

Piping Flexibility Analysis and the Development of PCS – Pipe Calculation System for Abaqus

Carlos Eduardo A. de C. e Sousa

RMC Consultoria, Brazil

Abstract: *The current framework for piping stress analysis is based on a simplified calculation method directly derived from experimental research performed over 60 years ago in the 1940s and 1950s. This framework was originally intended for hand calculations and, apart from minor changes and amendments, has been successfully employed by piping engineers since its development. As computational power increases and finite element analysis (FEA) becomes accessible for piping engineers, it has become clear that this framework is not well suited for complex FEA evaluation of piping. Advanced FEA procedures enable engineers to perform in depth evaluation of piping systems that are extremely difficult or even impossible to evaluate through traditional methods. Contrasting to traditional methods, a FEA simulation allow engineers to evaluate creep-fatigue interactions, advanced material models, complex loadings, complex geometries, complex support conditions, as well as the inherent evaluation of fatigue stress intensification factors. A major difficulty for performing piping FEA simulation is that currently there are no high performance FEA packages capable of efficiently generating the required analysis model for complex piping systems. This paper presents a comparison of Abaqus results and fatigue tests performed by Markl in 1952, as well as the development of PCS - Pipe Calculation System, a piping flexibility analysis application for Simulia Abaqus.*

1 Introduction

Industries such as Oil & Gas, Chemical, Petrochemical, Nuclear, Naval, Mining and Pulp & Paper employ pipes as a way of moving fluids between two separate points. On petrochemical plants, it is possible to identify several acres of piping systems of varying complexity, from the simplest layouts, for long pipelines interconnecting different units, to the extremely complex layouts, for piping inside high temperature process units. Pipework represent up to 35% of the materials, 40% of the erection labor and 48% of the engineering man-hour employed on a process plant erection project (Peng & Peng, 2009). As a perspective, it is important to point out that a refinery construction costs can reach figures as high as 15 billion US dollars (Kaiser & Gary, 2013).

Piping systems are typically composed by the combination of a large number of fittings such as bends, tees, flanges, valves etc. In addition, the piping layout supports locations, and the nature and position of the installed fittings, play a major role on the mechanical response of such system.

Final piping layout and support design are highly dependent of its global mechanical evaluation and should be properly defined during design phase. When necessary, several layout iterations may be needed until a satisfactory solution is found. These iterations are time consuming and all

changes must be propagated to other disciplines involved in the project (i.e.: civil works, stationary equipment, rotary equipment, instrumentation, etc.). (Basavaraju & Sun, 2004)

Even though during its operational life a piping system may experience several loading conditions, one of the most important is thermal expansion. The importance of this loading condition increases along with pipe lengths and temperatures, in many cases dictating the pipe route that must be followed.

A summary of some of the possible piping loads is presented on Figure 1.

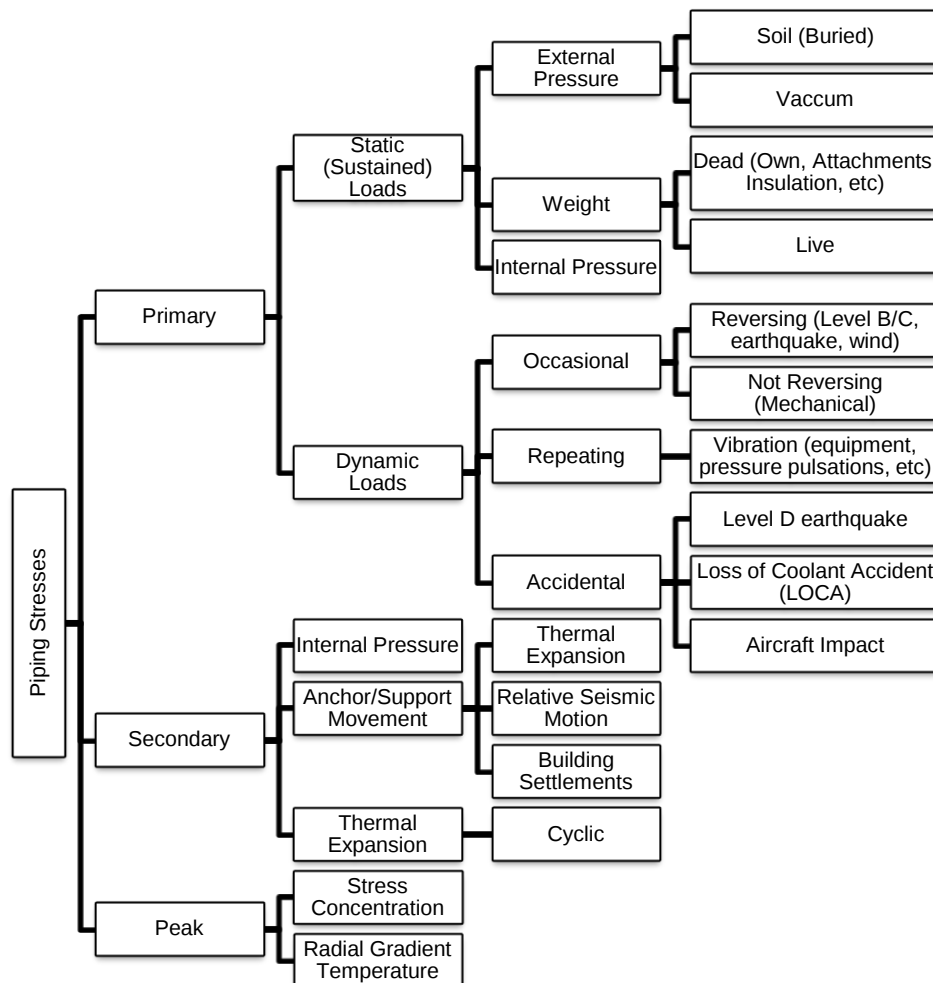


Figure 1. Piping Stresses and Loads
Adapted from (Avrithi & Ayyub, 2010)

Figure 2 presents some possible failure modes that can be associated with these loading conditions based on type of loading and/or environmental condition.

