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A Case Study on the Importance of Support Stiffness in Flexibility Stress Analysis (Static and Dynamic) Using Analysis Software

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***Abstract*—The primary objective of this study is to emphasize the significance of pipe support stiffness in both thermal expansion and seismic conditions. The actual support stiffness is included in the analysis by modeling the structural member using the CAESAR II software. Incorporating actual support stiffness is important because it helps accurately simulate the behavior of piping systems under different loading conditions, leading to more accurate results and better decision-making during the design and operational stages. Additionally, this study demonstrates how incorporating actual support stiffness allows for a more optimal design, reduces the risk of failure due to excessive stresses and displacements, and improves overall piping system performance.**

***Keywords*—CAESAR II, Flexibility Analysis, Stiffness.**

I. INTRODUCTION

All piping systems experience two types of loads such as force-based loads and strain-based loads. The force-based loads arise from factors such as internal pressure, components weight, and fluids flowing through the system. On the other hand, strain-based loads originate from thermal fluctuations, seismic forces, and machinery-induced forces (uneven forces resulting from operating equipment). These combined loads (forced and strain-based loads) play a crucial role in the design and analysis of piping systems ensuring safe and efficient operation of the piping system. In many cases, lower-stiffness pipe supports may often be required to accommodate thermal expansions, whereas higher-stiffness pipe supports are necessary to mitigate vibratory, seismic and dynamic loads, ensuring stability and minimizing the risk of resonance. Overall, the right choice of pipe supports along with stiffness, considering both thermal and vibration / seismic requirements, ensures the integrity and reliability of the piping system throughout its operational lifespan.

In order to perform the realistic simulation, actual support stiffness was included through modelling of the actual support member in the analysis using CAESAR II [5] software. Further analysis results compared the actual support stiffness value with the ideal (rigid) support stiffness to better understand the significance of support stiffness in the piping analysis.

A. Theoretical Background

The concept of piping designing is to ensure the proper functioning of piping systems. This involves balancing two critical aspects: flexibility and rigidity.

Flexibility: Piping systems are subject to thermal expansion and contraction as the temperature of the fluid inside the pipes changes. If the pipes are not flexible enough to accommodate these temperature variations, it can lead to overstress and potential failure of the system. In order to provide sufficient flexibility in a piping system, the pipe routing can be modified with offsets, bends, loops, expansion joints or flexible couplings. The pipe support's stiffness also influences the flexibility of the piping, and different pipe support configurations can be used to allow the system to move thermally. Combining suitable piping routing modifications and appropriate pipe support designs can create a flexible piping system that can accommodate thermal changes without compromising its structural integrity. This ensures that the system operates safely and efficiently under varying temperature conditions, reducing the risk of damage or failure due to thermal loading. The flexible support allows displacement in both thermal and vibratory. This may be suitable for thermal cases but does not significantly contribute to vibratory services.

Rigidity: On the other hand, excessive vibration in piping systems can also cause damage and compromise the system's integrity. To control vibratory loading, the piping system should be rigid by incorporating a hold-down clamp with a damping pad / high friction pad, directional anchor, sway braces, dampers, and isolators. Increasing the rigidity of a piping system can be achieved by increasing the mass, support dampening and stiffness. But support dampening and stiffness are the effective approaches. The overall system rigidity can be improved using stiffer materials or design configurations in the supports or damped support. Increasing the mass of components can also contribute to increased rigidity. Still, it can be a difficult process and may not always be the most practical solution due to other considerations like weight limitations, space constraints, and cost. The following clause explains exclusive techniques of stiffness estimation.

