packager and yard pipe designer to limit or restrict their analysis to only the piping within scope of their supply. Limiting the pipe flexibility analysis at the skid edge connection will limit the accuracy of the analysis. This paper will provide a description of typical design practices as well as the recommended design approach for a compressor pipe flexibility study.

1 Introduction

Piping flexibility studies (thermal analyses) are commonly done on piping systems to ensure the stress, force and deflection due to loads from pressure, temperature, and weight are within safe limits. Different parts of the piping system may be designed by two different companies.

In the case of a reciprocating compressor facility, the compressor packager will be responsible for the piping and other equipment within the skid or package limits. An engineering company (EC) will typically be responsible for the yard piping between the compressors and other process equipment such as coolers, coalescing filter and connections to the pipeline (Figure 1). The suction and discharge piping from the reciprocating compressor package will be connected to the yard piping at the package skid edge connection. A problem arises for the packager and EC pipe flexibility analysts as to how to simulate the piping within their scope considering that there is a shared tie-in or boundary condition at the skid edge.

The analyst for the compressor packager is only responsible for the piping within the package limits up to the skid edge connection. Design of the piping systems beyond this point is not the compressor packager’s responsibility so an approach for simulating their piping system is needed. The same is true for the engineering company’s flexibility analysis.

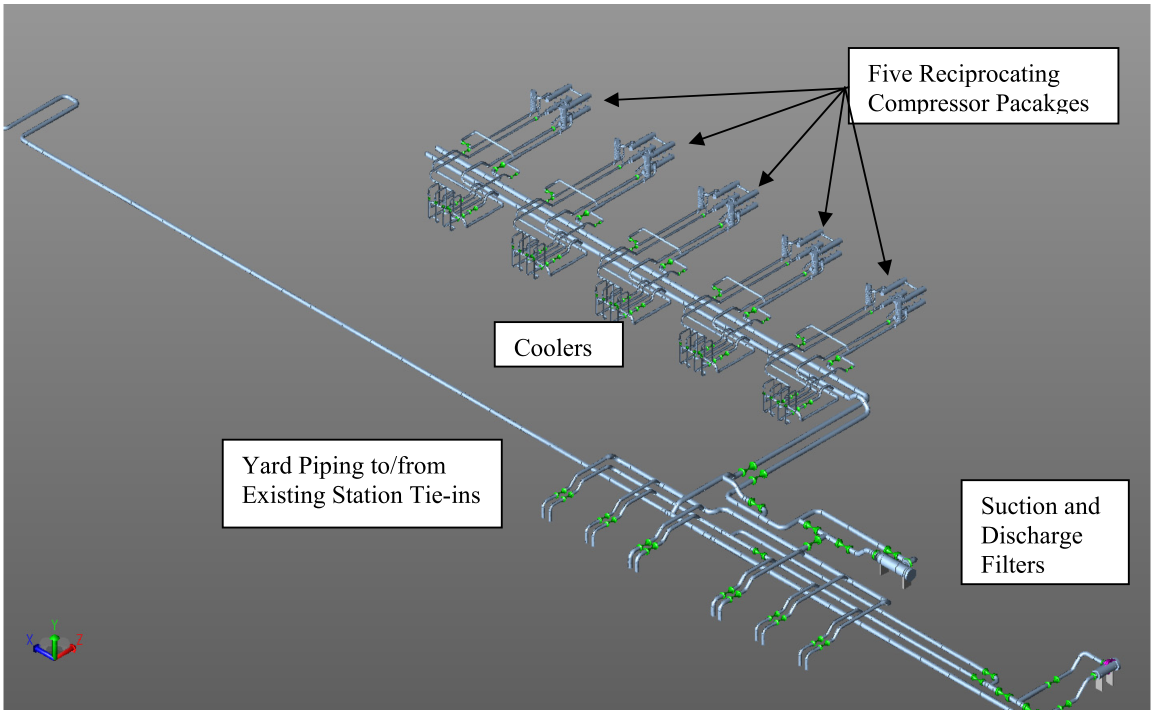


Figure 1: Pipe Flexibility Model of a Typical Reciprocating Compressor Installation

Consider a smaller part of this system, the 1st stage suction from the shared suction header to the scrubber and suction bottle within the compressor package, as shown in Figure 2. The area of responsibility for the packager and EC is illustrated in Figure 3. The flange set at the connection between these two areas of responsibility is the skid edge connection. The typical approach specifies that the support near the skid edge connection be an anchor. An allowable load at the skid edge connection anchor point is also specified.

The rationale for this approach is that the skid edge anchor is a means of isolating the flexibility response of the compressor package and yard piping from each other. There are several factors that make this approach inaccurate in a reciprocating compressor service. Also, the resulting design from this approach will be overly conservative meaning high cost and possibly longer schedule.

