Towards More Consistent Computer Analysis in Evaluating Sustained Stress in Operation Cases

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***Abstract*-- Sustained stress has been well known as one of the contributions or root causes of failures at the point of stress concentration along the piping system.**

The importance of evaluation of sustained stress in operating condition have been deliberated for nearly two decades in numerous papers and books but there are still uncertainties in understanding its philosophy. Due to the presence of various types of pipe stress software in the market with different approaches of analysis, engineers frequently overlook the most important elements associates to computer methodology in terms of software capability that need to be considered in the analysis for addressing sustained stress problems.

During operating conditions, piping system is subjected to combination of loading from weight, thermal expansion and any type of occasional load such as wind and earthquake. All of these loadings contribute stresses to the piping system. These stresses are divided into three main categories which are sustained, expansion and occasional. The evaluation of expansion and occasional stresses are mainly straight forward whereas sustained stresses need to be carefully evaluated against codes and standards.

Sustained stress is always referred as sustained loading that is imposed in vertical downwards direction. This loading is generated from the piping material weight associated with density of carry-over fluid/medium, pipe insulation, valves, flanges and all other pipe fittings. The problems arise when this vertical downwards force is not supported by sufficient pipe support. This phenomenon occurs when the pipe move in upward position during operating conditions. At this stage, pipe may lift off from it supports in which point of stress concentration will be created along the system that can lead to hot sustained stress issue.

This paper will demonstrate a methodology that can be applied to correctly evaluate the problems related to sustained stress in operating conditions using a pipe stress analysis software Caesar II, developed by COADE, now owned by Intergraph, Houston.

From the results of computer analysis, the behavior of the piping system related to sustained stresses can be observed and predicted correctly. A solution to the said problem will also be demonstrated in this technical paper for future reference.

***Index Term*— piping, sustained stress, CAESAR II, pipe failure**

I. Introduction

PETROLIAM NASIONAL BERHAD (PETRONAS) is well known as Malaysian's largest oil and Gas Company. The company owned a total of 198 producing fields and 355 offshore platforms and various onshore facilities worldwide[1].

There are various piping failure modes, which could affect a piping system. Piping failure modes could be excessive plastic deformation, plastic instability and brittle fracture. Each of these modes of failure is caused by a different kind of loading. Engineer shall design a piping system within stress limits in accordance with codes and standards.

According to ASME B31.3[2], the stresses to which a piping system is subjected may be separated in three main classes as follows[3] :

1) Sustained loads: Typical sustained loads are pressure and weight loads during normal operation[3].
2) Expansion loads: Loads due to displacement of piping such as thermal expansion, seismic anchor movement[3].
3) Occasional loads: These loads are present at infrequent interval during plant operation. Examples of occasional loads are earthquake, wind and relief valve discharge[3].

This article may lead to controversial discussions among engineers. However, the purpose of this article is mainly to provide some insight concerning the problems related to sustained stress from the many experiences gained in the past and present for references. It can also be used for future references if no other latest development of sustained stress is made in the near future.

Fig. 1 shows a flowchart that represents steps need to be considered in designing any piping system associated with hot sustained stress based on the results obtained from pipe stress analysis.

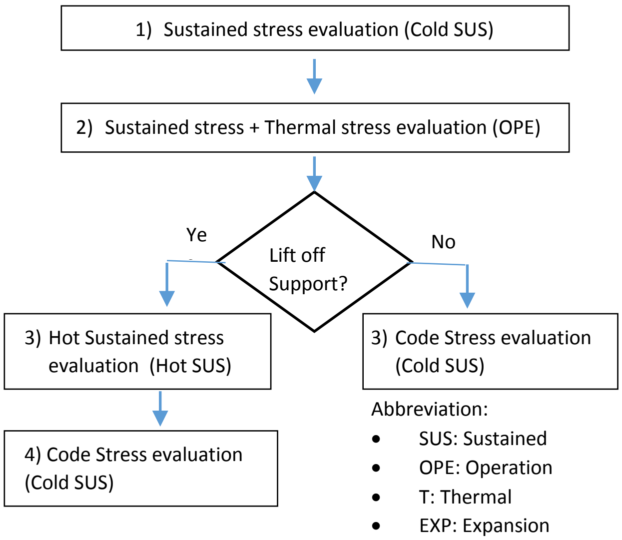

Fig. 1. Flow chart of piping system evaluation

From a series of PETRONAS database investigations conducted by PETRONAS Group Technical Solutions (GTS), it shows that the number of piping system failures within PETRONAS facilities had extremely increased particularly due to incorrect application of computerized pipe stress analysis methodology. Over the coming years, the piping system stresses may not be properly evaluated by the appointed contractors hence may lead to further increase in numbers of failure or damage of the piping system.