B. Different methods of estimating restraint stiffness.

i. Using Hooke's Law

Pipe support stiffness can be calculated using Hooke's law, often used to describe the behavior of linear elastic materials. Calculating pipe support deflection using beam deflection formulas is a common approach in engineering. The stiffness of the pipe support determines how much the support will deflect under a given load, and this can be crucial for ensuring the structural integrity of the pipe system.[2]

$$K = {}^{F}/_{\delta_{max}}$$

$$\delta_{max} = {}^{FL^3}/_{3EI} \ (Considered\ Cantilever\ Beam)$$

δ_{max} is the maximum deflection of the beam at the edge in meters.
F is the applied load in Newtons.
L is the length of the beam in meters.
E is the modulus of elasticity of the material in Pascals.
I is the moment of inertia of the beam's cross-sectional shape in meters^4.

It's important to note that while the basic beam formula and Hook's law provide a starting point for engineering, real-world engineering applications often involve more complexity, such as pipe material properties, pipe connections, support types, load distribution, and boundary conditions. Additionally, more complex pipe support configurations might require finite element analysis (FEA) or specialized software to accurately predict deflections and stiffness.

ii. Default (Infinite) restraint stiffness

CAESAR II is a widely used software tool for pipe stress analysis. The default restraint stiffness value of 1E12 lb/in (one trillion pounds per inch) that CAESAR II assumes when no stiffness value is provided for restraint in the analysis. This assumption essentially treats the supports as infinitely stiff, implying that the piping system would not experience any deformation or movement at those supports. This assumption can lead to conservative results in certain cases. The approximate weight of all humans living on Earth, around one trillion pounds, is a good way to illustrate the magnitude of this value.

iii. API recommended restraint stiffness

API 618 is a standard for reciprocating compressors in the oil and gas industry. Clause P.3.2 of API 618 [4] provides guidelines for the minimum required support stiffness for practical piping configurations, taking into account the minimum natural frequency guideline. Equation (P-2) in this clause is used to calculate the minimum required support stiffness.

$$minimum\ k_s = C_{KS}\ XA^{0.75}XI^{0.25}Xf_{n,T}^{1.5}(n - \frac{1}{n})$$

Where

C_{KS} – is the constant dependent on the support stiffness units
A - is the pipe cross-sectional metal area in mm2
I - is the pipe cross-sectional area moment of inertia in mm4
OD - is the outside diameter in mm
ID - is the inside diameter in mm
$f_{n,T}$ - is the minimum transverse natural frequency in HZ
N - is the number of active support or n=2 as a minimum

iv. Inclusion of Structural members

In CAESAR II, the Structural Modeling module creates a detailed representation of the support structure that interacts with the piping system. This involves adding support members like beams, columns, and bracing elements, which are typically used to connect and stabilize the piping system. The purpose of modelling the support structure is to accurately capture the stiffness characteristics of these elements, as they contribute significantly to the overall stiffness of the system.

II. CASE STUDY

A. System Description

The focus of this paper revolves around a covered marine structure designated for routine ship/vessel maintenance, repairs, and operational upkeep and it is made of heavy structural steel. The marine structure encompasses various piping systems like contaminated oil (oil bilge) which are used to collect the oily bilge from the ships and transport it to the intermediate tanks at each bay through the cope points, gas piping systems (oxygen, acetylene, low-pressure compressed air) which are used for welding, cutting, powering pneumatic tools, grit blasting, painting, cleaning and operation of hoists and water piping (Sea water, Fire water, chilled water, and potable water) which are used for fire protection, cooling, drinking and flushing requirements. All these piping systems are routed along the marine structure with cope points at regular intervals covering the entire marine structure area.

The piping system is subject to loads due to dead weights (pipe, fittings), the content (water, gas & oil) of pipes carrying, pressure, temperature, seismic, wind and relative displacement between the steel structures. These loads are subsequently transmitted to the marine structure.