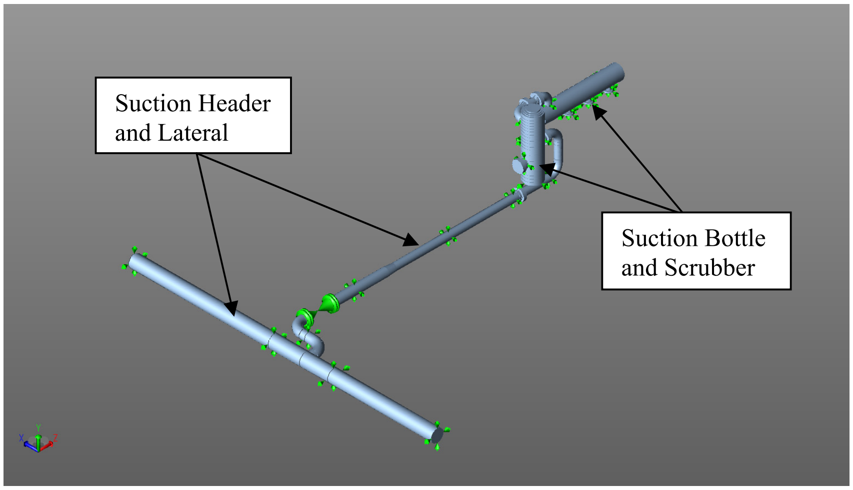


Figure 2: 1st Stage Suction Flexibility Model

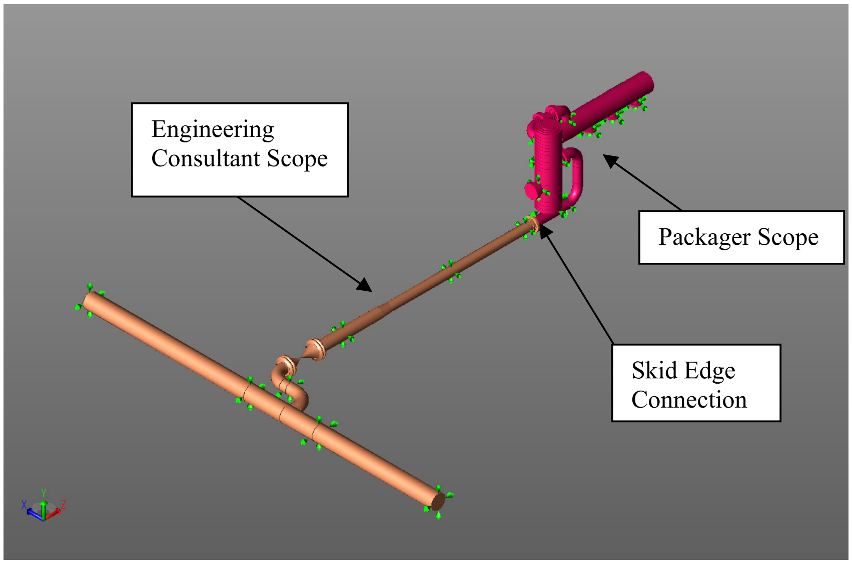
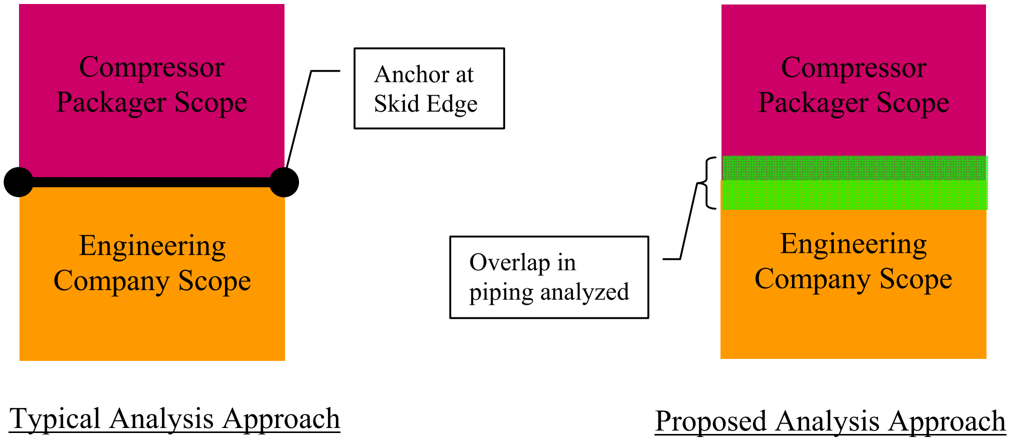


Figure 3: 1st Stage Suction Flexibility Model Showing Area of Responsibility

The proposed approach for the flexibility analysis in areas where there is shared responsibility for the pipe design is that both parties need to simulate a small part of the piping that is outside of their analysis (Figure 4).

The physics describing how the piping system will respond due to changes in pressure and temperature does not recognize the arbitrary boundary at the point where responsibility changes. The response of the overall system is calculated accurately and the system design has low cost for materials, construction and installation with the proposed approach. The approach is analogous to the building of the tunnel under the English Channel. The French and English contractors each set an end point where the respective tunnels would meet at the project completion. Regular updates on the tunnel progress and deviations due to site conditions are necessary to ensure the tunnels meet at the same point the trajectory of each tunnel is parallel. The overall success of the project relies on both parties making adjustments in their area of responsibility considering factors in the control of the other party.



Typical Analysis Approach

Proposed Analysis Approach

Figure 4: 1st Stage Suction Flexibility Model Showing Area of Responsibility

2 Limitations with Common Design Practices

As previously noted, a common design practice for piping systems where there is a shared responsibility is to split the piping system into two different models at the skid edge connection (Figure 5). Also, it is often a requirement that the maximum allowable forces and moments be supplied by the compressor packager at the skid edge connection. These allowable loads are then used by the EC for the analysis of the yard piping. There are limitations to this approach which can lead to an overly conservative design, which is unnecessary if alternative techniques are used. Following is a discussion of these limitations.

