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FLEXIBILITY STUDY OF A PIPELINE SYSTEM IN FIBER-REINFORCED POLYMER

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ABSTRACT

This study evaluates the flexibility of a fiber-reinforced polymer (FRP) pipeline system, focusing on its ability to withstand various loads and stresses while maintaining structural integrity. Key aspects include analyzing FRP material properties, assessing pipe geometry, evaluating external and internal loads, and performing a flexibility analysis using CAESAR II software. The initial findings indicated that the stress levels exceeded permissible limits, necessitating adjustments in support positions and types. These adjustments successfully reduced stress levels to acceptable thresholds, ensuring reliable system performance. This study highlights the importance of meticulous design and continuous optimization to guarantee the safety and durability of FRP pipeline installations.

Keywords**:** flexibility study, piping system, FRP (fiber-reinforced polymer), CAESAR-II software

INTRODUCTION

Exploring the flexibility of fiber-reinforced polymer pipelines, combined with the CEASAR II analytical tool, opens the way to optimizing industrial infrastructures. This study examines the system's ability to adapt to mechanical stress, using CEASAR II's advanced functions to model and evaluate these responses. By examining this synergy between composite materials and analytical software, this introduction highlights the importance of this integrated approach in ensuring the flexibility required in a constantly changing industrial environment.

CEASAR II software can be used to determine the cause of failure or to assess the severity of unexpected operating conditions, such as water hammer on the pipe, mechanical interactions or vibrations caused by rotating equipment. [1],[2],[3].

SOFTWARE INTERFACE

The CEASAR II interface provides an intuitive and efficient user experience for piping engineers and designers (fig. 1 and fig. 2).

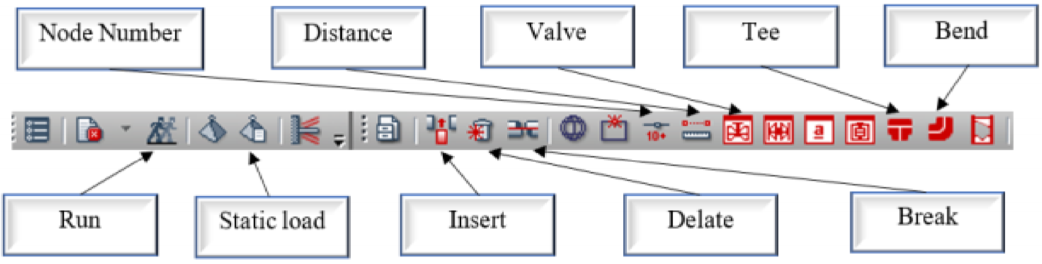
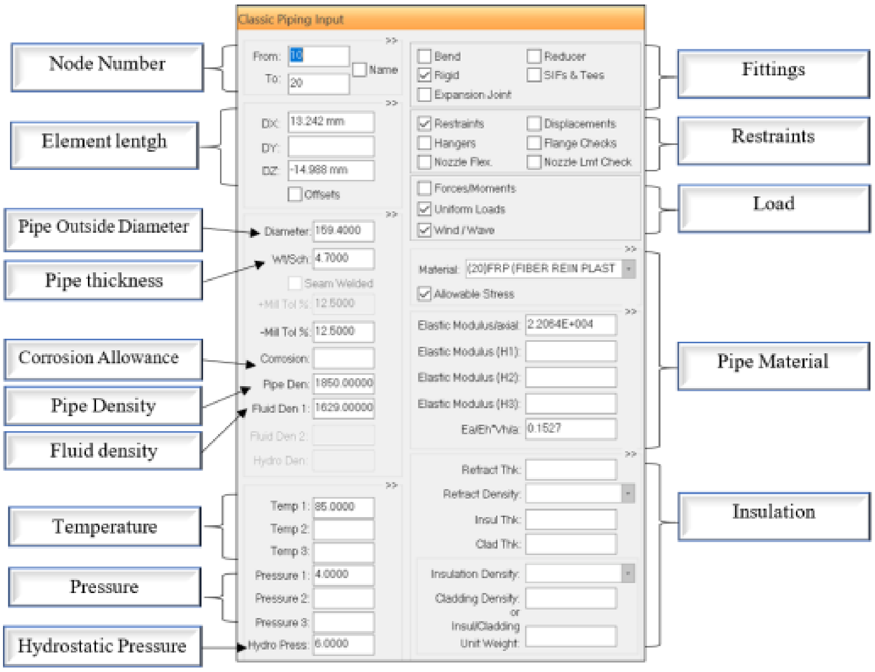


***Fig.1**. CAESAR II software control bar*



From: 10
To: 20
☐ Name
DX: 13.242 mm
DY:
DZ: -14.988 mm
☐ Offsets
Diameter: 159.4000
Wt/Sch: 4.7000
☐ Seam Welded
+Mill Tol %: 12.5000
-Mill Tol %: 12.5000
Corrosion:
Pipe Den: 1850.00000
Fluid Den 1: 1629.00000
Fluid Den 2:
Hydro Den:
Temp 1: 85.0000
Temp 2:
Temp 3:
Pressure 1: 4.0000
Pressure 2:
Pressure 3:
Hydro Press: 6.0000

☐ Bend ☐ Reducer
☑ Rigid ☐ SIFs & Tees
☐ Expansion Joint
☑ Restraints ☐ Displacements
☐ Hangers ☐ Flange Checks
☐ Nozzle Flex ☐ Nozzle Lmt Check
☐ Forces/Moments
☑ Uniform Loads
☑ Wind / Wave
Material: (20)FRP (FIBER REIN PLAST
☑ Allowable Stress
Elastic Modulus/axial: 2.2064E+004
Elastic Modulus (H1):
Elastic Modulus (H2):
Elastic Modulus (H3):
Ea/Eh*Vh/a: 0.1527
Refract Thk:
Refract Density:
Insul Thk:
Clad Thk:
Insulation Density:
Cladding Density:
or
Insul/Cladding Unit Weight:

***Fig.2**. Data entry interface of the software*

STRESS ANALYSIS OF THE MODEL BY CAESAR II

This project involves a seawater treatment plant (fig. 3) with hot and cold lines of different diameters, six pumps (four on small diameter lines and two on large diameter lines), two large filters, and heat exchangers. The inputs such as wind factor, uniform loads, fluid density, temperature, and pressure remain unchanged, despite the use of FRP material [8].