B. Modelling approach

The initiation of pipe stress analysis involves the development of a computer input model that accurately represents the physical piping system. Each piping component is represented mathematically for input into the computer analysis model. In defining the analysis model, the overall system geometry is defined by locating nodes. The nodes are inserted into the model to specify the geometry and other locations wherever aggregate results (such as displacements, forces, moments, stresses, etc.) are required. The additional mass points (nodes) are strategically inserted to achieve reasonable accuracy in dynamic analysis and sufficiently determine the system's dynamic response. Caesar II won't automatically generate mass points; therefore, a general rule is that at least one mass point is used between supports acting in the same direction.

The properties such as Material, Modulus of Elasticity (E), Coefficient of Thermal Expansion, Allowable Stress (Sc and Sh), and Yield Strength (Sy) are considered as per the design code (ASME B 31.3) [3] for all components in the system. In order to determine the fatigue and sustained load capacity of metallic piping components or joints ASME B31J / ASME B 31.3 flexibilities and SIFs (Stress Intensification Factor) are applied. The flange and valve are modelled as a rigid element with the same properties as the adjoining pipe and the weight of the flange and valves (including the weight of the nuts and studs) are applied to the rigid element. The flanges and valves are modelled as rigid elements in the piping system to represent their effect in the piping evaluation by providing an element of high relative stiffness in the piping model. The CAESAR II is not used to evaluate stress on rigid elements since the qualification of these components are not part of the analysis.

The integration of structural steel elements into the piping system model is facilitated by the structural steel input modeler, with separate files being saved. This involves defining structural elements like beams, columns, and supports, along with their respective properties. The structural model is incorporated into the piping model through the "include structural input file" option in the CAESAR II menu, attaching the pipe to the structure using the attachment node point on the structure as the restraint CNODE.

C. Analysis Approach

Case 1: Rigid Support Stiffness

In the first phase of analysis, piping systems are analyzed with CAESAR II default (infinitely rigid) restraint stiffness. The restraint stiffness refers to the stiffness of the supports that hold the piping system in place. In CAESAR II, the default setting for restraint stiffness (1E12 lb/in) assumes that the supports are infinitely stiff. (Refer Figure 1)

Case 2: Flexible Support Stiffness

In this analysis, structural models are included in the piping system to include actual (flexible) support stiffness. The boundary conditions of piping systems are terminated at restraint in all six degrees of freedom (fully anchor) / single degree of freedom (partial anchor) at equipment nozzles and battery limit locations, and all other piping supports are considered as rest supports along with a guide considering a friction coefficient of 0.3 for both phases of the analysis. (Refer Figure 2)

The load case (both cases) combinations in CAESAR II consider various loads that can act on the piping system simultaneously. The standard load case combinations [1] in ASME B31.3 are considered for stress analysis. These load cases include combinations of different types of loads such as hydrostatic load case (weight + Hydrotest Pressure), sustained load case (weight + Design pressure), operating load case (weight pressure + Temperature), Expansion load case (operating load case – sustained load case) along with seismic load. The accurate modelling of support stiffness and considering different load cases are crucial for this assessment.

D. Analysis results comparisons

The displacement, restraint loads, code stress evaluation and mechanical natural frequency are compared for the axial stopper support for the operating load case.

i. Displacement

Pipe support has a displacement (7 mm) in the axial direction due to flexible stiffness. This shows the realistic support behaviour and helps to prepare the mitigation plan (modify support design, remove redundancy, implement bellow etc) to prevent the equipment nozzle failure due to support displacement whereas support does not have displacement (0 mm) due to rigid stiffness. (Refer Table I)

ii. Restraint load

Restraint loads due to flexible stiffness are considerably reduced compared to those due to rigid stiffness. This reduction is approximately 6.5 times in the axial direction. This suggests that the flexible support system allows for more movement and flexibility in the piping system, which results in lower restraint loads on the structure. The stiffness of rigid supports often necessitates the use of heavy or robust members to withstand the generated loads and flexible stiffness offers simpler, more cost-effective support structures due to reduced restraint loads (Refer Table II)

iii. Code stress evaluation

In the case of rigid stiffness, the code stress evaluation failed, with stress levels reaching 224% of the allowable stress. This indicates that the rigid support stiffness system may not adequately handle the applied loads and should redesign the support type or change pipe routing.