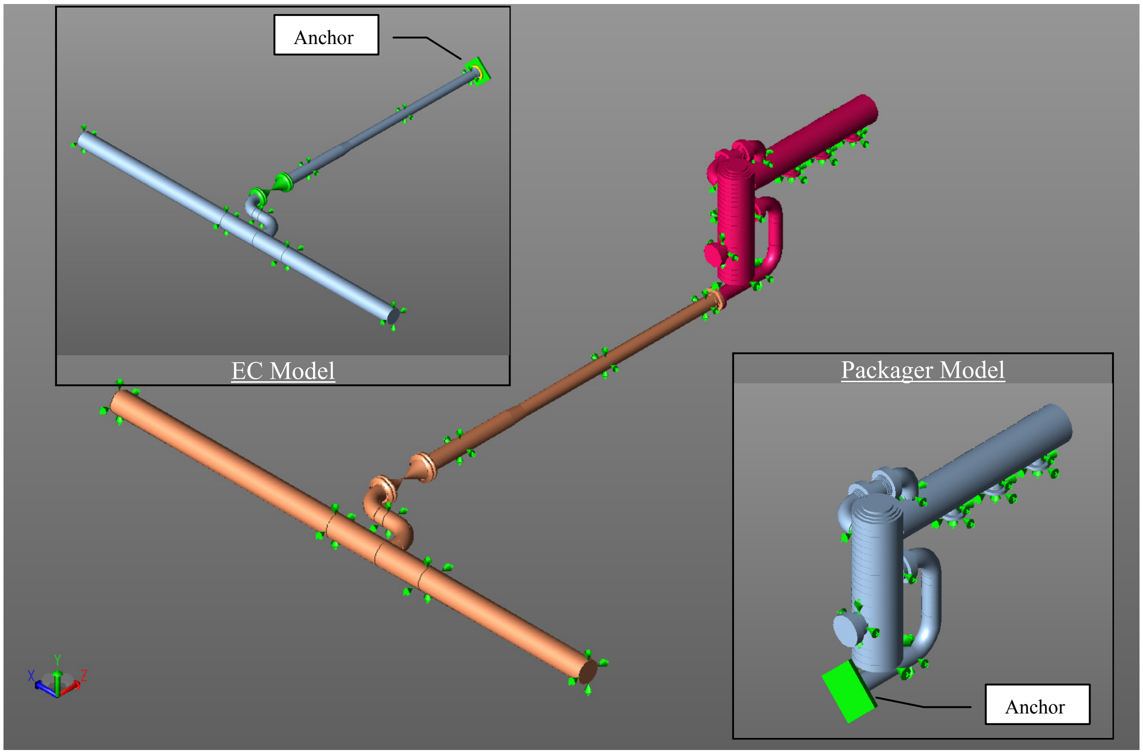


Figure 5: 1st Stage Suction System Broken Into 2 Separate Models

2.1 Anchor Specification at the Skid Edge Connection

The specification of an anchor point in the piping system (and in the engineer's computer model) is one method to minimize the interaction between the piping system on either side of the anchor. The practical limitations of fabricating a pipe support that is actually an anchor is very difficult in some cases.

A pipe anchor is one where the stiffness of the restraint is orders of magnitude greater than the other pipe restraints installed on the system. For example, process piping in a non-reciprocating compressor service often has simple pipe rests, guides and limit stops that allow the pipe to move freely in one or more directions. These pipe restraints can be characterized as being flexible. This support design is acceptable since only the forces from temperature changes, pressure and weight need to be considered. Installing a pipe anchor is often possible and practical since the simple restraints on the rest of the piping are flexible. Adding a pipe anchor that has more stiffness than the simple flexible restraints is easily done. (Figure 6a).

Simple pipe restraints such as rests and guides can be used on non-reciprocating compressor piping since there are no dynamic forces to cause vibration. Pipe restraints such as clamps, straps with wedges or pipe shoes are required on reciprocating compressor piping systems to minimize vibration from shaking forces caused by pressure pulsations. These pipe restraints have considerably more stiffness than a rest or guide type restraint. Adding an anchor to a pipe system that has clamps and other dynamic pipe restraints will require a large and robust pipe restraint, as well as an equally massive pipe support structure (Figure 6b). Designing, constructing, and installing an anchor in these applications is costly and, in some cases, impractical. The design of the anchor gets even more complicated when the piping is elevated. The stiffness of the pipe support structure is mathematically related to the elevation to the 3^{rd} power. A pipe support that is twice as high requires 2^3, or 8 times the stiffness. An anchor restraint for an elevated pipe arrangement would require a massive support structure.