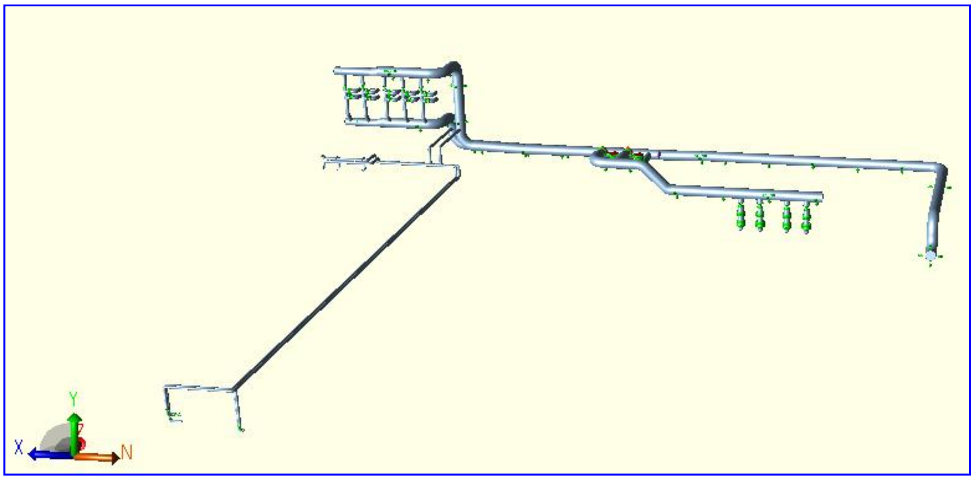


Fig.3. *Model sea water treatment line*

DESIGN AND RESULTS

The following entries in the Table 1 are mandatory for performing the stress analysis of an FRP piping system [1]:

Table 1. *Model data in FRP*

Temperature (T1)	65 °C
Pressure (P1)	10 bar
Hydrostatic pressure test	15 bar
Fluid density	1050 kg/m³
Pipe density	1660.8 kg/m³
Corrosion	0
Ea/Eh*Vh/a	0.58
Uniform weight	0.3870

With:

- ***Ea (Axial Elastic Modulus)***: This is the elastic modulus in the longitudinal or axial direction of the composite material.

- ***Eh (Hoop Elastic Modulus)***: This is the elastic modulus in the circumferential or hoop direction of the composite material.

- ***Vh (Hoop Fiber Volume Fraction)***: represents the proportion of fibers oriented in the circumferential direction relative to the total volume of the composite material.

- ***a (Geometric Parameter)***: This parameter can represent a specific dimension of the system, such as the radius or another characteristic length of the pipe.

- ***Ea/Eh*Vh/a*** is valuable for:

- Designing FRP Structures: Engineers can use it to optimize the material properties for specific applications, ensuring the right balance of stiffness and strength in both axial and hoop directions.

- Predicting Material Behavior: It helps predict how the material will behave under various load conditions, facilitating better design and material selection.
- Ensuring Safety and Durability: By understanding the directional stiffness and fiber distribution, engineers can design more reliable and durable FRP structures that meet safety standards.

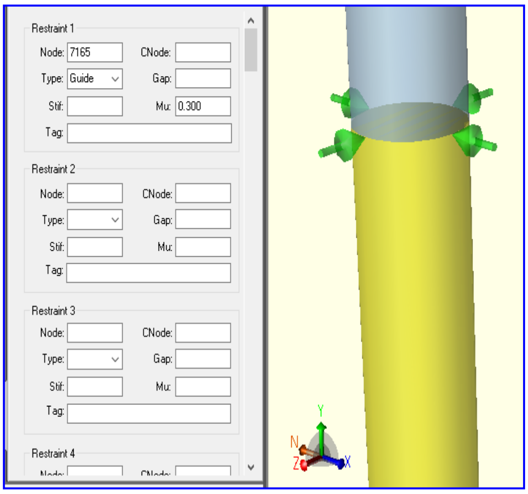
In summary, this composite formula provides a comprehensive evaluation of FRP material performance, incorporating crucial aspects of stiffness, fiber volume fraction, and geometric considerations. In Table 2 are presented different diameters of the FRP model.

***Table 2**. Different diameters of the FRP model*

Nominal Diameter (DN)	1200	900	700	600	300
Outer Diameter (OD)	1224 mm	920 mm	718 mm	616 mm	310 mm
Wall thickness	12.1 in	9.9 in	7.7 in	6.6 in	3.3 in