The code stress evaluation passed in the case of flexible stiffness, with stress levels only at 70% of the allowable stress. This suggests that the flexible support stiffness system is better at distributing and accommodating the loads, resulting in a safer side (Refer Table III)

iv. Natural frequency (MNF)

The first mechanical natural frequency (MNF) due to flexible stiffness is lower (4.718 Hz) and more closely spaced frequencies than that of rigid stiffness (8.629 Hz). A lower MNF and more closely spaced frequencies in the flexible system imply that the structure is more flexible and can resonate at lower frequencies. This helps for the mitigation plan to avoid resonance and related failure (Refer Table IV)

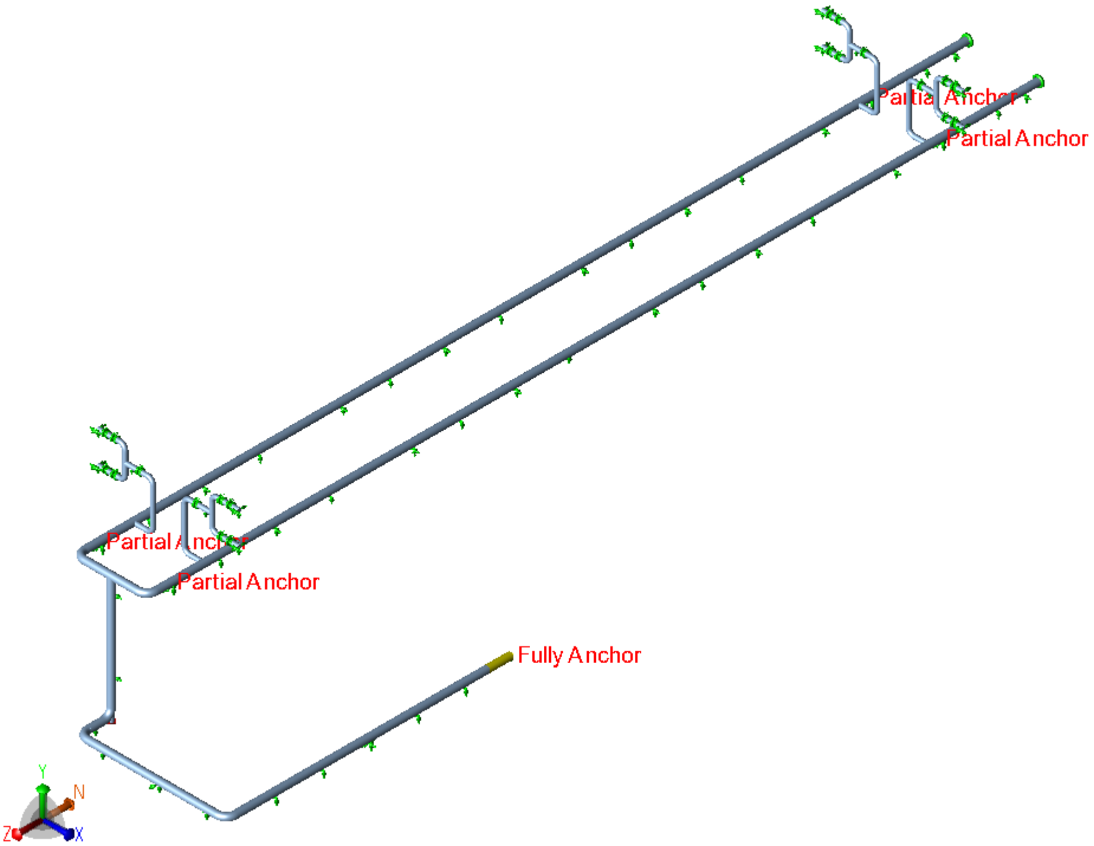


Fig. 1. CAESAR model representing Rigid Support Stiffness.