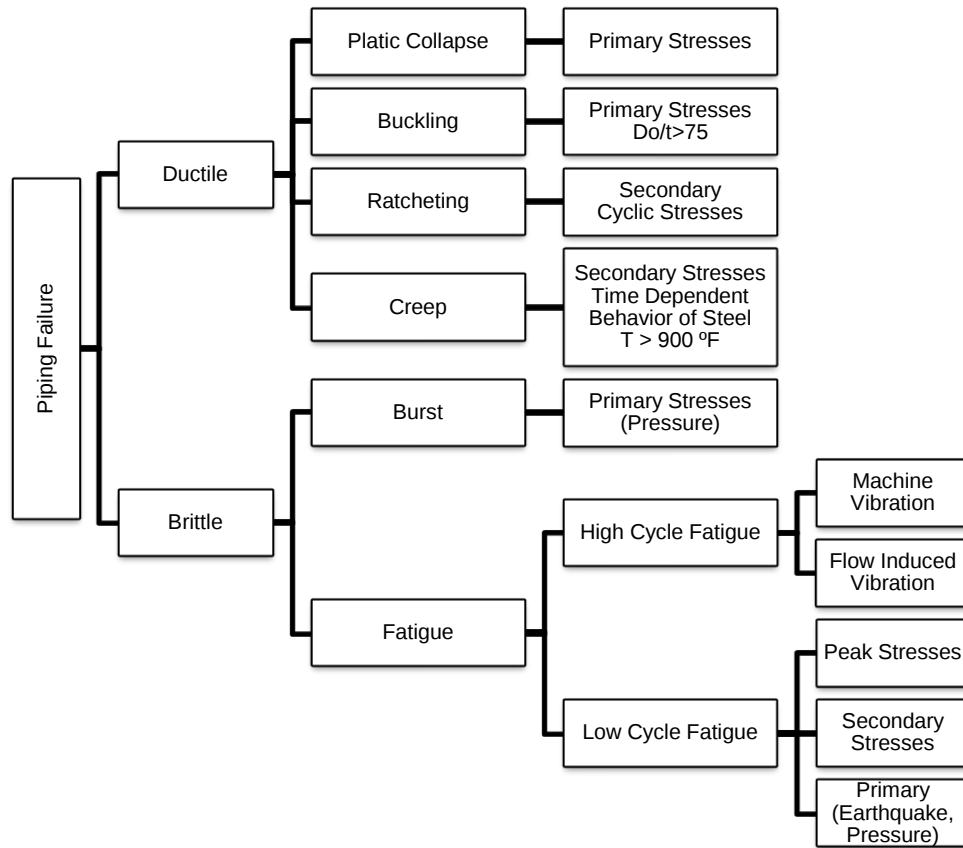


Figure 2. Failure modes for piping and their cause
Adapted from (Avrithi & Ayyub, 2010)

Technological advances in chemical processes and improvements in power plants energy efficiency are often limited by the operating pressure and temperature to which their piping plants are able to safely withstand. During the design phase, increasing process temperature and pressure may be accomplished through the use of advanced materials, or the development of new ones. Usually these solutions are not cost effective or even commercially available.

Another way of improving the allowable pressure and temperature of the pipe system is through its accurate stress analysis. Improvements in stress analysis accuracy would also represent economical gain through the rational use of materials and preventing unnecessary changes in layout, as well as substantially improving the piping system operational safety and reliability.

At the present time, the vast majority of industrial pipe systems are mechanically evaluated through a simplified stress analysis procedure called “*Piping Flexibility Analysis*”.

2 Background

2.1 Piping flexibility analysis

Even though a stress analysis represents a deeper and much more comprehensive evaluation of a piping system than a piping flexibility analysis, still today many pipe engineers regard them to be equivalent (Peng & Peng, 2009).

In order to ensure safety against piping failure or its attached structures, piping flexibility analysis aims at reducing pipe stresses and loads resulting from its operation. (Markl, 1955).

A set of papers published by A. R. C. Markl (Markl, 1947, 1950, 1952, 1955) in the late 1940’s and early 1950’s is arguably the most significant contribution to the current development of piping flexibility methods. (Koves, 2000)

A piping flexibility analysis is performed considering the pipe system as a set of straight beams. Some fittings, such as bends tees, present a reduction on their stiffness due to cross section ovalization. In order to correct its results, a set of flexibility factors is included in the analysis. This flexibility factors act as knock down factors to the stiffness whenever required.

Stress intensification factors (SIFs) need also to be included in the analysis in order to account for cyclic stresses. SIFs relate the fatigue life of a component with respect to a girth weld on a straight pipe, subjected to displacement loads.

2.2 Piping flexibility analysis inconsistencies

Even though the above framework allowed for safe design of many piping systems during the last six decades, several authors have raised questions regarding many aspects of its application (Hinnant & Paulin, 2008; Moore, Rodabaugh, Gwaltney, & Mokhtarian, 1987; Rodabaugh, 1987; Scavuzzo, 2006; E. A. Wais, Rodabaugh, & Carter, 2002; E. Wais & Rodabaugh, 1998a, 1998b)

Flexibility factors and SIFs for pipe bends and welding tees presented on (ASME-B31.3, 2012). Code standards usually provide SIFs and flexibility factors for a small amount of simple geometries. Whenever a certain geometry is not clearly permitted, the designer is required to develop this factors through testing (ASME-B31J, 2008) and since the geometries provided by the Codes are very simple, this is often the case. Due to the high costs of performing such tests, many users perform FEA of the component in order to determine the required factors.

Currently no piping Code present comprehensive rules for FEA evaluation, and it is not unusual for users resort to pressure vessel codes such as (ASME-VIII-2, 2013; BS-EN-13445-3, 2012).