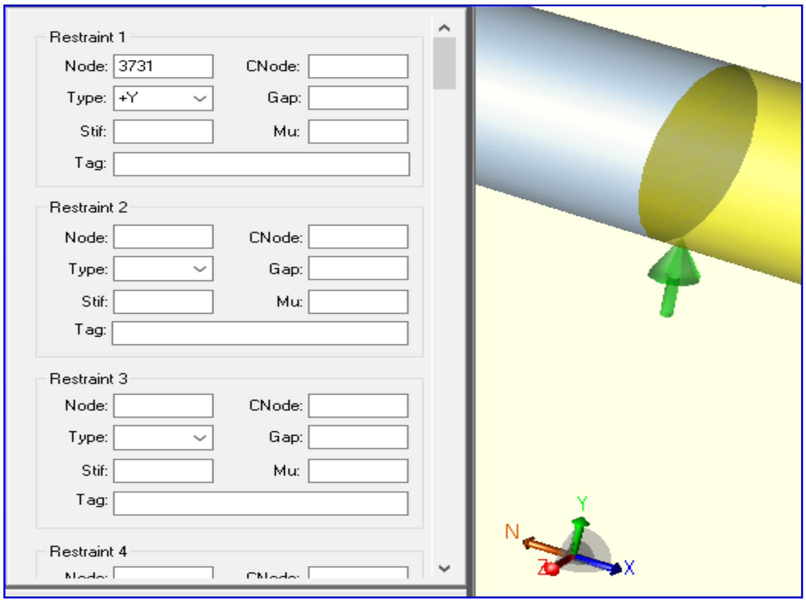
Above all, the model is created on AutoCAD plant 3D, it is converted into PCF and then imported and used in CAESAR II. On the latter, we have carried out the following steps on it:

- Check that all the nodes are connected to each other, i.e., that the model is continuous and does not present any discontinuities that hinder the calculation of the stress.
- Check the geometry of the model (thicknesses, diameters, corrosion allowances, and insulation thickness).
- Fill in design data such as temperature, pressure and hydrostatic vapor pressure, material density, insulation, and wind data
- Model the supports with Single Support (Y+), Guide Support (GUI) or Fixed/Anchor (ANC) weight supports (fig. 4, fig. 5 and fig. 6)
- Verify material and pipe properties according to customer specifications [1],[4]



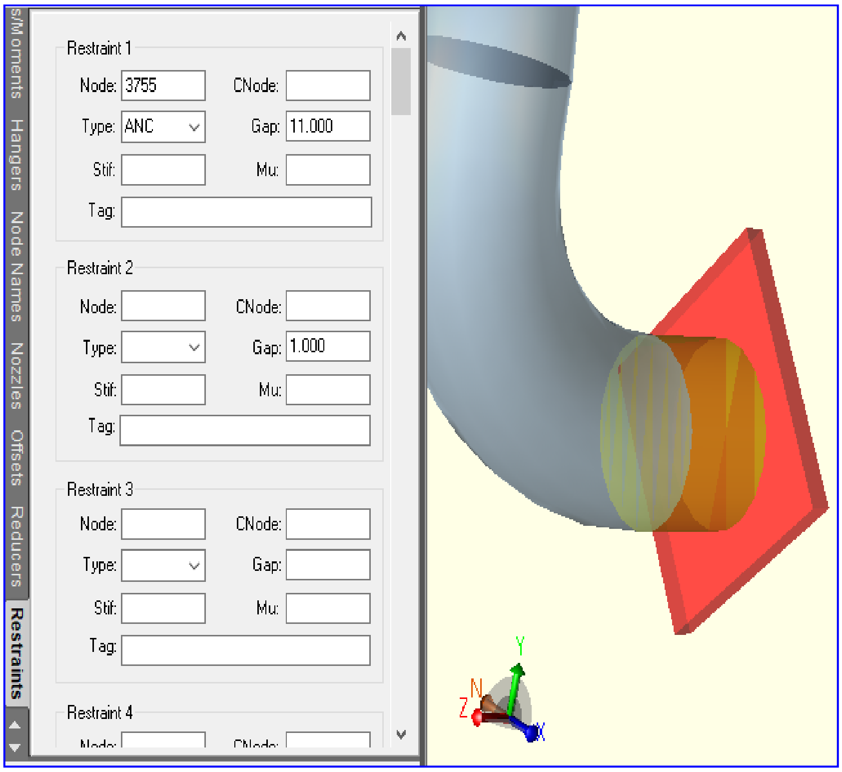
Restraint 1
Node: 7165
Type: Guide
Mu: 0.300

***Fig.4**. Support guide (GUI)*



Restraint 1
Node: 3731
Type: +Y

***Fig.5**. Single support (Y+)*

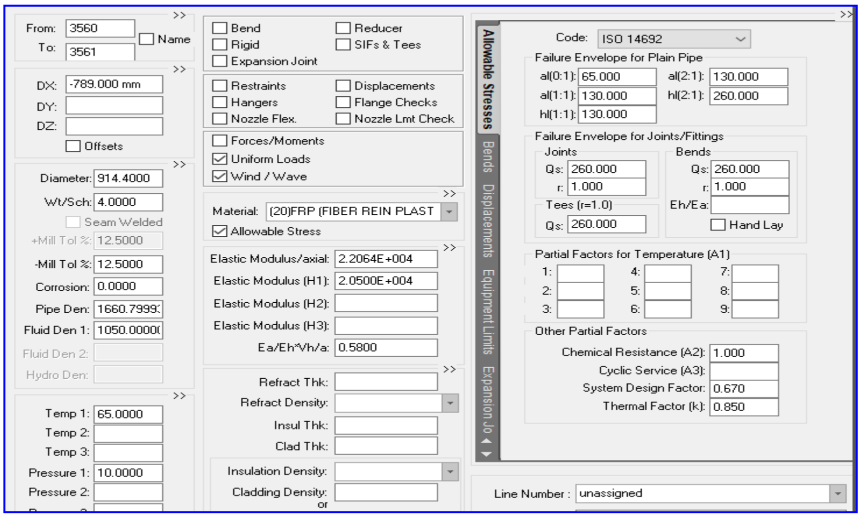


Restraint 1
Node: 3755
Type: ANC
Gap: 11.000

Restraint 2
Gap: 1.000

***Fig.6**. Anchor support*

Now we make sure to enter all the necessary data in the following boxes as is shown in the figure 7.