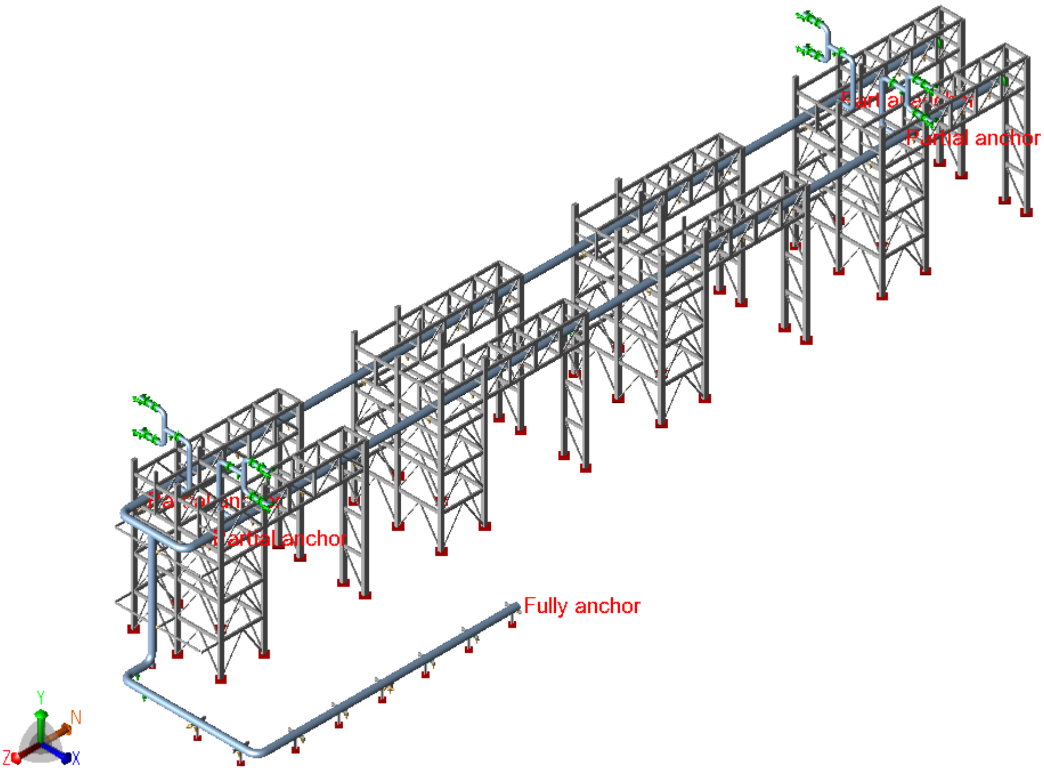


Fig. 2. CAESAR model representing flexible support stiffness.

TABLE I. DIISPLACEMENT COMPARISON BETWEEN CASE 1 AND CASE 2

		Flexible Stiffness (Case 2)							Rigid Stiffness (Case 1)					
Node	Load Case	DX mm.	DY mm.	DZ mm.	RX deg.	RY deg.	RZ deg.		DX mm.	DY mm.	DZ mm.	RX deg.	RY deg.	RZ deg.
31660	CASE 2 (OPE) W+T1+P1	0	0	7	0	0	0		0	0	0	0	0	0
32320		0	0	7	0	0	0		0	0	0	0	0	0
32390		0	0	-7	0	0	0		0	0	0	0	0	0
32400		0	-1	-7	0	0	0		0	0	0	0	0	0

