

THE VALUE OF FRP PIPE FLEXIBILITY

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ABSTRACT

This article examines the use of fibre-reinforced polymer (FRP) composites in pipeline transport applications, highlighting the advantages of these materials in terms of mechanical performance and durability. The properties and classification of FRP materials, manufacturing processes, joint types, and above-ground and underground installation solutions are analysed. In addition, reference is made to the ISO 14692 regulatory framework used to assess pipe flexibility, including experimental investigations of mechanical behaviour through tensile and bending tests. The last part of the study presents analytical models and numerical simulations designed to determine maximum stress and displacements, with the results obtained demonstrating compliance with the requirements of relevant international standards.

Keywords: FRP, pipes, stresses, flexibility, mechanical behaviour

INTRODUCTION

Pipelines are structures composed of tubular sections made of materials such as metal, concrete, or fibre-based composites, used to transport fluids (liquids or gases) along well-defined routes. Due to their reliability and high efficiency, these systems are widely implemented in industrial applications involving long-distance transport.

Pipe networks consist of interconnected segments designed to transport and distribute a working medium in a fluid or fluidized state. Its behaviour is determined by physical and chemical properties (aggregation, composition, purity, chemical aggressiveness, viscosity, density) and operational parameters (flow rate, pressure, temperature).

The components of a pipeline system can be classified into: transport elements (pipes, fittings, connections), protective devices, support structures, and auxiliary equipment. The tight connection of the components ensures the integrity of the transported flow.

Fibre-reinforced polymer (FRP) composites are made by incorporating reinforcing fibres (carbon, glass, aramid) into a polymer matrix to increase mechanical strength and chemical stability. They offer a viable alternative to conventional materials due to their low density, corrosion resistance [1], and structural adaptability in demanding environments.

Similar observations regarding the advantages of FRP were reported by Alabtah et al. [2], who highlight chemical resistance and performance under combined loads in industrial pipelines.

This study investigates the performance of FRP pipes under industrial operating conditions, focusing on their durability and adaptability compared to conventional materials. While previous research has highlighted their advantages, there is still a lack of comprehensive analysis regarding their long-term behaviour in aggressive environments. The novelty of the paper lies in addressing this gap through an integrated evaluation of FRP pipes, providing new insights for their optimization and broader industrial use.

GENERAL CONSIDERATIONS REGARDING FIBRE-REINFORCED POLYMER (FRP) PIPES

FRP pipes are made from a combination of reinforcing fibres (glass, carbon, aramid) and a polymer matrix (thermosetting or thermoplastic resins), sometimes supplemented with fillers and additives. The fibres provide mechanical strength, while the matrix ensures cohesion and protection of the structure. The final properties vary depending on the type of fibre and matrix used.

Classification:

- *By fibre*: GRP (glass fibre) – economical, chemically and mechanically resistant; AFRP (aramid) – high performance in terms of shock and temperature, but sensitive to moisture and compression.
- *By matrix*: Thermosets (e.g., epoxy) – stable at high temperatures, non-reusable; Thermoplastics – redesignable, impact resistant.

Joining FRP pipes

Joints are made using special adhesives (e.g., PSX 60), commonly used in epoxy-based bonding systems in the oil industry [3] that are compatible with various types of resins. The process involves preparing the surfaces, mixing, and applying the adhesive. Curing time varies depending on the ambient temperature and may require additional heating at low temperatures. Kits are available in different volumes, adapted to the size of the pipes.

Support system for above-ground installation

Aerially mounted pipes require appropriately sized supports that can allow expansion (unrestricted) or control movement (restricted). Elements include:

- **Supports** – support their own weight and that of the fluid,
- **Anchors** – limit axial displacement,
- **Guides** – control lateral movements.

It is recommended to use wear saddles covering 180° of the circumferences, using elastomeric liners when applicable, with intermediate materials (e.g., rubber), especially for large diameter pipes.[4]

Storage conditions

According to ISO 14692 [5], pipes can be stacked up to 2.5 m high, with support and lateral spacers. They may only be inserted into each other with separators. The ends must be protected, and in windy conditions, anchoring is necessary to prevent damage.

Joining systems and manufacturing technologies for fibre-reinforced polymer (FRP) pipes

Types of joints used in FRP pipes

Several types of joints (Figures 1 to 6) are used to assemble pipe segments made of fibre-reinforced composites, each with specific applications and distinct technical conditions.