Mixing of piping and pressure vessel Codes is not permitted by the Codes themselves, but is an industry-accepted practice. Both types of Codes have very different design criteria and this mixing leads to an inconsistent and possibly unsafe design (Peng, 2013).

Accurate determination of the flexibility factors are of major importance. Flexibility factors are directly used on the determination of support loads, nozzle loads and, along with SIFs, in the determination of the fatigue life of the system. The piping Codes provides flexibility factors

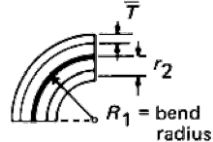
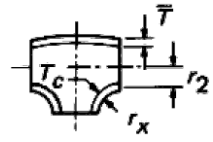
calculation formulas for pipe and mitered bends only, all other fittings have either flexibility factors of 1, or require the flexibility factor to be determined by testing.

It is clear that the Codes flexibility factor of 1 for tees and branch connections, for instance, might result on overestimation of the internal moments by a factor of 9 (Rodabaugh, 1987) or up to a factor of 20 (PRG, 2008). Inaccuracies on flexibility factors of other fittings may lead to errors of the same magnitude, while it is not possible to assure that these errors will lead to safe design.

Stress intensification factors were determined with respect to girth welds produced in the 1950's. Recent studies have shown that these Code values may need revision (Hinnant & Paulin, 2008).

These inconsistencies may lead to unnecessary re-routing of piping, incorrect estimation of loads on sensitive equipment nozzles (turbines, pressure vessels, pumps, compressors, etc.).

Table 1. Stress intensification factor (ASME-B31.3, 2012)

Description	Flexibility Factor, k	Stress Intensification Factor		Flexibility Characteristic, h	Sketch
		Out-of-Plane, i_o	In-Plane, i_o		
Welding elbow or pipe bend	$\frac{1.65}{h}$	$\frac{0.75}{h^{2/3}}$	$\frac{0.9}{h^{2/3}}$	$\frac{\bar{T}R_1}{r_2^2}$	
Welding tee in accordance with B16.9	1	$\frac{0.9}{h^{2/3}}$	$\frac{3}{4}i_o + \frac{1}{4}$		

3 Using Abaqus for Markl's Fatigue Tests

An alternative to avoid the inconsistencies presented on item 2.2 would be to perform the full piping stress analysis according to a modern pressure vessel Code such as (ASME-VIII-2, 2013; BS-EN-13445-3, 2012).

For a large piping system, stress analysis may become extremely time consuming and the proper use of specialized elements such as Abaqus ELBOW31 is of paramount importance. The performance of this elements have been evaluated at (Simulia, 2014).

In order to evaluate the capability of Abaqus specialized element ELBOW31 and the linear quadrilateral element S4R against the fatigue test results performed by (Markl, 1952), a set of 10 models was generated. General model dimensions are indicated in Figure 3. The fatigue evaluation of straight pipe, long radius elbow and ASME B16.9 tee were performed according to the ASME master S-N Fatigue curve (ASME-VIII-2, 2013). No safety factor on the Master Fatigue curve was considered. The cross section properties were taken according to the nominal dimensions of 4" STD pipe. Material properties according to ASTM A-106 Gr. B. For the straight pipe and long

radius elbow models, both elements ELBOW 31 and S4R were evaluated. Only S4R element was evaluated for the tee model. An “opening” displacement of 25 mm on the In-Plane and Out-of-Plane directions were applied to the free edge of each evaluated system.

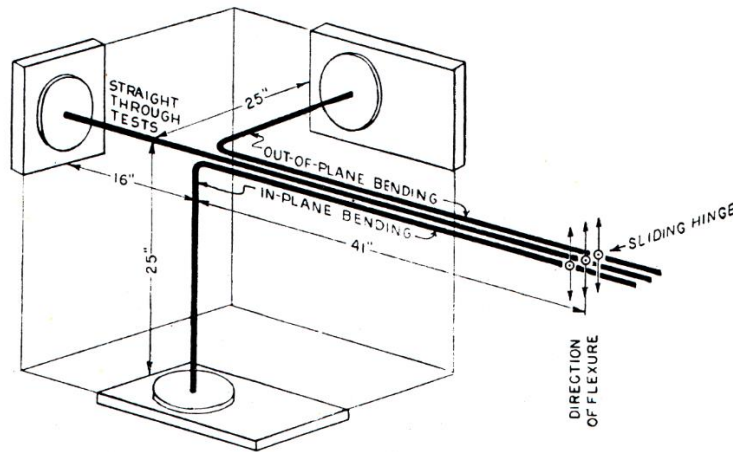


Figure 3. Markl's fatigue test general dimensions
Fig. 2 from (Markl, 1952)

3.1 Straight pipe ELBOW31 and S4R analysis

The analysis results for the straight pipe model displayed extremely good agreement to Markl's original results (Figure 5). All results from Abaqus were found to be within the test data scatter.

A sample analysis result for the S4R models is presented on Figure 4.

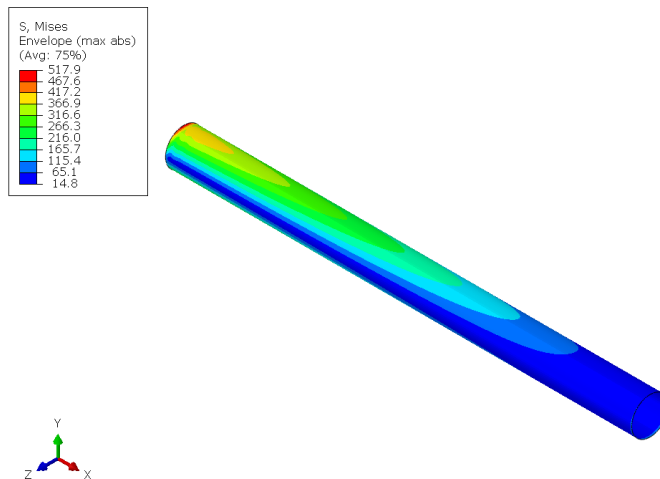


Figure 4. Sample straight pipe FEA results (S4R)