Analysis has been conducted for the reported cases within PETRONAS database and it was revealed that the most common caused for the piping system failures was associated with sustained stress evaluation problems. Several inquiries were made to various contractors with working experienced in PETRONAS facilities on the issues related to sustained stress analysis. . The results was quite surprising whereby some of them were not very clear on the basic principles of sustained stress evaluation in the piping system.

Therefore, it can be concluded that many engineers involves in the piping stress analysis may have overlooked that sustained stress is much more important than expansion stress[4] thus explained the problems encountered in PETRONAS facilities.

In order to minimise the errors made by PETRONAS contractors, GTS has developed lines categorization. The lines categorization is used to identify the criticality of each piping line number in the whole PETRONAS groupwide facilities. A series of selection of lines criteria have been developed based on references made to various code and standards as well as internal PETRONAS experiences in managing daily trouble shooting related to piping stress isues[7]. All piping line numbers that are classified under the most critical piping category shall be subjected to computerize analysis software.

II. Background Theory

Sustained stress evaluation for process piping system varies depending on the code and standards of application used. The most common approach for code and standards for process piping in PETRONAS facilities is ASME B31.3[2] which is utilized as a reference in evaluating the piping system stresses.

Sustained stress, S_L, is the sum of the longitudinal stresses in any component in a piping system, due to sustained loads as explained in ASME 31.3[2]. It is the combination of live weight and pressure of the system. The terms *live weight* described the dead weight of the pipe and every component attached to the piping system such as valve, flange and all types of fitting. This weight is also combined with the weight of gas or liquid contents in the piping system. It is important to emphasize the role of pressure in the sustained stress evaluation as some may not understand its role.

In order to transfer products from one point to another, the piping system needs to be pressurized. Some product generates thermal effects to the internal pipe wall and therefore creates expansion to the piping system. When the system is shut down, thermal stresses will gradually reduce until the system completely goes back to its original states at ambient temperature. Subject to no purging is required to the system after system shutdown, the operating pressure is also reduced but the system is still in pressurized mode. This condition of system stresses are considered as sustained and shall be evaluated based on equation 1. Another term used for this sustained case is "*cold sustain*"[5] as the stresses was obtained at ambient temperature or cold condition.

The system's stress evaluation for sustained stress shall satisfy Equation (1) where sustained stress, S_L shall not exceed basic allowable stress (S_h) limit of the materials at its maximum temperature expected during displacement cycle under analysis [2].

$$S_L \leq S_h \tag{1}$$

What would happen to system sustained stresses when the system is in operating temperature mode or hot conditions? There are not many references available when this question was pointed out by engineers. A very common problem related to sustained stress at operating condition is when the pipe lift off from pipe support during operation but sits on the support when the system is shutdown. Some of details explanation concerning this issue have been presented in Appendix S of ASME B31.3[2]. Other term frequently used for this scenario is "hot sustain"[5] as the stresses was obtained at operating temperature or hot conditions.

Another good example of application of sustained stress theory for the piping system has been explained by John. C. Luf in his article of "*sustained stresses*"[6]. Although the article explained explicitly about the sustained stress mechanism, he also specified some may not agree with the explanation. However, the article has provides some insight from different angle and can also be used as a reference in understanding the theory behind the word sustained stresses.

III. METHOD

A. Piping system example

Due to the proprietary items of the piping stress analysis studies made by PETRONAS contractor, the failure system could not be revealed for this paper. However, a new piping system as per Fig. 2 has been developed to illustrate the common problems exist in the piping system related to sustained stresses.