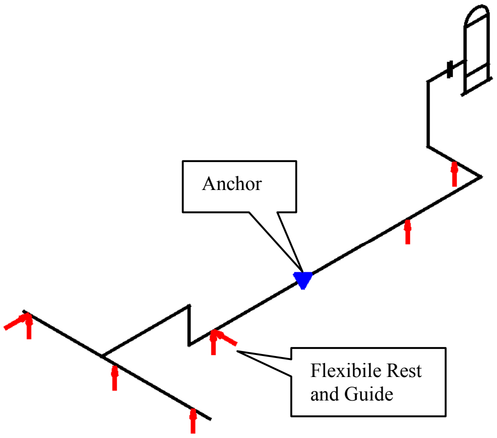


Figure 6a: Pipe Support for Non-Reciprocating Compressor Service

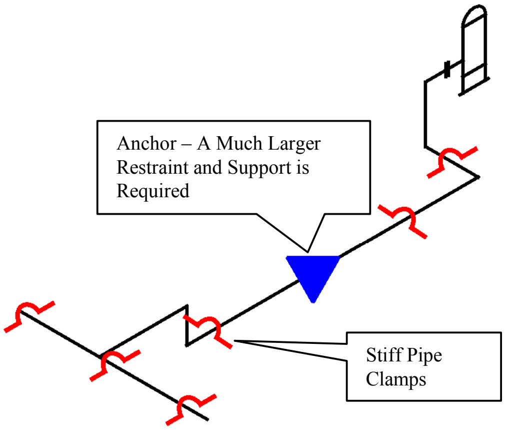


Figure 6b: Pipe Support for a Reciprocating Compressor Service

If an anchor point is possible and practical to install at the skid edge location, there can be negative effects from the anchor on the package and/or yard piping. The anchor restraint will force all the thermal expansion to act away from the anchor. This expansion can result in very high loads and stress on the piping, vessel connections and other equipment (Figure 7a). The pipe system will often need to be redesigned with a more flexible layout (expansion loops) or reinforcements to vessel connections and supports. These changes can have a significant impact on the project schedule.

If the pipe arrangement from the compressor to the yard piping is analyzed as a continuous system, the stress and loads are often reduced to acceptable levels (Figure 8) or the magnitude of the stress is minimized and the changes required to achieve an acceptable design are minimized.

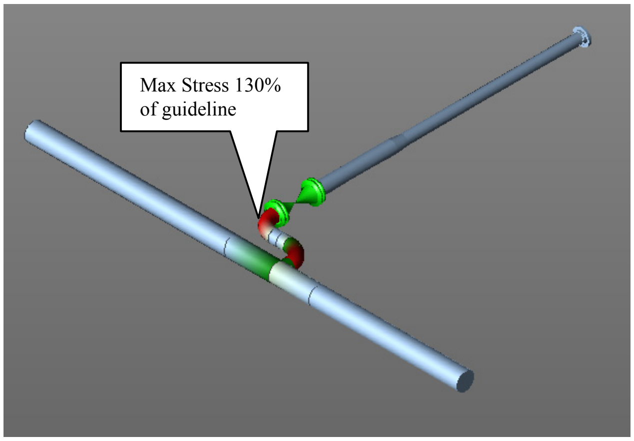


Figure 7a: Yard Pipe Model Result

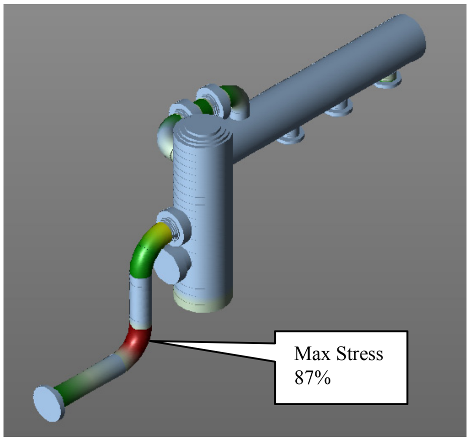


Figure 7b: Compressor Package Model Result

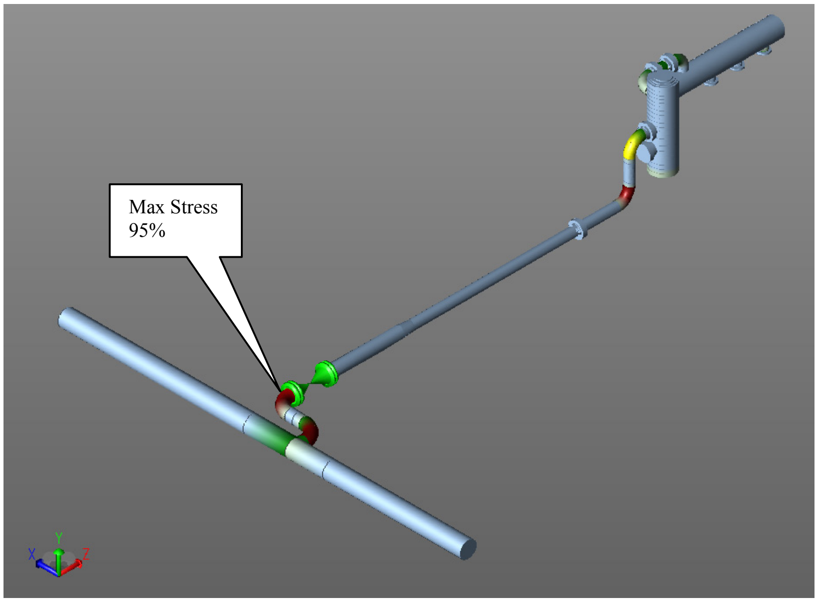


Figure 8: Complete System Model Result

2.2 Allowable Skid Edge Loads

Allowable skid edge loads are often specified based on the assumption that there will be an anchor at the skid edge. The specification of an allowable skid edge nozzle load is based on the concept of allowable nozzle loads for equipment such as heat exchangers, pumps, and vessels. Pipe stress engineers are very familiar with these criteria. The allowable nozzle loads are based on the stress induced in the pressure containing device, or minimizing deflection of equipment casings (to avoid damage to the moving parts inside the equipment). The approach of using an allowable nozzle load for vessels and equipment is reliable, since the equipment is typically well supported so the displacement and stress results can be easily inferred to determine an allowable load. The same cannot be said for a piping skid edge connection. The displacement of the pipe at the skid edge connection cannot be generalized to determine an allowable load. The pipe displacement will vary greatly depending on the pipe arrangement within and outside the package, the support arrangement and the applied temperature and pressure loading.