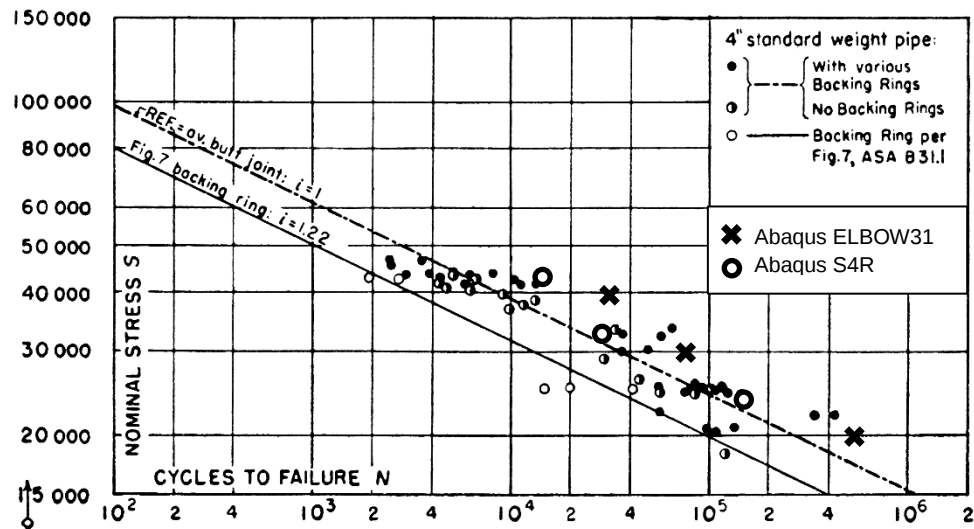


Figure 5. Fatigue results for butt-welded joints in straight pipe
Fig. 5 from (Markl, 1952)

3.2 Long radius ELBOW31 and S4R analysis

The analysis results for the long radius pipe model displayed extremely good agreement to Markl's original results (Figure 7 and Figure 8). All results from Abaqus were found to be within the test data scatter.

A sample analysis result for the S4R models is presented on Figure 6.

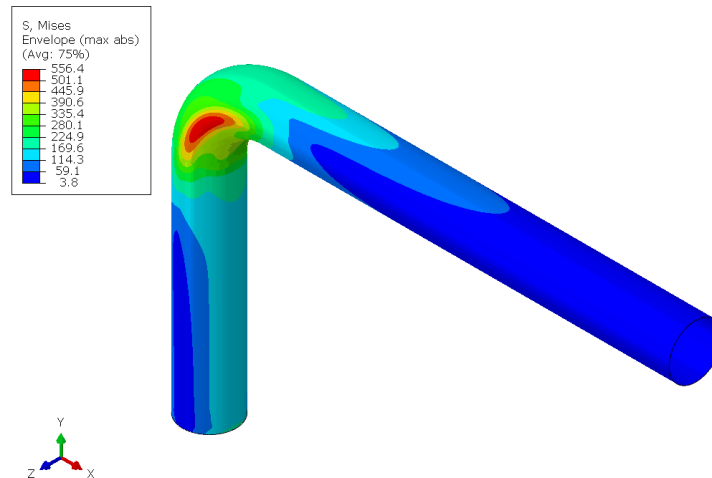


Figure 6. Sample long radius FEA results (S4R)

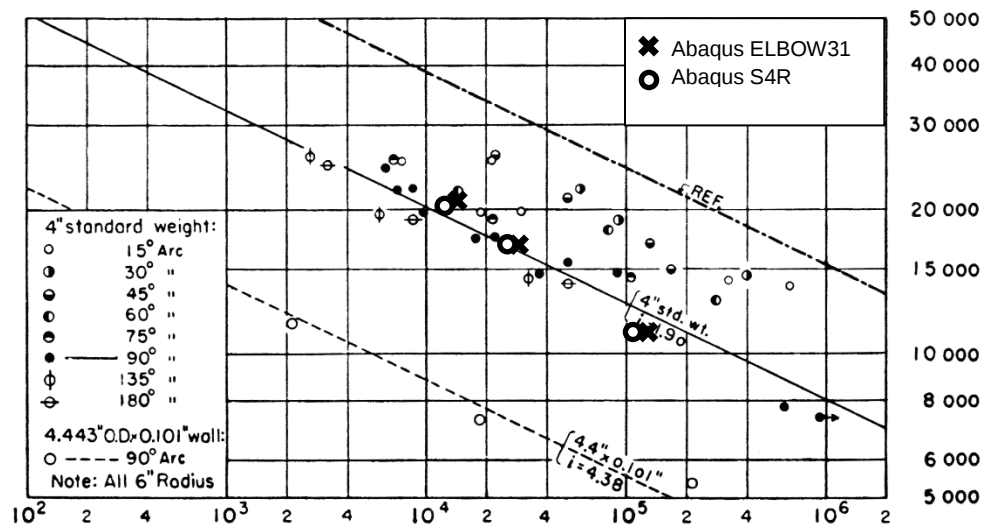


Figure 7. Fatigue results for long radius elbows, in-plane
Fig. 8 from (Markl, 1952)