From: 3560
To: 3561
☐ Name
DX: -789.000 mm
DY:
DZ:
☐ Offsets
Diameter: 914.4000
Wt/Sch: 4.0000
☐ Seam Welded
+Mill Tol %: 12.5000
-Mill Tol %: 12.5000
Corrosion: 0.0000
Pipe Den: 1660.7999
Fluid Den 1: 1050.0000
Fluid Den 2:
Hydro Den:
Temp 1: 65.0000
Temp 2:
Temp 3:
Pressure 1: 10.0000
Pressure 2:

☐ Bend ☐ Reducer
☐ Rigid ☐ SIFs & Tees
☐ Expansion Joint
☐ Restraints ☐ Displacements
☐ Hangers ☐ Flange Checks
☐ Nozzle Flex. ☐ Nozzle Lmt Check
☐ Forces/Moments
☑ Uniform Loads
☑ Wind / Wave
Material: (20)FRP (FIBER REIN PLAST
☑ Allowable Stress
Elastic Modulus/axial: 2.2064E+004
Elastic Modulus (H1): 2.0500E+004
Elastic Modulus (H2):
Elastic Modulus (H3):
Ea/Eh*Vh/a: 0.5800
Refract Thk:
Refract Density:
Insul Thk:
Clad Thk:
Insulation Density:
Cladding Density:

Code: ISO 14692
Failure Envelope for Plain Pipe
al(0:1): 65.000 al(2:1): 130.000
al(1:1): 130.000 hl(2:1): 260.000
hl(1:1): 130.000
Failure Envelope for Joints/Fittings
Joints
Qs: 260.000
r: 1.000
Tees (r=1.0)
Qs: 260.000
Bends
Qs: 260.000
r: 1.000
Eh/Ea:
☐ Hand Lay
Partial Factors for Temperature (A1)
1: 2: 3: 4: 5: 6: 7: 8: 9:
Other Partial Factors
Chemical Resistance (A2): 1.000
Cyclic Service (A3):
System Design Factor: 0.670
Thermal Factor (k): 0.850
Line Number : unassigned

***Fig.7**. Data entry interface*

Determination of the failure envelope and the long-term design envelope is illustrated in figure 8.

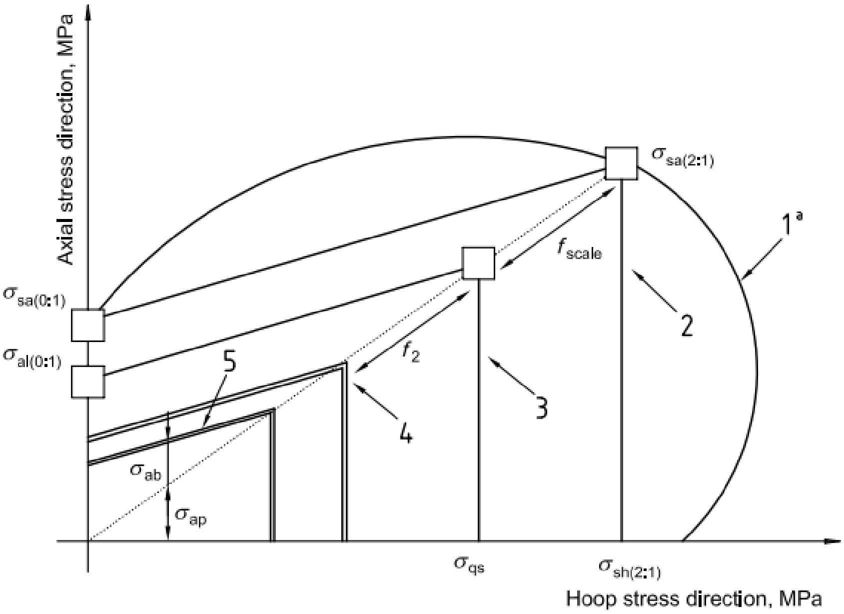


***Fig.8**. Envelope of failure* [6]

With:

1- schematic representation of the short-term failure envelope;

2- idealized short term envelope;

3- idealized long term envelope;

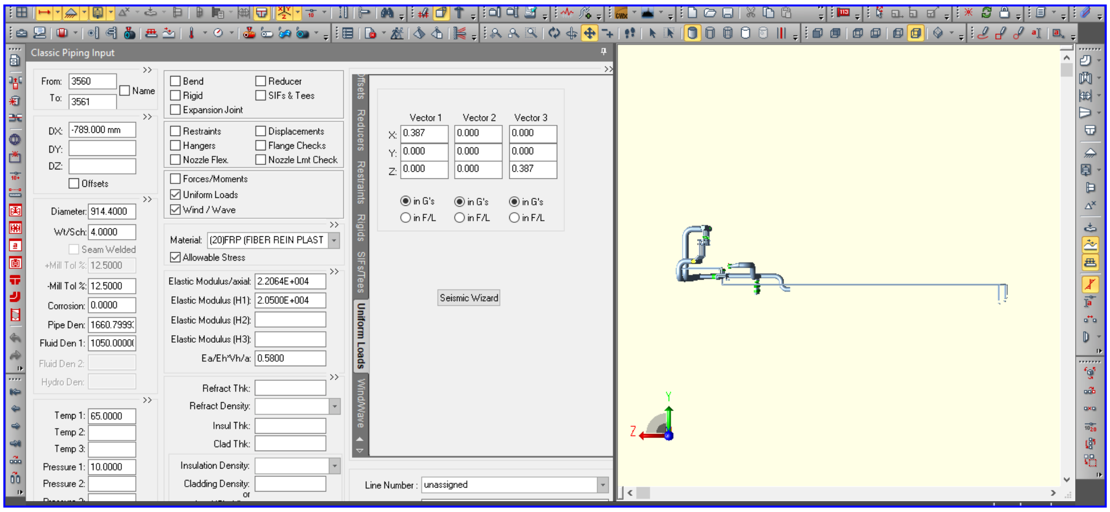
4- non-factored long-term design envelope;

5- long term design envelope.