The pseudo process conditions of the system have been created as per Table I.

The project ambient temperature to be used in the analysis has been set at 21°C.

TABLE I
SYSTEM PROCESS CONDITIONS

Line Number	Design Temperature, °C	Design Pressure, barg
PL-10345-3C101	400	30
PL-10355-3C101	400	30

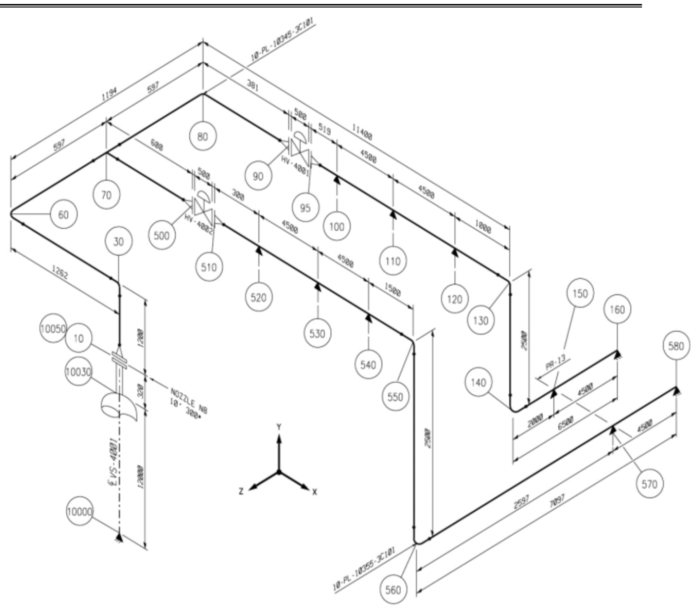

Fig. 2. Piping Stress Isometric

B. Material Properties and Simulation Parameters

The material properties used in the analysis for the piping system and pressure vessels are as per Table II and Table III respectively.

TABLE II
PIPING MATERIAL PROPERTIES

Specifications	Parameters
Pipe Size, inch	10
Pipe Schedule, mm	9.27
Insulation Thickness, mm	150
Insulation Density, kg/m^3	184.21
Fluid Density, kg/m^3	500
Corrosion Allowance, mm	3
Class Rating, lb	300
Material	API 5L Grade A Seamless

TABLE III
PRESSURE VESSEL PROPERTIES

Specifications	Parameters
Nozzle No,	N8
Nozzle Size, NPS	10
Nozzle Thickness, mm	12.5
Vessel OD, mm	2500
Skirt OD, mm	2500
Vessel Thickness, mm	15
Skirt Thickness, mm	10
Material	A516 Grade 70

The pressure vessel VS-4001 is made from carbon steel material, A516 Grade 70; Vessel and skirt outer diameter are 2500 mm; vessel thickness 15 mm; skirt thickness 10 mm; Nozzle N8 is NPS10; N8 thickness is 12.5 mm.

All other data properties of the materials are based on Caesar II version 2014 database system.

The system is operating below than 7000 cycles and therefore the factor f for allowable stress equation is set to 1.

C. System Definition

Based on Fig. 2, the piping system was connected to the top head nozzle N8 of pressure vessel VS-4001. Line number PL-10345 was the main product line whereas PL-10355 was used for product testing line. PL-10345 was installed with actuated control valve HV-4001 which was normally open whereas PL-10355 was installed with HV-4002 which was normally closed. Both control valves weighed at 5000 N including the weight of 300# rating flange connections. At certain conditions, both systems may be operating simultaneously depending on valve operation sequence. The two valves are located at the VS-4001 service platform which is attached to the pressure vessel. This platform is also supporting the two piping, PL-10345 and PL-10355 at node 100 and 520 respectively. The operation scenarios of the piping system can be easily read as per Table IV.

TABLE IV
SYSTEM OPERATIONS

Operation Scenario	Valve HV-4001 Open	Valve HV-4001 Close	Valve HV- 4002 Open	Valve HV- 4002 Close
Case 1	YES	-	-	YES
Case 2	-	YES	YES	-
Case 3	YES	-	YES	-

The node numbers (numbers in circle) have been used to identify the location of pipe supports, flanges and all pipe fittings such as elbow and tee connections. The details illustration of these node numbers are explained in Table V.