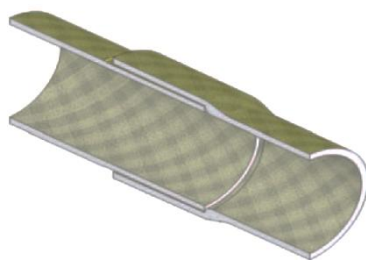


Figure 1. Conical-cylindrical joint [6]

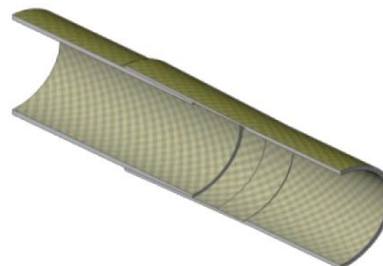


Figure 2. Con-con joint [6]



Figure 3. Flange joint [6]

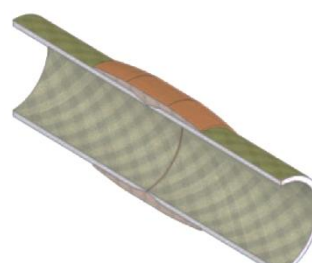


Figure 4. Laminated joint [6]

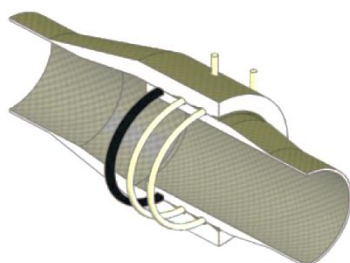


Figure 5. O-ring mechanical joint [6]

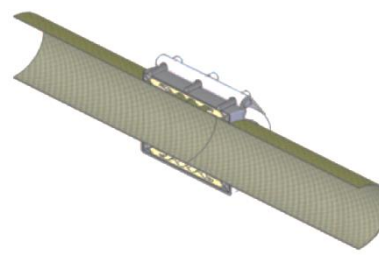


Figure 6. Mechanical coupling [6]

FRP PIPE MANUFACTURING TECHNOLOGIES

The production of FRP pipes involves two main stages: forming the fibre preform and impregnating it with a polymer matrix.

- **Manual lamination** (Figure 7) is a simple and versatile method, suitable for complex shapes, but it has low productivity and requires additional finishing.
- **RTM (Resin Transfer Moulding)** involves injecting resin into a closed mould with dry fibres, providing dimensional accuracy and good mechanical properties, but requires expensive equipment and rigorous control.

Functional properties of FRP pipes

Pipes made of fibre-reinforced composite materials offer multiple benefits:

- **High mechanical strength**, allowing thin walls without compromising rigidity.
- **Corrosion resistance**, reducing maintenance costs compared to steel.

- **Electrical and magnetic insulation**, useful in sensitive environments.
- **Design flexibility**, with the possibility of aesthetic and functional customization.



Figure 7. Hand lay-up [9]

Experimental studies on GFRP pipes have confirmed that stiffness and circumferential strength remain constant even under cyclic loads, as validated by ISO 8521 standardized testing methods [7].

The overall performance of fibre-reinforced composite pipes - such as mechanical resistance, corrosion stability, and thermal behavior - has been extensively reviewed in recent literature, confirming their advantages over traditional materials in structural and fluid transport applications [8].

Installation of FRP pipes

a) Underground installation

FRP pipes adapt well to soil deformation. Efficient installation depends on:

- **Soil type and modulus**, which influence compaction (recommended min. 1,000 psi),
- **The shape of the trench**, which must ensure access and stability,
- **Adequate protection** through uniform bedding and drainage layers in areas with groundwater.

b) Above-ground installation

For aerial applications:

- **Fixed or sliding supports** are used, depending on expansion,
- Pipes must be equipped with **wear saddles of min. 180°**,
- **Clamps** must include a soft layer for even load distribution.

Above-ground installation of FRP pipes

For overhead installation of fibre-reinforced composite pipes, it is essential to use appropriate support systems, verified in accordance with the execution plans (see Figure 8). Supports can be fixed, guided sliding, or free sliding.

1. Protective saddles must exceed the estimated maximum displacement by at least 50 mm, plus the width of the support.
2. In vertical installation, O-ring couplings are oriented downward to prevent water accumulation.

3. O-ring joints require a support point at max. 20% of the pipe length from the joint area.
4. Pipes must be equipped with 180° wear saddles, fixed to the surface, to prevent damage caused by movement to prevent abrasion and compensate for thermal expansion, as recommended in standard GRE installation guides. [8]



Figure 8. Above-ground pipe system [6]

ANALYSIS OF FRP PIPE FLEXIBILITY IN ACCORDANCE WITH ISO 14692

Technical framework for FRP pipes

ISO 14692 is the main standard for fibre-reinforced polymer (FRP) pipes used in the oil and gas industry. It covers the entire life cycle: design, manufacture, installation, and operation.