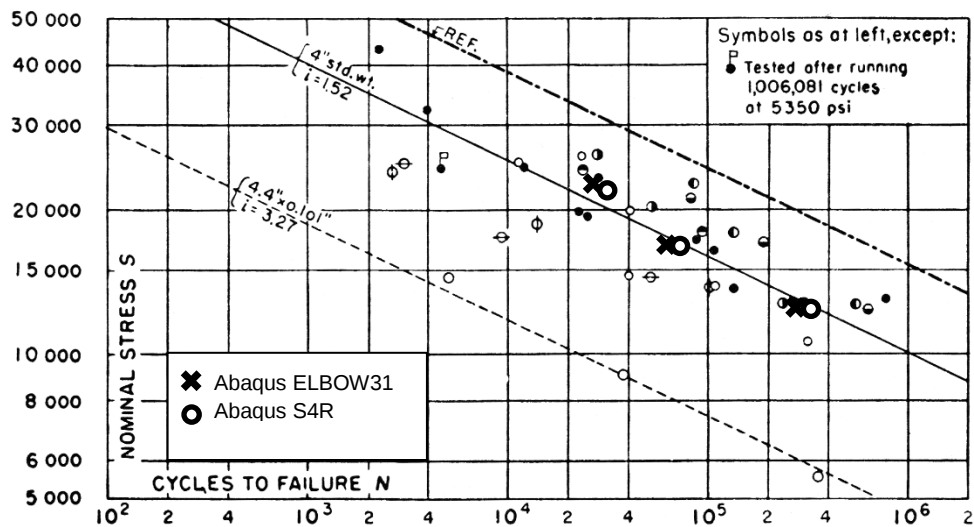


Figure 8. Fatigue results for long radius elbows, out-of-plane
Fig. 9 from (Markl, 1952)

3.3 ASME B16.9 Welding tee S4R analysis

Result analysis for the welding tee model presented good agreement to Markl's original results for the out-of-plane loading condition and Abaqus results were within the test data scatter (Figure 11). FEA results for the in-plane loading conditions were below the reference line (Figure 10). Further analysis is required, but the probable cause for the adverse result is a geometric difference between the crotch radius of Markl's welded tee and the one modeled on the present study.

A sample analysis result for the S4R models is presented on Figure 9.

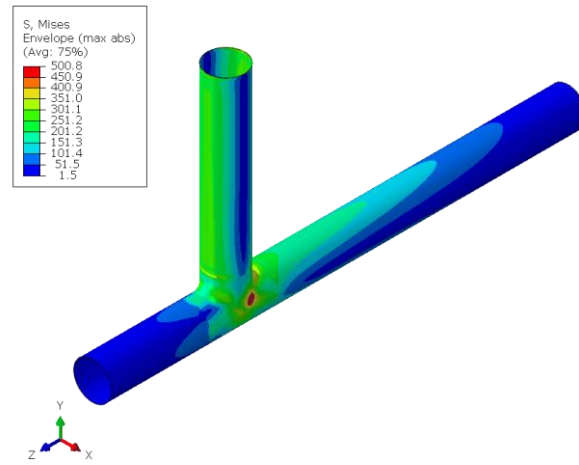


Figure 9. Sample welding tee FEA results (S4R)

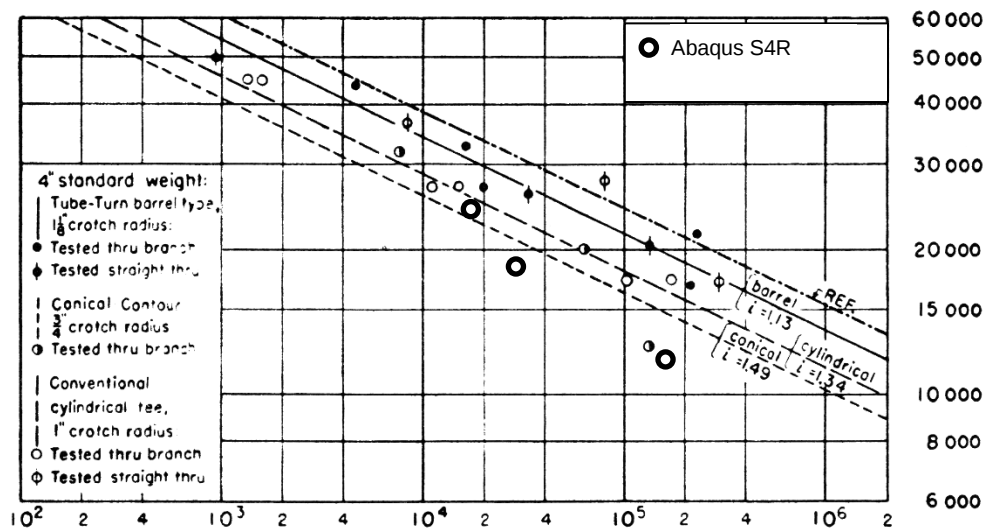


Figure 10. Fatigue results for welding tees, in-plane
Fig. 10 from (Markl, 1952)

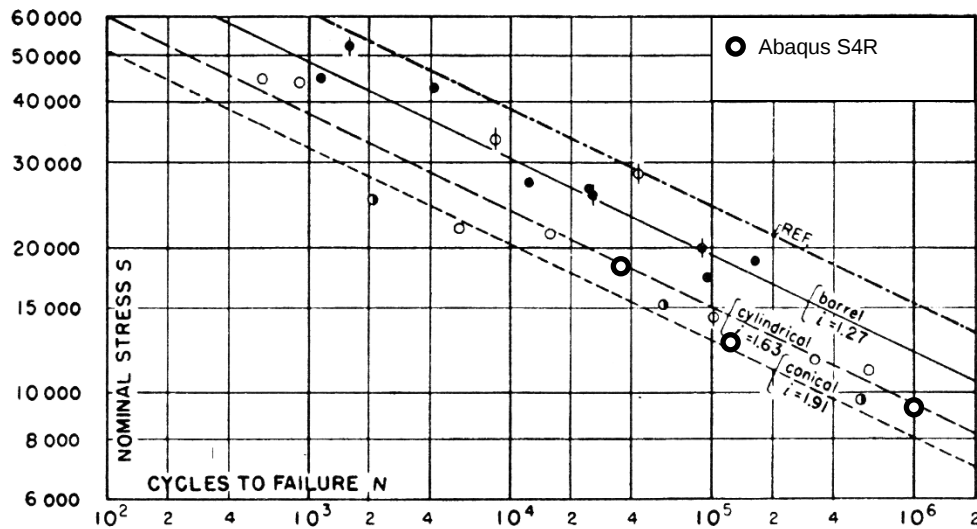


Figure 11. Fatigue results for welding tees, out-of-plane
Fig. 11 from (Markl, 1952)

4 Pipe Calculation System

4.1 Introduction

Finite element simulation on large industry piping systems required the development of an application for Abaqus to improve speed and ease the geometry creation process. The developed application is called Pipe Calculation System (PCS). PCS focuses in select industries such as Oil & Gas, Chemical, Petrochemical, Nuclear, Naval, Mining and Pulp & Paper.