TABLE V
NODE NUMBERS IDENTIFICATION

Node Numbers	Identification
10000	Vessel anchor
10030	Nozzle neck
10, 10050	Nozzle flange
30, 60, 80, 130, 140, 550, 560	Pipe elbow
70	Pipe tee
90, 95, 500, 510	Valve flange
100, 110, 120, 150, 520, 530, 540, 570	Pipe support (simple resting)
160, 580	Pipe support (anchor)

The first two typical supports for nodes 100 and 520 were attached to the service platform. These two supports have upwards displacements of 53.221 mm in all three operation scenarios shown in table 3.0 due to thermal expansion of the pressure vessel during operation modes. The other two sets of typical supports which were present at node 110, 530 and 120, 540 were supported by independent beam.

All other supports were located on the pipe rack PR-13.

For analysis purposes, friction factor and wind impact were considered negligible.

D. Computer simulation parameters

Caesar II software has been selected as a primary software in PETRONAS to be used in all piping stress and vibration analysis as specified in PETRONAS Technical Standard (PTS)[7]. The software has been developed by COADE now INTERGRAPH, Houston.

The analysis has been using International Standards (SI) Units file name as PETRONAS.fil. The detailed unit file used in the program input is shown in Fig. 3.

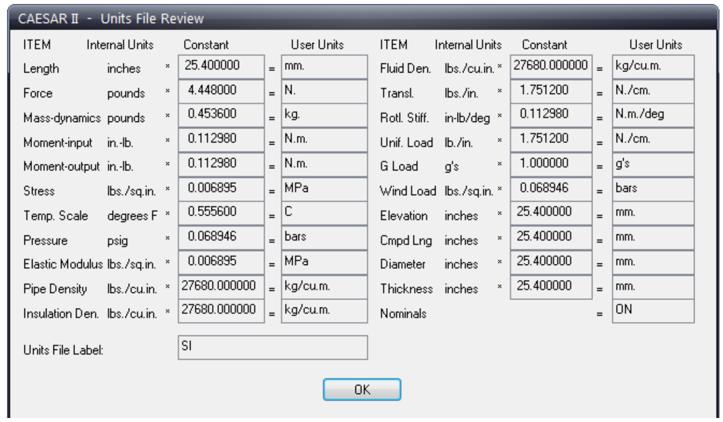

Fig. 3. Snapshot of Caesar II unit file

All other input program data used in the analysis are based on Caesar II database version 2014.

The Caesar II input spreadsheet is shown in Fig. 4. The details of input spreadsheet features are defined in Table VI

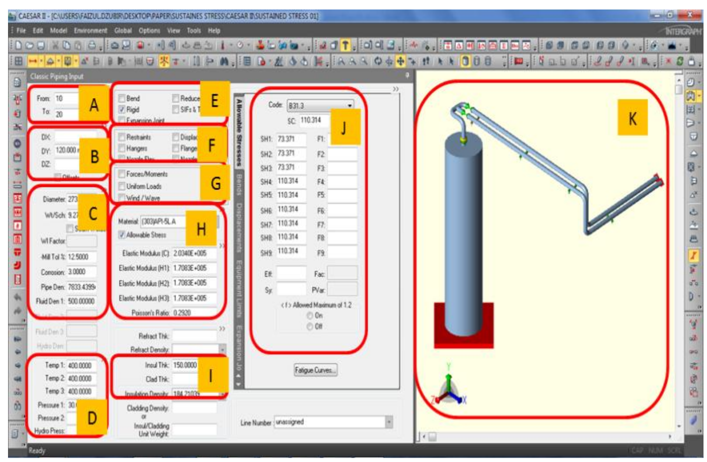

Fig. 4. Caesar II spreadsheet

TABLE VI
CAESAR II SPREADSHEET COLUMN DEFINITION

Item	Definition
A	Node number
B	Dimension
C	Piping and vessel parameters
D	Temperature and pressure
E	Pipe fittings
F	Pipe support types
G	Occasional loadings
H	Piping and vessel materials properties
I	Insulation properties
J	Selected industrial code for material allowable stresses
K	Input modelled

Caesar II has used simple abbreviation for load cases applied in every calculation. These load cases shall be developed right before any pipe stress analysis being executed. The abbreviation used in Caesar II load cases are defined in Table VII.