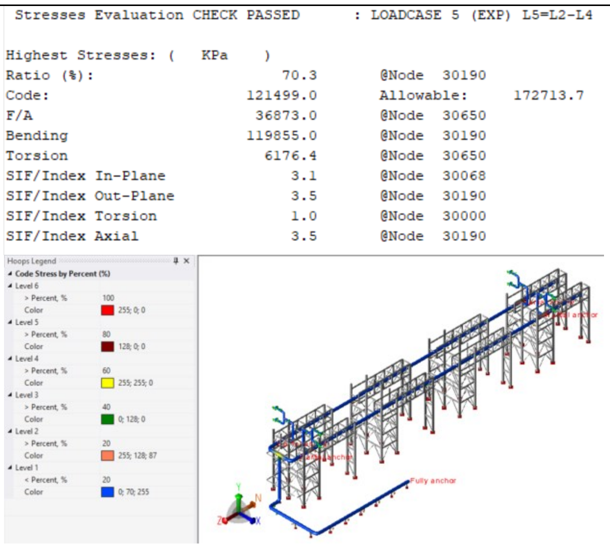
TABLE II. RESTRAINT LOAD COMPARISON BETWEEN CASE 1 AND CASE 2

			Flexible Stiffness (Case 2)				Rigid Stiffness (Case 1)		
Node	Support Type	Load Case	FX N.	FY N.	FZ N.		FX N.	FY N.	FZ N.
31660	TYPE=Rigid +Y; Rigid Z;	CASE 2 (OPE) W+T1+P1	3785	12015	79785		-224	29954	523460
32320			-3863	12439	90359		55	30153	522756
32390			-773	-2717	-85303		-732	15815	-514246
32400			1010	-1333	-74575		707	15729	-513988

TABLE III. CODE STRESS EVALUATION COMPARISON BETWEEN CASE 1 AND CASE 2

Flexible Stiffness (Case 2)	Rigid Stiffness (Case 1)

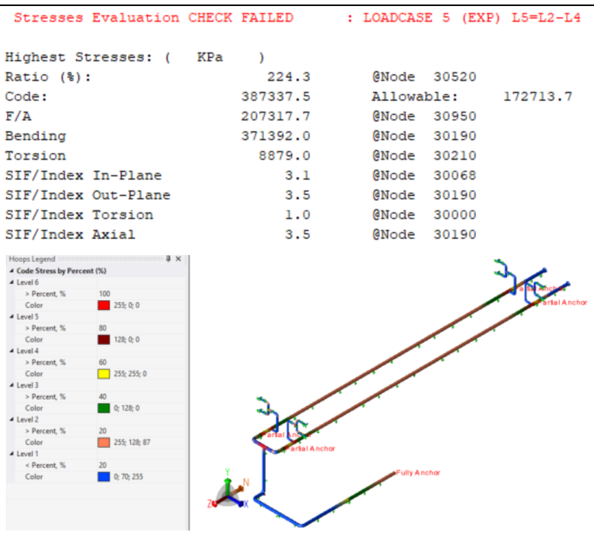
Flexible Stiffness (Case 2)



```
 Stresses Evaluation CHECK PASSED       : LOADCASE 5 (EXP) L5=L2-L4

Highest Stresses: (   KPa    )
Ratio (%):                        70.3      @Node  30190
Code:                         121499.0      Allowable:      172713.7
F/A                            36873.0      @Node  30650
Bending                       119855.0      @Node  30190
Torsion                         6176.4      @Node  30650
SIF/Index In-Plane                 3.1      @Node  30068
SIF/Index Out-Plane                3.5      @Node  30190
SIF/Index Torsion                  1.0      @Node  30000
SIF/Index Axial                    3.5      @Node  30190
```