Popular software for piping flexibility analysis currently available to end-users are Caesar II (Intergraph), Triflex (Piping Solutions) and Rohr2 (Sigma). The first two software are based on the calculation criteria originally developed by (Markl, 1955) and described on item 2, while the last one is able to perform mixed flexibility and FEA calculations. Intergraph estimated that Caesar II currently controls 75% of the piping stress analysis market share (Intergraph, 2012).

Improvements introduced by the use of PCS can be seen on the overall analysis quality, where finite element simulation provides better and more reliable results compared to regular piping flexibility. This allows the pipe system to be designed with a proper estimation of its lifespan, reducing the probability of unforeseen maintenance plant stops due to pipe failure. Additionally, PCS reduces design time with its intuitive user-interface by the use of up-to-date, consistent and reliable engineering requirements, together with easy and effective reporting with state-of-art technology.

4.2 Development

Developing such application requires merging of different expertise: a wide knowledge of the traditional framework of piping flexibility analysis; proficiency on Abaqus CAE its qualities and weaknesses regarding its use for piping flexibility analysis; knowledge on software development and Abaqus integration. With these set of skills, it is possible to define requirements and changes that must be implemented on Abaqus, in order to develop a suitable application for modern piping flexibility analysis to the end-user.

These expertise can be extended to deeper issues. Defining PCS requirements contemplates awareness of several software currently available with their strengths and weaknesses, along with how the users expect applications to react to input data and how output data should be presented.

Comprehending Abaqus can be broken down to an understanding of its internal structures, documentation, mesh generation capabilities and simulations execution. On the developer's end, integration of the application with Abaqus needs to benefit from all features already available on the software, minimizing development costs and providing foundation to PCS' results.

4.2.1 PCS Features

PCS creates an interface between the user and Abaqus in order to create the pipe system geometry, define its loads and properties, also incorporating proprietary tools previously developed by RMC to integrate PCS with different file formats broadly used. The application is also scriptable through the python interface already provided by Abaqus and a seamless user interface (UI) with Abaqus allows users to make use of the latest features developed by Simulia.

- Geometry creation

PCS allows a simplified creation of specific pipe geometries from the application's smart UI as pipes, reductions, valves and supports. Setting of material properties can be achieved by selecting it from the material database provided (). This sets the required properties such as temperature and diameter for each element modeled. This database includes properties and fittings dimensions from several piping and pressure vessels standards. The material database can also be edited, in order to modify existing values or include new ones.

- Third party file import

Previously developed pipe geometry, created on several common piping software, can be imported as seen on Figure 14. Integration to Intergraph Caesar II binary file (C2) and neutral file (CII) is available. It is also possible to import almost any 3D geometry created by all major 3D pipe design software through PCF files.

Imported data depends on the file type and amount of usable data it contains. For instance, Caesar II files allows importing geometry, temperatures, pressures and load cases, which will be automatically included in the analysis of the piping system. PCF files allow importing only basic geometry information.