Seismic load identification

Here and there, the seismic load is indicated by the following section (fig. 9):

- Vector 1 in *X*
- Vector 3 in *Z*



From: 3560
To: 3561
☐ Name
DX: -789.000 mm
DY:
DZ:
☐ Offsets
Diameter: 914.4000
Wt/Sch: 4.0000
☐ Seam Welded
+Mill Tol %: 12.5000
-Mill Tol %: 12.5000
Corrosion: 0.0000
Pipe Den: 1660.7999
Fluid Den 1: 1050.0000
Fluid Den 2:
Hydro Den:
Temp 1: 65.0000
Temp 2:
Temp 3:
Pressure 1: 10.0000
Pressure 2:

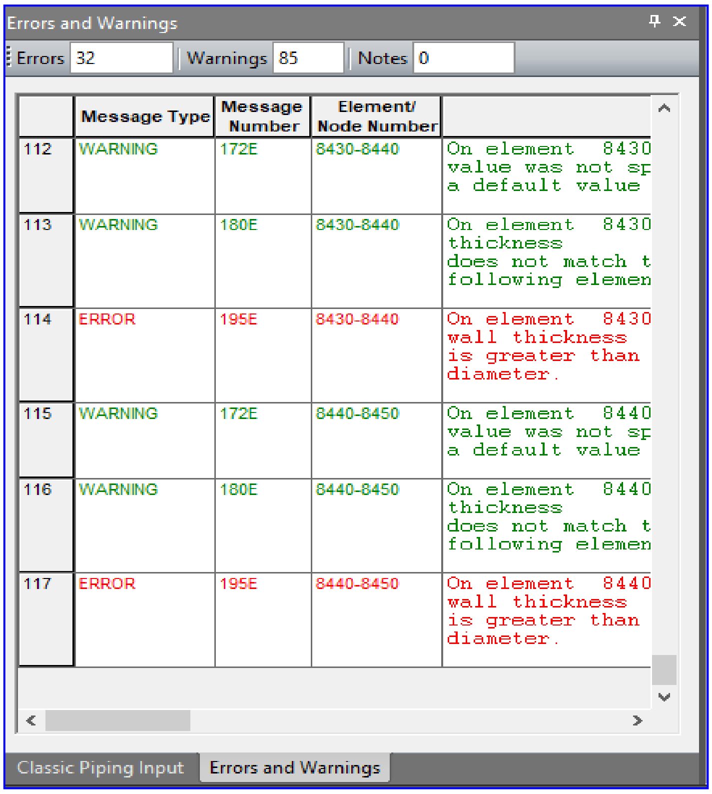
☐ Bend ☐ Reducer
☐ Rigid ☐ SIFs & Tees
☐ Expansion Joint
☐ Restraints ☐ Displacements
☐ Hangers ☐ Flange Checks
☐ Nozzle Flex. ☐ Nozzle Lmt Check
☐ Forces/Moments
☑ Uniform Loads
☑ Wind / Wave
Material: (20)FRP (FIBER REIN PLAST
☑ Allowable Stress
Elastic Modulus/axial: 2.2064E+004
Elastic Modulus (H1): 2.0500E+004
Elastic Modulus (H2):
Elastic Modulus (H3):
Ea/Eh*Vh/a: 0.5800
Refract Thk:
Refract Density:
Insul Thk:
Clad Thk:
Insulation Density:
Cladding Density:

	Vector 1	Vector 2	Vector 3
X:	0.387	0.000	0.000
Y:	0.000	0.000	0.000
Z:	0.000	0.000	0.387
	● in G's	● in G's	● in G's
	○ in F/L	○ in F/L	○ in F/L

Line Number : unassigned

Fig.9*. Calculation sheet for uniform load in CAESAR II*

Once all the necessary entries have been made, the error checking phase can begin, with the aim of ensuring that there are no warnings to correct and to modify (fig. 10).



Errors 32 Warnings 85 Notes 0

	Message Type	Message Number	Element/ Node Number	
112	WARNING	172E	8430-8440	On element 8430 value was not sp a default value
113	WARNING	180E	8430-8440	On element 8430 thickness does not match t following elemen
114	ERROR	195E	8430-8440	On element 8430 wall thickness is greater than diameter.
115	WARNING	172E	8440-8450	On element 8440 value was not sp a default value
116	WARNING	180E	8440-8450	On element 8440 thickness does not match t following elemen
117	ERROR	195E	8440-8450	On element 8440 wall thickness is greater than diameter.

Fig.10*. List of error checking tables (with errors and warnings)*

After thorough error checking, the static load cases were specified. The following lists the available loads and constraint types, including the individual load cases and their combinations [9]:

- Available loads that are defined in the input.
- Available constraint types.

Particularly, the following list refers to the names of the individual load cases and their names:

- W= Weight
- T1= Design Temperature (maximum temperature)
- P1= Design pressure (maximum pressure)
- HP= Hydrostatic test.
- WW= Water weight.