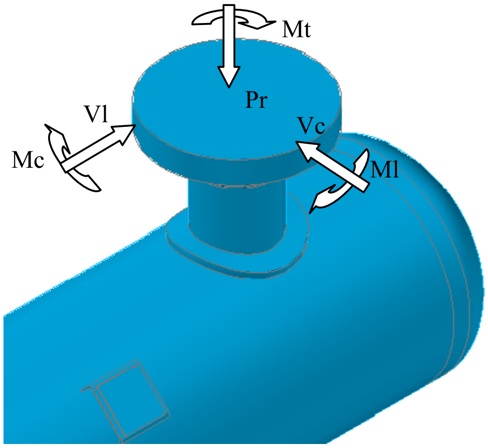
A second factor to consider with respect to allowable nozzle loads is that the typical approach for pipe stress engineers is to use these loads as a guideline or first pass check of the system design. If the nozzle loads are exceeded, a more detailed analysis is conducted to assess the system design. Many companies have developed their own set of allowable nozzle loads based on many factors. Often these allowable loads include a healthy design margin to ensure these design loads are acceptable. Table 1 is an example. As previously stated, these loads are not meant to be the maximum absolute allowable, but are instead a design guideline for the pipe stress engineer. If the allowable loads are exceeded, the designer has two options. One option is to make changes to the piping system design to minimize the nozzle load. A second approach is if pipe layout changes are undesirable, a stress specialist is retained to do a more detailed analysis of the nozzle. The same can be said for the pipe stress analysis. Rather than doing separate stress analysis for the yard piping and compressor package piping, a model of the complete system to consider how the overall system will respond is recommended (Figure 8). This approach does not rely on the questionable assumption of a skid edge anchor and conservative allowable nozzle loads.

Table 1: Typical Allowable Nozzle Loads

NPS Nozzle Size (inch)	Flange Rating	Pr (lb)	Vc, Vl (lb)	Fr (lb)	Mt (lb-ft)	Mc, Ml (lb-ft)	Mr (lb-ft)
6”	150	850	1042	1701	3008	2126	4255
	300	1035	1267	2070	3587	2539	5078
	600	1281	1569	2562	4329	3059	6123
	900	1631	1998	3263	5303	3750	7499
	1500	2384	2919	4766	7089	5015	10027
	2500	2384	2958	4831	7160	5063	10127

Nozzle Load Nomenclature

- Pr is the radial loading on the nozzle
- Vc is the circumferential shear force on the nozzle
- Vl is the longitudinal shear force on the nozzle
- Mt is the torsion moment on the nozzle
- Mc is the circumferential moment on the nozzle
- Ml is the longitudinal moment on the nozzle
- Fr, Mr are the resultant force and resultant moment



Applying the allowable nozzle loads as shown in Table 1 is a reasonable approach for vessel nozzle connections. However, these allowable nozzle loads should not be used as design values for all skid edge connections. The skid edge connection in a majority of cases is not a nozzle on a vessel or a piece of equipment. In most instances the skid edge connection is a flange set connecting two pipe spools. The pipe spool may be very long, or include several bends or supports and not be directly connected to a vessel or other equipment. Developing an allowable skid edge nozzle load for piping connections is not a practical approach considering the wide variation in pipe spool designs.

Techniques and standards for evaluating loads on flange sets to check for the possibility of leakage do exist. Assessing loads for the potential to cause leakage is not considered by the typical skid edge nozzle loads represented in Table 1. Typically, allowable loads for flange leakage are much higher.

3 Recommended Design Practice

The best approach to ensure the piping system flexibility design is acceptable is to model the interaction between the compressor package piping and the yard piping. This requires creating a model that includes a portion of the piping system beyond the limit of responsibility for a particular supplier. For example, the analysis of the compressor package piping must include a portion of the yard piping so that the true response of the package piping is captured. The amount of piping to include in the model will vary from case to case but in general it should include:

- the piping up to at least two supports past a change in direction from the orientation of the skid edge connection
- the flexibility of the pipe restraints and supports
- the flexibility of the nozzle-shell intersection if the model is terminated at a vessel connection.

Figures 9 and 10 show the plan view of a typical compressor installation. The yellow highlighted areas show the additional piping that is required to be added to the compressor packager's and EC's flexibility model. The additional piping does not need to be modeled in great detail as only the general response of the piping due to the applied loading is required. The effort to add this extra piping is relatively small given the benefit in accuracy and reliability of the results.