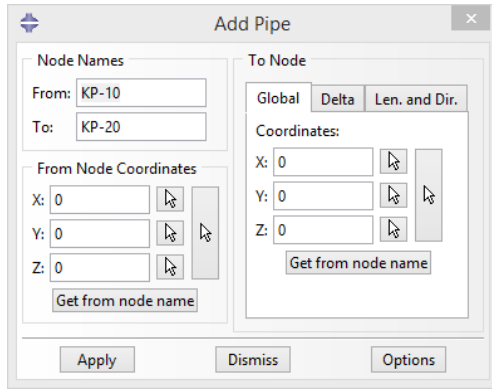


Figure 12. Pipe creation window

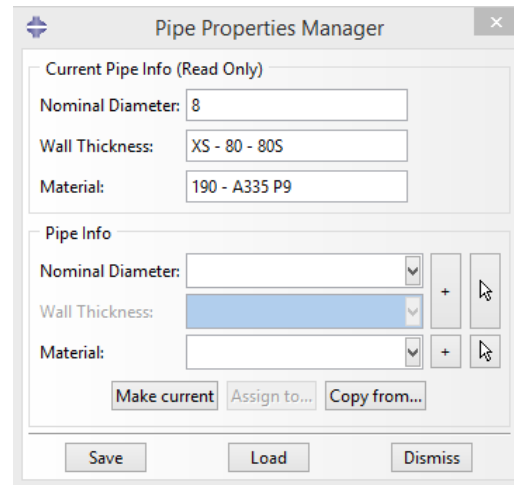


Figure 13. Pipe properties window

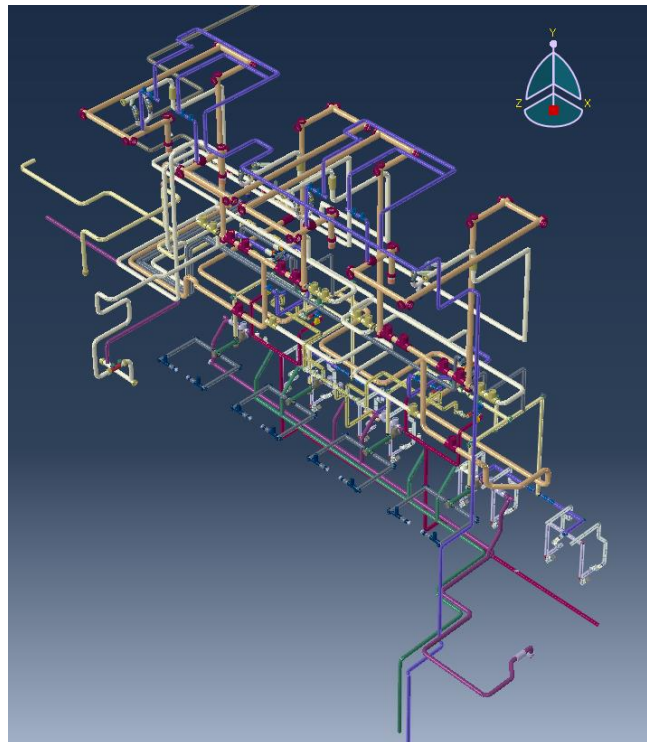


Figure 14. Caesar II Imported Model

- **Mesh**
PCS automatically optimizes 1D meshes by generating elbow type elements, which have relatively high performance and low computational cost (Simulia, 2014). 2D meshes are also automatically generated under user request.
- **Constraints**
Before simulation starts all required constraints, such as elbows MPCs and support connectors, are applied to the model. Including constraints in a large piping flexibility analysis is a tedious effort that would consume considerable amount of time. This feature benefits user experience also reducing time and minimizing modeling errors.
- **Reports**
In order for a flexibility analysis to be checked and reviewed by a piping engineer, it has to be presented in a way that current professionals can readily evaluate, without representing a major change on the current project workflow.
PCS reports are generated in just a few user clicks. Information includes basic model data, restraint loads, displacements, stresses and allowable stresses.

4.3 Sample Results

Consider a sample piping system consisting of four parallel air-coolers. Each air-cooler has four inlet nozzles that are connected to the process unit through a 20" diameter, 1/4" thick, ASTM A672 B60 pipe header. The final section of the feed pipe consists of an extremely flexible pipe arrangement in order to reduce piping loads on the equipment nozzles. The fluid is a hydrocarbon gas at 450 °C.

The PCS model consisted of 142053 linear quadrilateral elements of type S4R, geometrically non-linear and the material model was linear elastic. The evaluation of the four load steps took less than 6 minutes on a standard desktop computer (i7-4790 @ 3.6 Ghz), running Abaqus Standard on a single processor.

Figure 15 present PCS stress results for the load step WNC+P1+T1, which consists of loadings from piping weight with no contents (WNC), pipe pressure (P1), and pipe temperature (T1). These results were compared to the ASME B31.3, calculated using Coade Caesar II 5.1, a standard pipe flexibility analysis software.

The stresses computed with Caesar II converted into cycles through Markl's methodology were compared to cycles calculated according to ASME master S-N curve. The master S-N curve approach resulted on a fatigue life 20% higher than Markl's. Differences of up to 120% on nozzles reaction forces were found between the two approaches. These differences may be attributed to inaccuracies of ASME B31.3 flexibility factors that are of great importance on compact regions with several pipe fittings, such as the nozzle region of this model.

The Caesar II calculation, indicates that the piping system needs to be redesigned due to overstress, while calculation through PCS and ASME VIII div. 2 part 5 clears the system for safe operation.

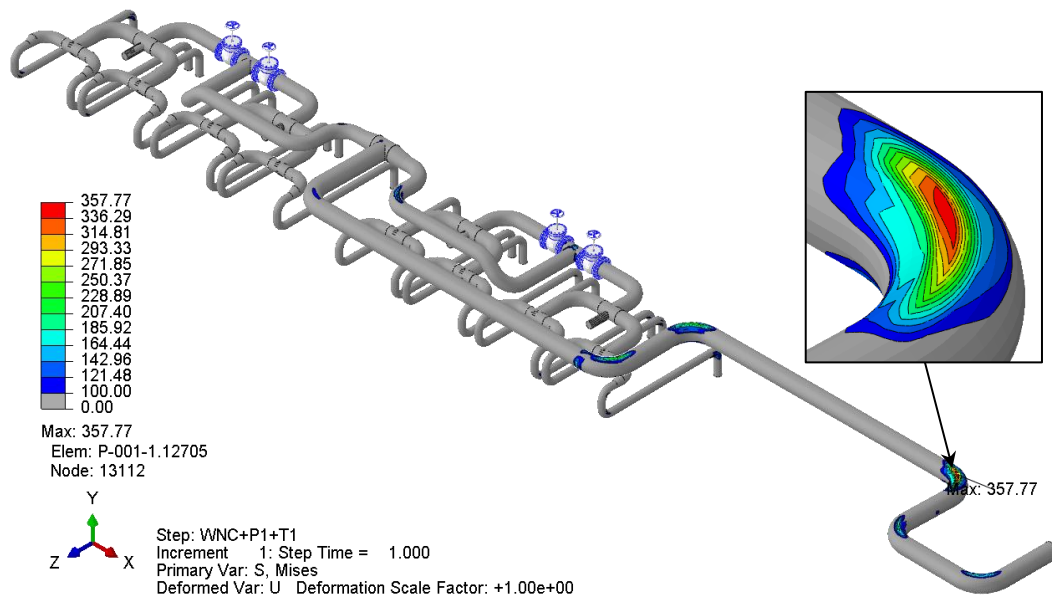


Figure 15. Sample air-cooler model

5 Conclusions

On the present paper, a comparison of fatigue analysis on Simulia Abaqus and historical results from (Markl, 1952) is performed.

Elements ELBOW31 and S4R were used in the FEA models while the ASME master fatigue curve (ASME-VIII-2, 2013) was used to determine the expected life of each component.

Results show that it is possible to obtain extremely satisfactory results from using Abaqus for the fatigue analyses of regular piping components.