The different basic load cases types that are the following:

- (HYD) Hydrostatic test
- (OPE) Operational stress
- (SUS) Sustained load case
- (EXP) Extensional load case
- (OCC) Occasional load case

The following list in the table 3 shows the range of individual load combinations:

***Table 3**. Load cases for the FRP model* [1]

Case numbers	**Types of combinations**	**Types of stresses**
L1	WW+HP	HYD
L2	W+T1+P1	OPE
L3	W+P1	SUS
L4	W+T1+P1+WIN1	OPE
L5	W+T1+P1+WIN2	OPE
L6	W+T1+P1+WIN3	OPE
L7	W+T1+P1+WIN4	EXP
L8	W+T1+P1+U1	OPE
L9	W+T1+P1+U3	OPE

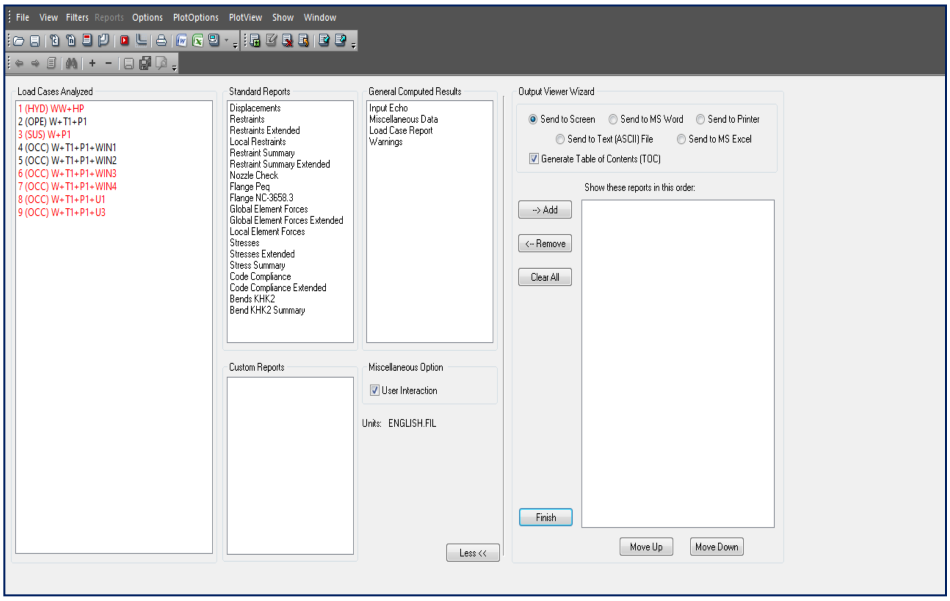
In the static load analysis, wind loads were identified as follows [10]:

- WIN1 = wind load case 1 direction X= 1.000
- WIN2 = wind load case 2 direction X= -1.000
- WIN3 = wind load case 3 direction Z= 1.000
- WIN4 = wind load case 4 direction Z= -1.000

Output

In order to extract the data from the software, the following steps are important:

a) Batch execution: error checking and job analysis (fig. 11)



Load Cases Analyzed
1 (HYD) WW+HP
2 (OPE) W+T1+P1
3 (SUS) W+P1
4 (OCC) W+T1+P1+WIN1
5 (OCC) W+T1+P1+WIN2
6 (OCC) W+T1+P1+WIN3
7 (OCC) W+T1+P1+WIN4
8 (OCC) W+T1+P1+U1
9 (OCC) W+T1+P1+U3

Standard Reports
Displacements
Restraints
Restraints Extended
Local Restraints
Restraint Summary
Restraint Summary Extended
Nozzle Check
Flange Peq
Flange NC-3658.3
Global Element Forces
Global Element Forces Extended
Local Element Forces
Stresses
Stresses Extended
Stress Summary
Code Compliance
Code Compliance Extended
Bends KHK2
Bend KHK2 Summary

General Computed Results
Input Echo
Miscellaneous Data
Load Case Report
Warnings

Custom Reports

Miscellaneous Option
☑ User Interaction

Units: ENGLISH.FIL

Output Viewer Wizard
● Send to Screen ○ Send to MS Word ○ Send to Printer
○ Send to Text (ASCII) File ○ Send to MS Excel
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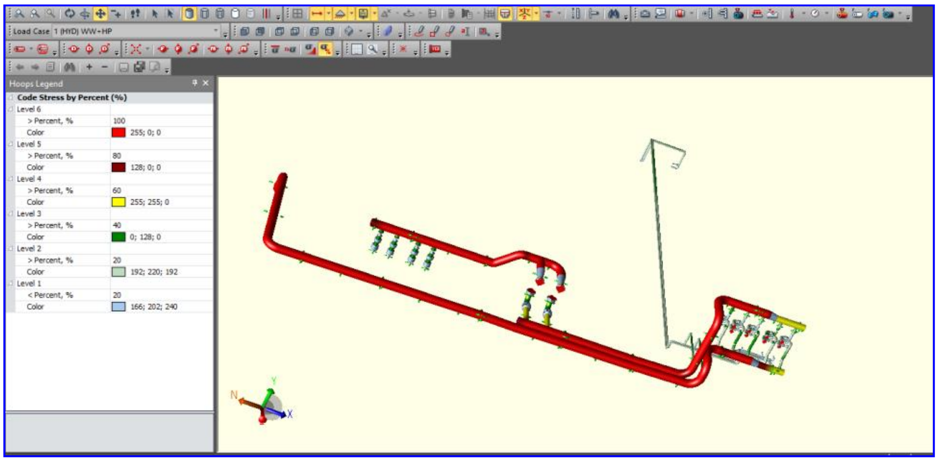
***Fig.11**. CAESAR II spreadsheet for static output*

b) 3D plot: stress color by percentage for each load case (must be less than 80%) as is shown in figure 12



Load Case 1 (HYD) WW+HP

Hoops Legend

Code Stress by Percent (%)	
Level 6	
> Percent, %	100
Color	🟥 255; 0; 0
Level 5	
> Percent, %	80
Color	🟥 128; 0; 0
Level 4	
> Percent, %	60
Color	🟨 255; 255; 0
Level 3	
> Percent, %	40
Color	🟩 0; 128; 0
Level 2	
> Percent, %	20
Color	🟩 192; 220; 192
Level 1	
< Percent, %	20
Color	🟦 166; 202; 240