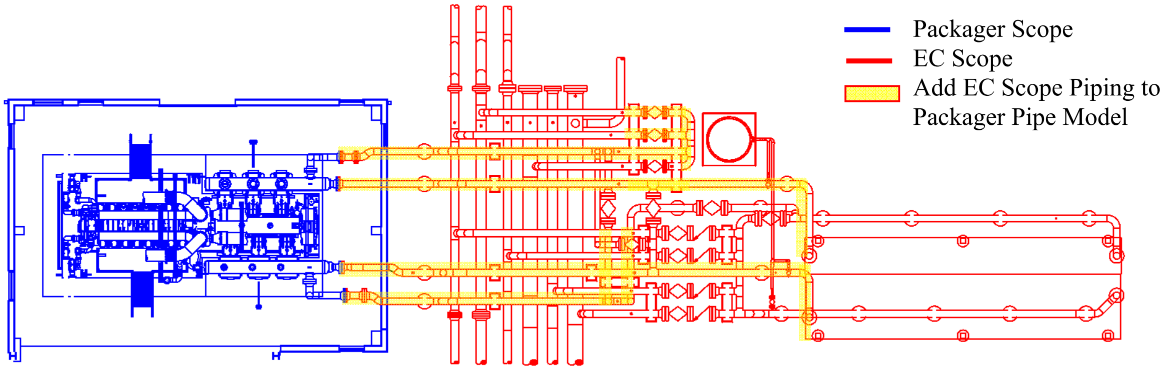


Figure 9: Yard Piping to Add to Packager Flexibility Model

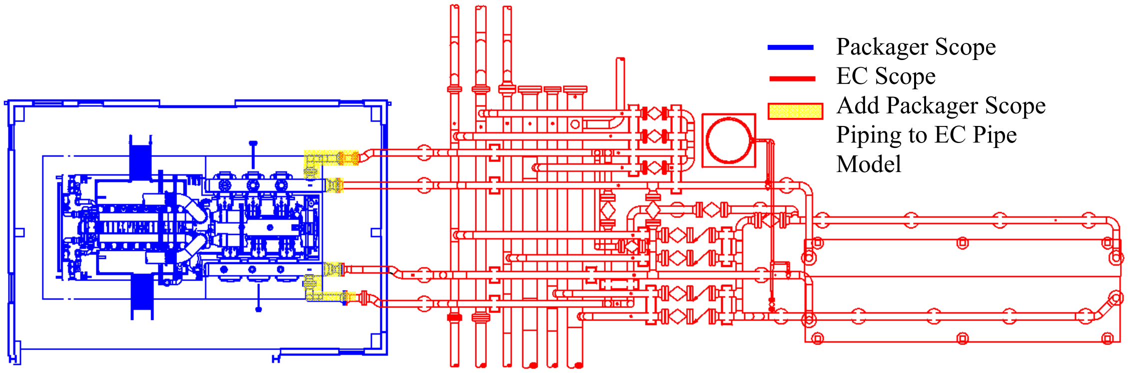


Figure 10: Compressor Package Piping to Add to EC's Flexibility Model

Ideally, a complete model of the yard piping and compressor package piping should be done to evaluate the design. However, the final design for the yard piping is usually completed sometime after the compressor package is finalized. A two step analysis approach may be necessary in some cases. An initial analysis can be done to evaluate the interaction of the yard piping and compressor package piping using a limited amount of piping as described above. If there are areas of where stresses or loads are near guidelines, a second analysis should be conducted when the pipe design is nearing the final stages. Often small changes in the restraint designs can be made at this late stage to avoid stress problems. Major pipe and support layouts are not usually required if the initial analysis is done.

There will be some overlap in the modeling effort by the EC and the compressor packager to model the effect of the complete system. It may be to the benefit of the owner to specify that the flexibility analysis for the compressor package and yard piping be conducted by one party. The compressor system piping will typically be analyzed by a vibration consultant to ensure the pipe layout and support arrangement will have acceptable vibrations. The same model, which is used for the vibration analysis, can be used in the flexibility analysis of the complete system thereby eliminating the duplication of modeling effort. Also, API 618, 5th Edition recommends that the piping vibration analysis and flexibility analysis be conducted by the same party. Trade-offs are required between the vibration and flexibility design requirements. These competing design requirements can be most efficiently dealt with by one party.

4 Case Study

This case study shows the differences between simulating the piping system from the typical practice of an anchor at skid edge and the recommended approach of using a comprehensive system model.

The case study includes an equipment package with elevated piping between the package and the heat exchangers (air coolers). Figure 11 shows the overall arrangement of the package, piping and coolers. As is typical for packaged equipment, the EC conducted a flexibility analysis of the yard piping including the piping from the main suction and discharge including the heat exchanger, up to the equipment skid edge connection. Their analysis assumed the skid edge connection would be an anchor, in this case, a combination guide and line stop.