TABLE VII
CAESAR II SPREADSHEET DEFINITION

Item	Definition
W	Weight with fluid content
P1,…. Pn	Pressure case 1, …. n
T1,….. Tn	Temperature case 1, … n
D1,…. Dn	Displacement case 1, … n
H	Spring hanger
L1, …. Ln	Load Case 1 … n,

The complete load cases combination for operation sequence, sustain and thermal stresses have been developed as per Table VIII in accordance with ASME B31.3[2] codes and standards requirements. Table VIII load combination can be varies depending on methodology of analysis and the total operation cases being analyzed as explained in Table I.

TABLE VIII
CAESAR II LOAD COMBINATION

Load Case No.	Load Combination	Definition
L1	W + D1 + T1 + P1	Operation case 1
L2	W + P1	Cold Sustain Stress
L3	D1 + T1	Initial Displacement 1 and Thermal case 1
L4	L1 - L2	Thermal case 1
L5	L1 - L3	Hot Sustain Stress

From Table VIII, the most interesting load combination to be evaluated is Load Case no. 5 (L5) for hot sustained stresses.

A series of steps which consisted of Calculation 1, Calculation 2 and Calculation 3 were carried out to correctly analyze the hot sustained stress undergone by the pipe system. Each step is explained below and results in each calculation are demonstrated and discussed.

IV. RESULTS AND DISCUSSION

A. Calculation 1

CAESAR II with file name "sustain stress 01" was created to model the entire piping system as per Figure 1 using all parameters as defined in previous given data.

Standard input setup parameter for this file system was applied with no thermal bowing impact; no hydrostatic test pressure involved; and no bourdon effect was considered.

The load combinations considered in the analysis are shown in Table IX.

TABLE IX
CAESAR II FILE "SUSTAIN STRESS 01" LOAD COMBINATION AND CASES

Load Case No.	Load Combination	Definition
L1	W + D1 + T1 + P1	Operation case 1
L2	W + D2 + T2 + P1	Operation case 2
L3	W + D3 + T3 + P1	Operation case 3
L4	W + P1	Cold Sustain Stress
L5	L1 – L4	Thermal stress case 1
L6	L2 – L4	Thermal stress case 2
L7	L3 – L4	Thermal stress case 3

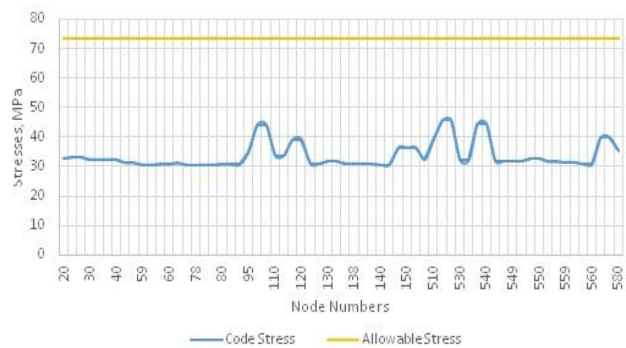

Fig. 5. Stress profile against Node Number for Case No L4 (Cold Sustained Stress) (from Sustain Stress 01 Output File)

From the analysis results, the designer is always looking at the percentage of stresses versus allowable for L4, L5, L6 and L7 at each node number given in Fig. 2 based on the load cases defined in Table IX.

The designer may notice that load case L4 for sustain code stress is in compliance to allowable stress limit as defined in ASME B31.3[2] as per Fig. 5. The designer were then decided that no further evaluation of stresses are needed. The calculations were then presented and full report submitted to PETRONAS.

However, upon reviewing Load case 1 to Load case 3 of the design, it was noticed that several locations of pipe supports do not support the pipe as shown in Table X. This makes the pipe support not active or not taking any pipe loadings under operating conditions.