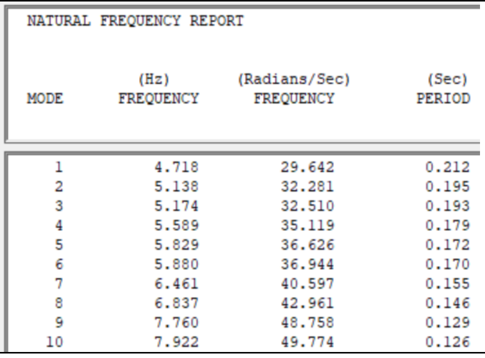
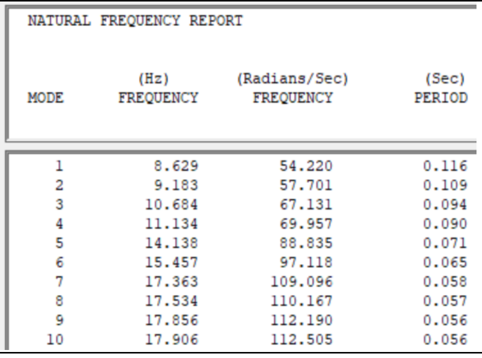
Rigid Stiffness (Case 1)



```
 Stresses Evaluation CHECK FAILED       : LOADCASE 5 (EXP) L5=L2-L4

Highest Stresses: (   KPa    )
Ratio (%):                       224.3      @Node  30520
Code:                         387337.5      Allowable:      172713.7
F/A                           207317.7      @Node  30950
Bending                       371392.0      @Node  30190
Torsion                         8879.0      @Node  30210
SIF/Index In-Plane                 3.1      @Node  30068
SIF/Index Out-Plane                3.5      @Node  30190
SIF/Index Torsion                  1.0      @Node  30000
SIF/Index Axial                    3.5      @Node  30190
```

TABLE IV. NATURAL FREQUENCY COMPARISON BETWEEN CASE 1 AND CASE 2

Flexible Stiffness (Case 2)	Rigid Stiffness (Case 1)
	

Flexible Stiffness (Case 2):

```
NATURAL  FREQUENCY  REPORT


                 (Hz)        (Radians/Sec)          (Sec)
MODE          FREQUENCY        FREQUENCY            PERIOD

     1          4.718           29.642               0.212
     2          5.138           32.281               0.195
     3          5.174           32.510               0.193
     4          5.589           35.119               0.179
     5          5.829           36.626               0.172
     6          5.880           36.944               0.170
     7          6.461           40.597               0.155
     8          6.837           42.961               0.146
     9          7.760           48.758               0.129
    10          7.922           49.774               0.126
```

Rigid Stiffness (Case 1):

```
NATURAL  FREQUENCY  REPORT


                 (Hz)        (Radians/Sec)          (Sec)
MODE          FREQUENCY        FREQUENCY            PERIOD

     1          8.629           54.220               0.116
     2          9.183           57.701               0.109
     3         10.684           67.131               0.094
     4         11.134           69.957               0.090
     5         14.138           88.835               0.071
     6         15.457           97.118               0.065
     7         17.363          109.096               0.058
     8         17.534          110.167               0.057
     9         17.856          112.190               0.056
    10         17.906          112.505               0.056
```

III. CONCLUSION

These observations suggest that considering flexibility stiffness in the design of the support system has a significant impact on both the restraint loads and structural behaviour. The flexible stiffness system not only requires lower restraint loads but also results in lower stresses, making it more compliant with code requirements. Additionally, the lower natural frequency in the flexible scenario might indicate a shift in dynamic behaviours. It also provides realistic support displacement and mechanical natural frequency to prevent resonance conditions and related failures.

CAESAR II Structural modeller helped to avoid the modification of steel structure and predict the natural frequency to avoid the resonance failure and reduced the cost of using specialized finite element analysis software to find the actual support stiffness with reduced man-hours.

REFERENCES

[1] Pipe Stress Engineering by Liang-Chuan (L.C.) Peng and Tsen-Loong (Alvin) Peng
[2] Design of Piping System by The M.W.Kellogg Company
[3] ASME B 31.3 – Process Piping
[4] API 618 – Reciprocating Compressors for Petroleum, Chemical, and Gas Industry Services
[5] CAESAR II User Manual.