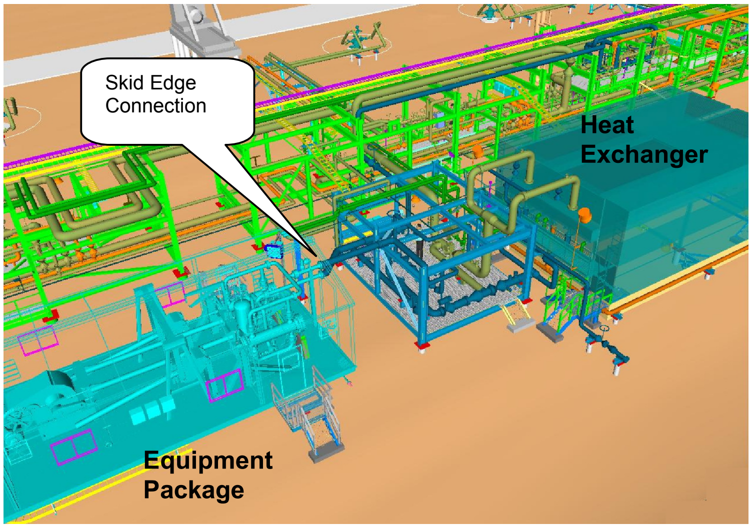


Figure 11: System Arrangement

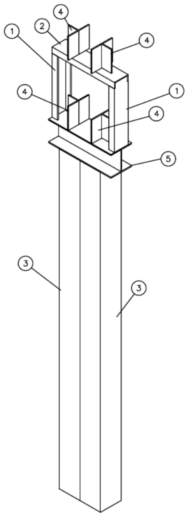


Figure 12: Skid Edge Support

The equipment packager was responsible for the piping on the skid up to the skid edge connection. The support at the skid edge connection was an elevated support fabricated from two, 6”x 6” (150mm x 150mm) structural tubes approximately 92” (2.3m) long. The pipe support included a guide, but not the line stop as shown in Figure 12. The piping spools and pipe support had been fabricated and the package was scheduled to ship when the missing line stop, required by the EC analysis, was noticed. The packager was in a tough spot and was looking for help.

A piping flexibility analysis was conducted on the suction and discharge piping within the packager’s responsibility. Figure 13 is a plot of the package piping.

The first step of the analysis was done using the typical approach of breaking the system into two separate models. The EC had already completed their analysis and supplied the calculated loads and displacements at the skid edge termination of model, assuming a line stop was not installed at the skid edge. These results were applied to the package piping model in addition to the loads from pressure,

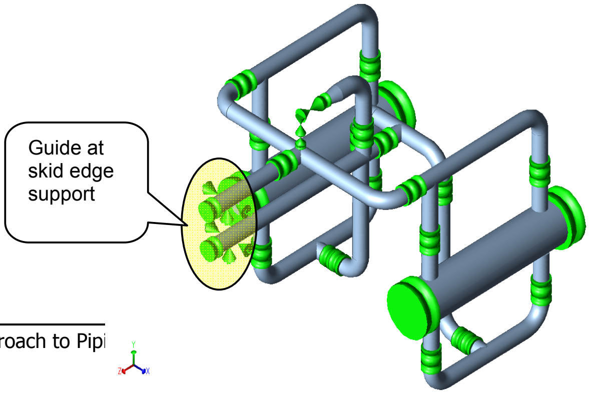


Figure 13: Package Piping Model

temperature, and weight. The results show that the stress in the package piping could be more than 2.5 times the allowable stress, Figure 14.

The simulation was then rerun with a guide and line stop at the skid edge support as per the original design and the EC's original model. The forces and moments calculated by the EC were applied at the skid edge connection of the package pipe model. The results from the analysis showed that the maximum stress in the pump piping was 62% of the design guideline. The design was acceptable with the guide and line stop.

Normally, the analysis would not have proceeded past this point since the EC was satisfied that their system design was acceptable and the packager piping was also acceptable. However, the package construction had already been completed and the package was scheduled to be shipped within a few days. Adding the line stop would have required modifications to the piping system – an additional cost to the packager. A bigger factor than the cost for the piping modification was the delay in shipping that would be caused while modifications were made. The shipping delay has an impact on the overall project schedule.

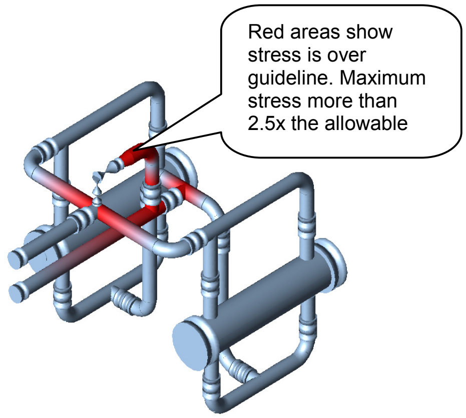


Figure 14: Package Piping Showing Over-stress Areas

During review of the package piping system flexibility analysis, it was demonstrated that the elevated design of the skid edge pipe support design would not provide enough stiffness to be an effective line stop. The height of the support results in the support being very flexible in the horizontal direction, perhaps even more flexible than the piping. This support will not provide a rigid line stop as was simulated by the piping flexibility models. A different analysis approach was proposed to evaluate the requirement for the pipe support at the skid edge.

A more accurate method of determining the response of the piping and the support requirements is to create a combined model with the yard and cooler piping to determine the overall system response. Figure 15 is a plot showing the combined system model including the elevated support at the pump skid edge. Figure 16 is a zoomed-in view of the same model showing the package with the support at skid edge.