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TABLE X
PIPE SUPPORT ACTIVE AND INACTIVE

Load Case No.	Load Combination	Node Numbers	
		Pipe Support Active	Pipe Support Inactive
L1	W + D1 + T1 + P1	100, 150, 520, 570	110, 120, 530, 540
L2	W + D2 + T2 + P1	100, 150, 520, 570	110, 120, 530
L3	W + D3 + T3 + P1	100, 150, 570, 570	110, 520, 530, 540

Based on information provided in the introduction of this paper, this phenomenon shall not be neglected even the stresses of the piping system in Load Case 4 as shown in Fig.5 are below the allowable limits.

The designer should also evaluate the sustained stress conditions during operating conditions which is called "hot sustained". The computer analysis does not recognize this condition and therefore, the designer should instruct the computer to perform this calculation, which was achieved by the following calculation 2 and calculation 3.

B. *Calculation 2*

CAESAR II with file name "sustain stress 02" was created which was actually based on "sustain stress 01" CAESAR II model. In this case, few new load cases have been introduced in the calculation as per Table XI.

TABLE XI
CAESAR II FILE "SUSTAIN STRESS 02" LOAD COMBINATION AND CASES

Load Case No.	Load Combination	Definition
L1	W + D1 + T1 + P1	Operation case 1
L2	W + D2 + T2 + P1	Operation case 2
L3	W + D3 + T3 + P1	Operation case 3
L4	W + P1	Cold Sustain Stress
L5	D1+T1	Thermal case 1 (NEW)
L6	D2+T2	Thermal case 2 (NEW)
L7	D3+T3	Thermal case 3 (NEW)
L8	L1 – L4	Thermal stress case 1
L9	L2 – L4	Thermal stress case 2
L10	L3 – L4	Thermal stress case 3
L11	L1 - L5	Hot sustain stress 1 (NEW)
L12	L2 – L6	Hot sustain stress 2 (NEW)
L13	L3 – L7	Hot sustain stress 3 (NEW)

Load cases for L5, L6 and L7 have been introduced for thermal load case for cases 1, 2 and 3. These thermal load cases are not to be used for code stresses evaluation. It has been developed primarily to be subtracted with load cases L1, L2 and L3. Load case L8, L9 and L10 are the hot sustain stresses that need to be evaluated against load case L4.

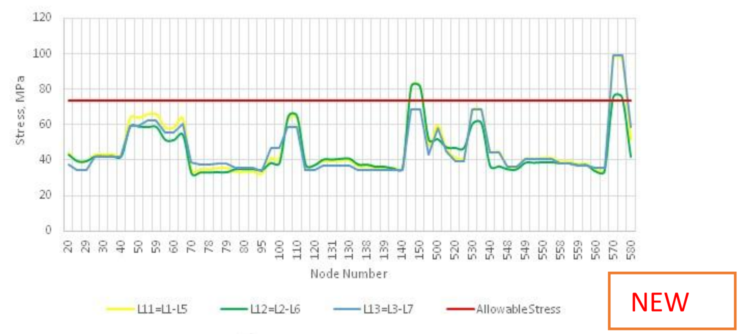

Fig. 6. Stress profile against Node Number (from Sustain Stress 02 output file)

Based on the results obtained as per Fig. 6, the piping system is actually is not in compliance to appendix S of ASME B31.3[2] code requirements. All hot sustained load cases of L11, L12 and L13 exceeded the limitation of allowable stresses of the material.

Looking at the load combination definition, it seems that all L5, L6 and L7 load cases will give the same results as per load case L4. However, the evaluation of load case L4 and L5, L6 and L7 are practically not the same. L4 would only consider that the system is perfectly supported whereas the load cases L5, L6 and L7 do not.

In load cases L5, L6 and L7, all pipe supports that are not supporting the pipe will automatically not be included in the stress evaluation for hot sustain. All weight stresses due to the forces in downwards direction will be distributed along the piping system. The most vulnerable positions of piping system will experience high stresses.

Several node numbers have exceeded the allowable stress limitation as per Fig. 6. These results are quite surprising as none of all three cases of L5, L6 and L7 give the same results. Furthermore, none of these three cases sharing the same results as per L4 in Fig. 5.