***Fig.12**. CAESAR II stress greater than 80%*

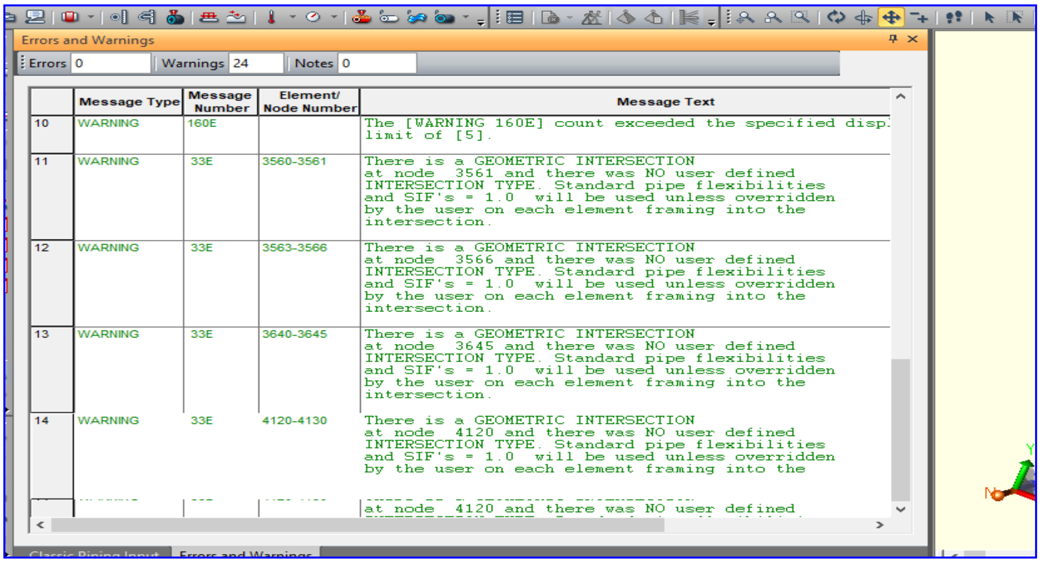
Initial stress levels exceeded allowable limits. Adjustments to the support positions and types reduced these stresses. In Table 4 are presented allowable and maximum values of stress for sea water treatment line in the high stress conditions.

***Table 4**. Stress for sea water treatment line with high stress*

LOADCASE	***Allowable Stress (N/mm^2)***	***Max Stress (N/mm^2)***	***Ratio (%)***	***Piping code***
L1 (HYD) WW + HP	1789.7	36373.9	200.9	ISO 14692
L2 (OPE) W+T1+P1	15651.5	28714.3	167.7	ISO 14692
L3 (SUS) W+P1	12632.3	24474.1	177.5	ISO 14692
L4(OCC)W+T1+P1+Win1	16801.0	28714.3	156.2	ISO 14692

Adjusted outputs

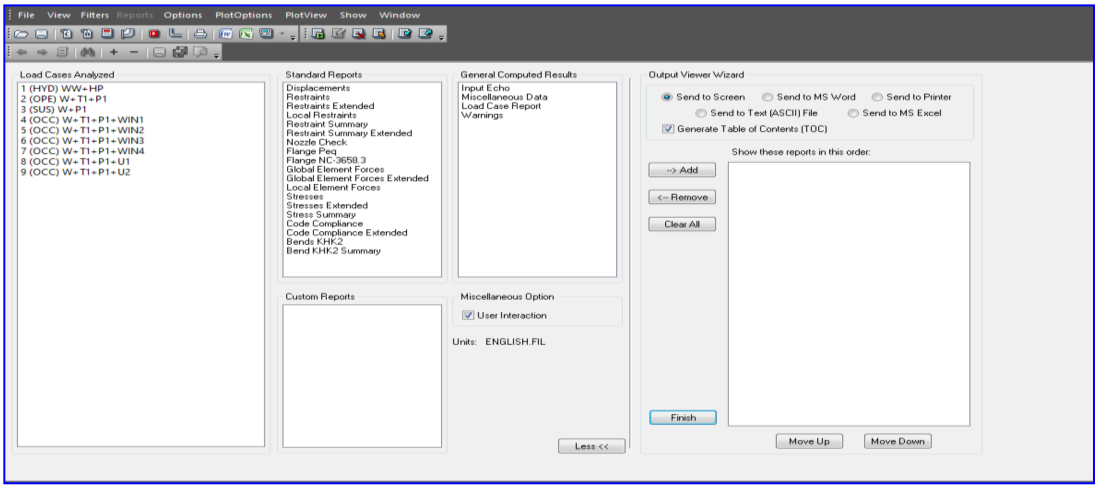
In this part, the objective is now how to minimize the localized stresses on the pipes with more than 80% stresses. Thus, after several tests of modification of the position and types of supports we obtained unstressed merely unstressed loads (fig. 14, 15, 16).



Errors 0 Warnings 24 Notes 0

	Message Type	Message Number	Element/ Node Number	Message Text
10	WARNING	160E		The [WARNING 160E] count exceeded the specified disp. limit of [5].
11	WARNING	33E	3560-3561	There is a GEOMETRIC INTERSECTION at node 3561 and there was NO user defined INTERSECTION TYPE. Standard pipe flexibilities and SIF's = 1.0 will be used unless overridden by the user on each element framing into the intersection.
12	WARNING	33E	3563-3566	There is a GEOMETRIC INTERSECTION at node 3566 and there was NO user defined INTERSECTION TYPE. Standard pipe flexibilities and SIF's = 1.0 will be used unless overridden by the user on each element framing into the intersection.
13	WARNING	33E	3640-3645	There is a GEOMETRIC INTERSECTION at node 3645 and there was NO user defined INTERSECTION TYPE. Standard pipe flexibilities and SIF's = 1.0 will be used unless overridden by the user on each element framing into the intersection.
14	WARNING	33E	4120-4130	There is a GEOMETRIC INTERSECTION at node 4120 and there was NO user defined INTERSECTION TYPE. Standard pipe flexibilities and SIF's = 1.0 will be used unless overridden by the user on each element framing into the
				at node 4120 and there was NO user defined