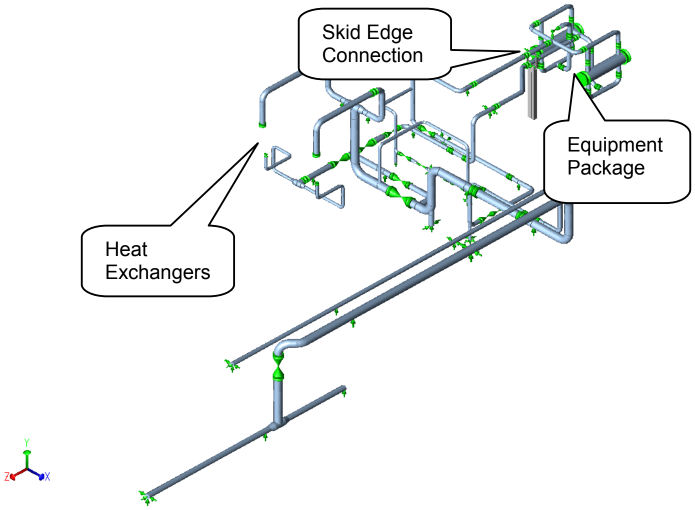


Figure 15: Complete Piping System Model

The simulation was rerun for the overall system model to determine if the system design was acceptable with the guide pipe support at the skid edge. The analysis determined that the maximum stress was 53% of the design limit, therefore, the proposed design was acceptable.

The location of the maximum stress occurred at a dummy leg support for the yard piping, as shown in Figure 17. The maximum stress in the pump package piping was

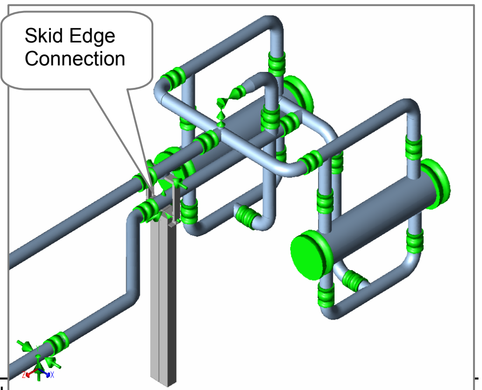


Figure 16: Package Piping with Skid Edge Support and System Piping

45% of guideline when all the piping was added, compared to 62% of guideline when the line stop was assumed at the skid edge.

The analysis shows that when the complete system model is simulated, the stress in the package piping is actually lower than the simplified model. The package piping and support did not need to be modified and the unit could be shipped on schedule.

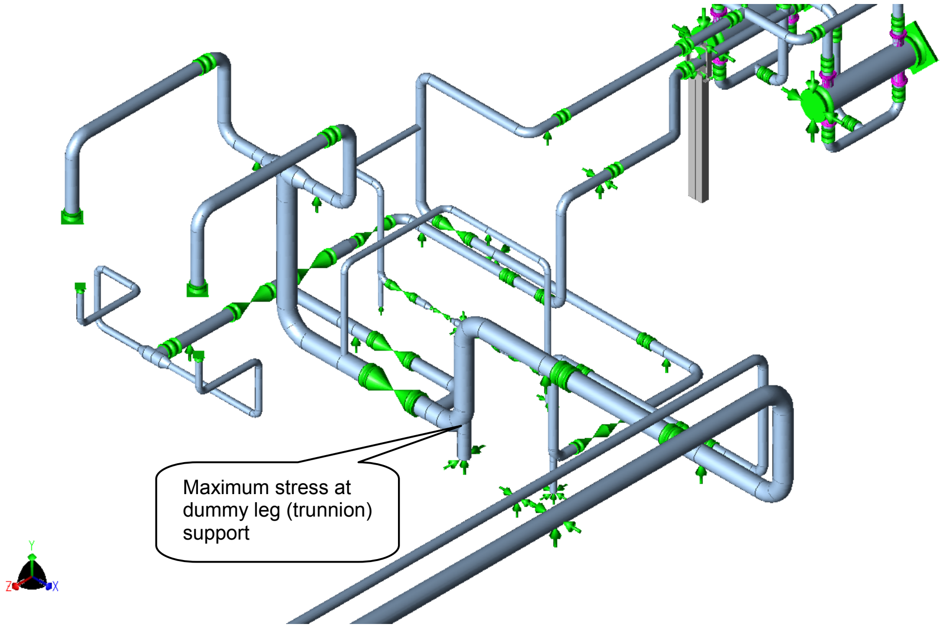

Maximum stress at dummy leg (trunnion) support

Figure 17: Complete System Model

5 Conclusions and Summary

The flexibility model for reciprocating compressor and pump packages must include simulation of the effect of the piping outside the package limits. The typical approach of conducting separate flexibility studies by splitting the piping system at the point where responsibility changes between parties does not give reliable results, or will result in a conservative and more costly system design.

The flexibility model does not need to be a model of the complete piping system. The compressor packager's stress analyst shall generate a detailed model of their piping and a simplified model of a portion of the EC's piping to evaluate the interaction between the piping system. The packager's stress analyst does not need to model the complete pipe system designed by the EC. Knowing how to simplify the model of the EC piping takes the understanding of an experienced pipe stress analyst.

Similarly, the EC's stress analyst shall generate a detailed model of their piping and a simplified model of the compressor packager's piping to evaluate the interaction of the overall piping system.

The owner may wish to specify that a single party conduct the flexibility analysis of the complete system rather than separate parties duplicating their efforts. The approach of a single party doing the flexibility analysis parallels the API 618, 5th Edition recommendation that a single party conduct the flexibility analysis and the vibration analysis. The effort to model the piping is minimized when these studies are done by the same party. Also, the competing interests of the flexibility and vibration analysis can be best resolved when these studies are done by one party.