With these results, it seems that the stresses for load cases L4, L5, L6 and L7 are not consistent. A solution needs to be provided and new Caesar II file need to be opened.

C. *Calculation 3*

Caesar II Input file name "sustain stress 03" has been created mainly to provide solutions to the problems encountered for the previous two Caesar II files. Since the main findings to the problems of the previous files are related to sustain stresses, thus the system need some pipe supports which can hold the sustain forces that is acting in downwards direction.

The most suitable pipe support mechanism to hold such forces is variable spring support. The selection of spring support is basically based on problems related to weight issue that contribute to high stresses to the system in sustain cases. The terms variable for the spring support is because the spring is capable of holding various numbers of loadings depending on the pipe vertical movement.

When the piping system lift off from its supporting structure, any downwards forces particularly due to the weight issue will be absorbed by the spring support. In this case, the suitable position for the spring support to be provided are at node 110, 120, 530 and 540 that have been identified as lift off position on common supporting structure in Table X.

For this new Caesar II file, a spring support database from Carpenter & Paterson[8] spring manufacturer catalogue has been used in the analysis. The details of the spring support selection are described in Table XII.

TABLE XII
CAESAR II SPRING SELECTION

Node number	Spring Preset Load (N)	Spring Rate (N/mm)
110	3500	13.1
120	8200	29.8
530	3500	13.1
540	8200	29.8

The previous Caesar II files for load combination were not provided with spring support function. Therefore, the load combination shall be modified as per Table XIII. The symbol "H" represents spring support in Caesar II terminology.

TABLE XIII
CAESAR II LOAD COMBINATION

Load Case No.	Load Combination	Definition
L1	W + D1 + T1 + P1 + H	Operation case 1 (NEW)
L2	W + D2 + T2 + P1 + H	Operation case 2 (NEW)
L3	W + D3 + T3 + P1 + H	Operation case 3 (NEW)
L4	W + P1 + H	Cold Sustain Stress (NEW)
L5	D1+T1	Thermal case 1
L6	D1+T2	Thermal case 2
L7	D1+T3	Thermal case 3
L8	L1 – L4	Thermal stress case 1
L9	L2 – L4	Thermal stress case 2
L10	L3 – L4	Thermal stress case 3
L11	L1 - L5	Hot sustain stress 1
L12	L2 – L6	Hot sustain stress 2
L13	L3 – L7	Hot sustain stress 3

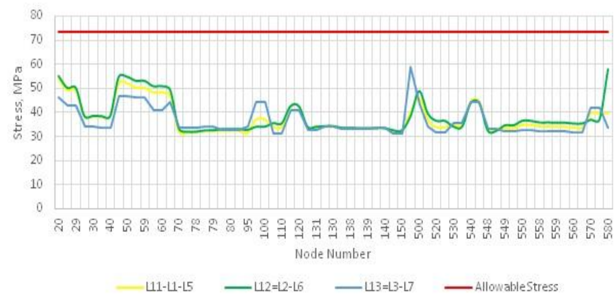

Fig. 7. Stress profile against Node Number (from Sustain Stress 03 output file)

Based on the results obtained in Fig. 7, all stresses for load case L11, L12 and L13 are below than allowable limit of the materials. With these conditions, the piping stress evaluation to the whole piping system design is now completed. The system is now ready to be sent for detailed engineering phase.

V. CONCLUSIONS

There are several steps that need to be followed by the respective stress engineers in order to obtain definitive sustained stress results for a complete piping system. The "cold sustain" [5] and "hot sustain" [5] shall be evaluated thoroughly when using any computer software.

Other computer analysis software may have different approaches in order to obtain the required sustained stresses. Therefore, the stress engineers must equip themselves with the required levels of knowledge and skill related to the selected computer software application.

Caesar II software has been developed with automatic load cases built-in before the full piping system input is analyzed. With good knowledge and skills to navigate the software, accurate results can be achieved by applying and using the correct techniques and load cases selection.

This paper has demonstrated only one example that can be applied using Caesar II software application to solve any sustain stress related issue. However, there are other methods also available for engineers to investigate before instruction can be given to Caesar II for analysis.

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