***Fig.13**. List of error checking tables (without errors and warnings)*



Load Cases Analyzed
1 (HYD) WW+HP
2 (OPE) W+T1+P1
3 (SUS) W+P1
4 (OCC) W+T1+P1+WIN1
5 (OCC) W+T1+P1+WIN2
6 (OCC) W+T1+P1+WIN3
7 (OCC) W+T1+P1+WIN4
8 (OCC) W+T1+P1+U1
9 (OCC) W+T1+P1+U2

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Displacements
Restraints
Restraints Extended
Local Restraints
Restraint Summary
Restraint Summary Extended
Nozzle Check
Flange Peq
Flange NC-3658.3
Global Element Forces
Global Element Forces Extended
Local Element Forces
Stresses
Stresses Extended
Stress Summary
Code Compliance
Code Compliance Extended
Bends KHK2
Bend KHK2 Summary

General Computed Results
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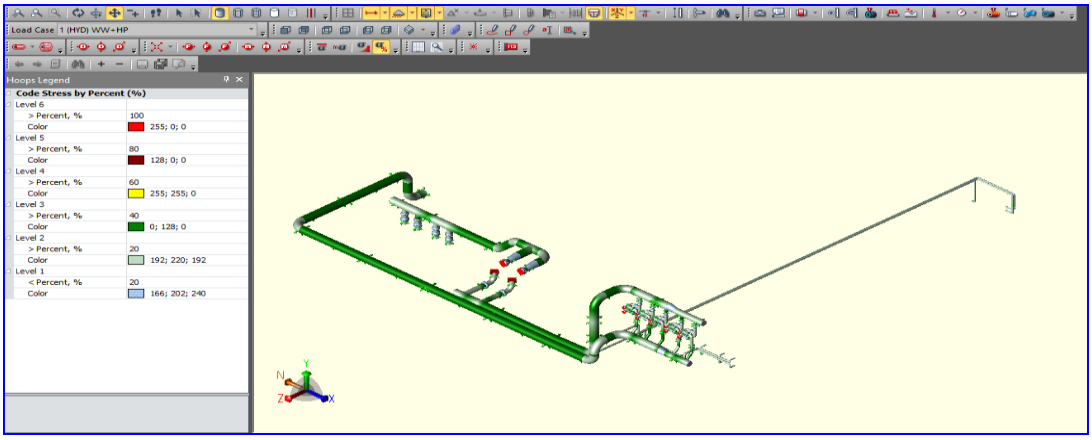
***Fig.14**. CAESAR II spreadsheet for static output processor of FRP line sea water treatment*



Load Case 1 (HYD) WW+HP

Hoops Legend

Code Stress by Percent (%)	
Level 6	
> Percent, %	100
Color	🟥 255; 0; 0
Level 5	
> Percent, %	80
Color	🟥 128; 0; 0
Level 4	
> Percent, %	60
Color	🟨 255; 255; 0
Level 3	
> Percent, %	40
Color	🟩 0; 128; 0
Level 2	
> Percent, %	20
Color	🟩 192; 220; 192
Level 1	
< Percent, %	20
Color	🟦 166; 202; 240

Fig.15. *CAESAR II spreadsheet 3D plot & stress report summary for FRP sea water*

Post-adjustment, the stresses were within permissible limits. In Table 5 are presented allowable and maximum values of stress for sea water treatment line in the lower stress conditions.

Table 5. *Stress for the seawater treatment line with lower stress*

LOADCASE	***Allowable Stress (N/mm²)***	***Max Stress (N/mm²)***	***Code stress (N/mm²)***	***Ratio (%)***	***Piping code***
L1 (HYD) WW + HP	16801	15960	9478	56.4	ISO 14692
L2 (OPE) W+T1+P1	15651.5	10640.3	8985	57.4	ISO 14692
L3 (SUS) W+P1	12632.3	10640.3	7857.6	62.2	ISO 14692
L4(OCC)W+T1+P1+ Win1	16801	10640.3	9006.6	53.6	ISO 14692

CONCLUSIONS

The results of the study show that the fibre-reinforced polymer (FRP) piping system can withstand the applied stresses and loads while maintaining its structural integrity. The maximum stress values initially calculated exceeded the permissible stresses, meaning that the system was initially undersized or poorly supported. Modifications to the positions and types of supports reduced the stresses to acceptable levels, as shown in the adjusted stress tables.

The final results show a significant reduction in the maximum stresses, bringing them below the permissible limits defined by ISO 14692.

FRP pipes show sufficient flexibility for seawater treatment applications [11-14], making them a viable choice for installations where load and temperature variations are common.

The analysis highlights the importance of a good support and anchoring system to minimise local stresses. Correct positioning and selection of supports (e.g. single supports, guides, anchors) is crucial to ensure system stability.

The use of ISO 14692 ensures that pipes are designed and installed to recognised standards, improving the safety and reliability of the installation.

FRP piping systems require continuous monitoring to detect and correct potential failures before they become critical. Regular inspection and proper maintenance of supports and joints are essential.

Adjusting supports and optimising the initial design can reduce long-term costs by minimising repairs and replacements due to overstress.

REFERENCES

[1] International Organization of Standardization ISO 14692: part 1, part 2, part 3, part4

[2] Dey Kumar Anup, “What is Process Piping? Its Definition, Materials, Codes, Applications, and Differences with Power Piping and Plumbing”, https://whatispiping.com/process-piping-definition-materials-codes/?utm_content=cmp-true

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