Further analysis will be required for the welding tee under in-plane loading model, which was the only analysis case where results did not fall within Markl's data scatter. A probable cause for this result inconsistency is a geometric difference between the crotch radius of Markl's welded tee and the one modeled on the present study.

This paper also introduces PCS - Pipe Calculation System, a piping flexibility analysis application for Simulia Abaqus, a tool for fast modelling and result analysis of finite element piping systems.

A sample PCS calculation for an air-cooler pipe assembly is provided and some general results are evaluated. These results indicate a clear advantage on using advanced finite element models to evaluate common pipe flexibility analysis problems.

General use of advanced finite element software on piping stress analysis will enable users to achieve better understanding of the mechanical behavior of their piping systems, reducing calculation uncertainties, increasing fatigue life and allowing for proper evaluation of non-standard fittings. Additionally, the use of these techniques will make it possible for the piping industry to take advantage of the latest developments and trends of the simulation community.

6 References

1. ASME-B31.1, "*Power Piping*", New York, N.Y., (2012).
2. ASME-B31.3, "*Chemical Plant and Petroleum Refinery Piping*", New York, N.Y., (2012).
3. ASME-B31.4, "*Pipeline Transportation Systems for Liquids and Slurries*", New York, N.Y., (2012).
4. ASME-B31.8, "*Gas Transmission and Distribution Piping Systems*", New York, N.Y., (2010).
5. ASME-B31J, "*Standard Test Method for Determining Stress Intensification Factors (i-Factors) for Metallic Piping Components*", New York, N.Y., ASME, (2008).
6. ASME-VIII-2, "*ASME Boiler and Pressure Vessel Code (BPVC), Section VIII, Division 2: Alternative Rules*", New York, N.Y., (2013).
7. Avriithi, K., & Ayyub, B. M., "Load and Resistance Factor Design (LRFD) of Nuclear Straight Pipes for Loads That Cause Primary Stress", *Journal of Pressure Vessel Technology*, 132, 021101, (2010), doi:10.1115/1.4000976.
8. Basavaraju, C., & Sun, W. S., "CHAPTER B4 Stress Analysis of Piping Systems", In *Piping Handbook* (pp. 107–214), (2004).
9. BS-EN-13445-3, "Unfired pressure vessels. Design", (2012).
10. BS-EN-13480-3, "*Metal industrial piping - Part 3: Design and calculation*", (2012).
11. Hinnant, C., & Paulin, T., "Experimental Evaluation of the Markl Fatigue Methods and ASME Piping Stress Intensification Factors", In *Volume 1: Codes and Standards* (pp. 97–113), ASME, (2008), doi:10.1115/PVP2008-61871.
12. Intergraph, "Intergraph Cadworx & Analysis Solutions Flyer", (2012), Retrieved February 10, 2015, from <http://www.intergraph.com/assets/pdf/Flyer.pdf>.
13. Kaiser, M. J., & Gary, J. H., "A Review of Refinery Markets and Cost Estimation", 597–630, (2013).
14. Koves, W. J., "Process Piping Design: A Century of Progress", *Journal of Pressure Vessel Technology*, 122(August 2000), 325, (2000), doi:10.1115/1.556199.
15. Markl, A. R. C., "Fatigue Tests of Welding Elbows and Comparable Double-Mitre Bends", *Transactions of the ASME*, 869–879, (1947).
16. Markl, A. R. C., "Fatigue Tests on Flanged Assemblies", *Transactions of the ASME*, 78–87, (1950).
17. Markl, A. R. C., "Fatigue Tests of Piping Components", *Transactions of the ASME*, 287–303, (1952).
18. Markl, A. R. C., "Piping-Flexibility Analysis", *Transactions of the ASME*, 127–149, (1955).

19. Moore, S. E., Rodabaugh, E., Gwaltney, R., & Mokhtarian, K., "*Review and Evaluation of Design Analysis Methods for Calculating Flexibility of Nozzles and Branch Connections*", (1987).
20. Peng, L. C., "Understanding Piping Code Stress Evaluation Paradoxes And ASME B31.3 Appendix P", (2013), Retrieved December 20, 2014, from <http://www.pipestress.com/papers/piping-code-paradoxes-b31-3-p.pdf>.
21. Peng, L. C., & Peng, T. L., "Pipe stress engineering", New York, NY ASME Press, (2009).
22. PRG, "Pipe Stress Errors - When You're Off by 10 Times! Evaluating Pipe Stress Errors Due to Incorrect SIFs and Stiffnesses", (2008), Retrieved January 07, 2015, from http://www.paulin.com/WEB_FESIF.pdf.
23. Rodabaugh, E. C., "WRC-329 - Accuracy of Stress Intensification Factors for Branch Connections", *Welding Research Council*, (1987).
24. Scavuzzo, R. J., "Effect of Loading on Stress Intensification Factors", *Journal of Pressure Vessel Technology*, 128(1), 33, (2006), doi:10.1115/1.2148420.
25. Simulia, "Parametric Study of a Lner Elastic Pipeline Under In-Plane Bending", In *Abaqus 6.14 - Example Problems Guide - Volume I: Static and Dynamic Analysis* (pp. 1.1.3–1–1.1.3–7), (2014).
26. Wais, E. A., Rodabaugh, E. C., & Carter, R., "Investigation of Torsional Stress Intensification Factors and Stress Indices for Girth Butt Welds in Straight Pipe", In *Design and Analysis of Piping, Vessels, and Components* (Vol. 2002, pp. 83–89), ASME, (2002), doi:10.1115/PVP2002-1266.
27. Wais, E., & Rodabaugh, E. C., "TR-110755 - Stress Intensification Factors and Flexibility Factors for Pad-Reinforced Branch Connections", *EPRI*, (1998a).
28. Wais, E., & Rodabaugh, E. C., "TR-110996 - Stress Intensification Factors and Flexibility Factors for Unreinforced", *EPRI*, (1998b).