The standard establishes calculation methods for wall thickness and stresses induced by internal pressure and external factors (vibrations, wind), as well as requirements for mechanical testing and quality control. Installation instructions are aimed at preventing defects, and minimum wall thickness (t , in) is critical for structural safety.

Analysis of installation cases for FRP pipes

GPI standards incorporate correction factors for thermal expansion and chemical exposure in FRP pipe design, complementing ISO provisions [21].

There are two distinct situations in which pipes can be analysed [10]:

1. Unrestrained pipes (with free ends),
2. Restrained pipes (with fixed ends).

Various axial and circumferential stresses act on the pipes [11], [12], as shown in the Figure 9.

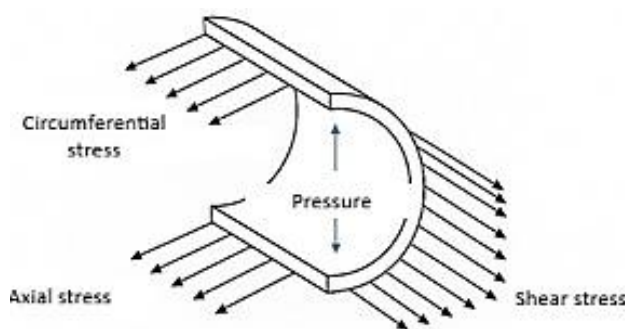


Figure 9. Stresses applied to the pipe [10]

For unrestrained pipes (with free ends), stresses develop in both the circumferential and axial directions [11], [12]. These stresses can be calculated using relations (1), (2):

$$\sigma_{hp} = \frac{p \cdot D}{2 \cdot t} \text{ [MPa]} \quad (1)$$

$$\sigma_{ap} = \frac{p \cdot D}{4 \cdot t} \text{ [MPa]} \quad (2)$$

σ_{hp} – represents the stress in the circumferential plane,

σ_{ap} – represents the stress in the axial direction,

p – represents the internal pressure value,

D – represents the outer diameter of the pipe,

t – represents the thickness of the pipe wall.

For unrestricted pipe systems, the unit deformation in the axial direction is evaluated based on the relation (3):

$$\varepsilon_a = \frac{\sigma_a}{E_a} - \nu_{ha} \frac{\sigma_h}{E_h} = \frac{\alpha \Delta T E_a + 0.5 \sigma_h}{E_a} - \nu_{ha} \frac{\sigma_h}{E_h} = \alpha T + (0.5 - \sigma_{ha}) \frac{\sigma_h}{E_h} \quad (3)$$

For restrained pipes (with fixed ends), a series of stresses are generated, including [11], [12]:

- Internal pressure.
- Forces due to their own weight.
- External stresses (such as those caused by earthquakes or wind action).
- Hydraulic stresses (such as overpressures or rapid fluid movements).

An essential aspect in pipe design is wall thickness. According to the provisions of ISO 14692-2017, the average wall thickness, symbolized by t_r , must comply with the following relationship:

$$t_r \leq 0.1 \cdot D \quad (4)$$

For FRP pipes, a minimum wall thickness is considered in mechanical strength checks. This value must give the pipe adequate strength, complying with the following criteria (relations (5), (6)).

For $D_i \geq 100$ mm:

$$t(r_{min}) \geq 3 \text{ mm} \quad (5)$$

For $D_i < 100$ mm:

$$\left[\frac{t_{rmin}}{D_i} \right] \geq 0.025 \text{ mm} \quad (6)$$

t_{rmin} – represents the minimum wall thickness.

D_i – represents the inner diameter.

The ISO 14692-2017 standard provides the following formula for calculating the minimum pipe wall thickness.

$$t_{r,min} = \frac{MPR \cdot D_{r,min}}{2 \cdot f \cdot 3 \cdot 0,67} \quad (7)$$

t_{rmin} – represents the minimum permissible value for the pipe wall thickness.

$D_{r,min}$ – represents the smallest internal diameter of the pipe.

MPR – represents the maximum pressure at which the system can operate safely.

Determination of permissible stresses using nomograms

The allowable stress in FRP pipes is determined using a nomogram presented in Figure 10, obtained from tensile and internal pressure tests [8]. This highlights five key points that describe the behaviour of the material in the axial and circumferential directions, outlining the distribution of allowable stresses. [19], [20]

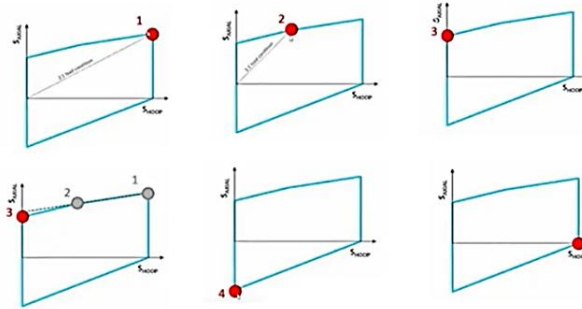


Figure 10. Dependency point nomogram [13]

According to ISO 14692, the nomogram is constructed based on five representative points, each corresponding to a specific stress state (Figure 11).

Point 1 corresponds to the application of pure internal pressure, as a result of which the circumferential stress becomes twice as high as the axial stress.

Point 2 reflects a combined state of traction and internal pressure, generating equal stresses in both directions – axial and circumferential.

Point 3 is determined by a simple tensile test, in which stress occurs exclusively in the axial direction.

Point 4 results from applying a pure compression load.

Point 5 is also obtained by tension, but with an emphasis on achieving a specific ratio between axial and circumferential stresses.

Based on these experimental tests and specific coefficients, the limits of the nomogram were defined in accordance with the requirements of ISO 14692:

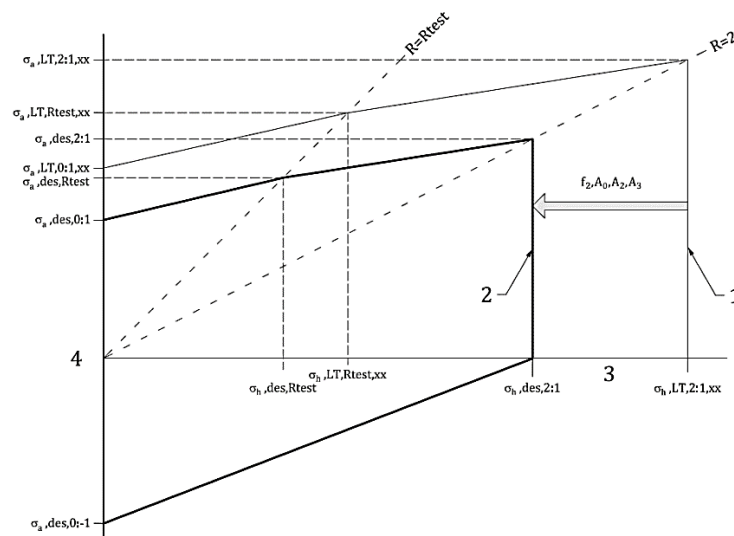


Figure 11. Final nomogram of dependency points [14]

$$\sigma_{h,des,2:1} = f_2 \cdot A_0 \cdot A_3 \cdot \sigma_{h,LT,2:1} \quad (8)$$

$$\sigma_{a,des,2:1} = f_2 \cdot A_0 \cdot A_2 \cdot A_3 \cdot \sigma_{h,LT,2:1} \quad (9)$$

$$\sigma_{h,des,fest} = f_2 \cdot A_0 \cdot A_2 \cdot A_3 \cdot \sigma_{h,LT,Rtest,x} \quad (10)$$

$$\sigma_{a,des,fest} = f_2 \cdot A_0 \cdot A_2 \cdot A_3 \cdot \sigma_{a,LT,Rtest,xx} \quad (11)$$

$$\sigma_{a,des,0:1} = f_2 \cdot A_0 \cdot A_2 \cdot A_3 \cdot \sigma_{aLT,0:1} \quad (12)$$

f_2 – represents the factor reflecting the nature of the applied stress;

A_0 – represents the factor associated with the estimated duration of use of the material;

A_2 – represents the coefficient expressing the resistance of the material under conditions of chemical exposure.

A_3 – represents the factor that considers the interval between maintenance operations.

EXPERIMENTAL ANALYSIS OF MECHANICAL CHARACTERISTICS

The test specimens presented in Figures 12 and 13 were produced by water jet cutting (CNC Water Jet), using FRP pipe (Ø116 mm) and a steel pipe as a fixing core. The "polyline" cutting design included a 0.4 mm addition outside the standard contour to compensate for erosion during the cutting process.

Similar results have shown that CFRP pipes manufactured using modern methods have an elastic modulus comparable to that of steel, but at a fraction of the weight.

Numerical analyses were performed on GFRP pipes, confirming the correlation between the experimentally determined elastic modulus and the values from the durability simulations. [15]



Figure 12. Pipe after cutting



Figure 13. Test specimens after cutting

TENSILE AND BENDING TESTING OF TEST PIECES

After the test pieces were made, they were subjected to mechanical tests for both tensile and bending strength (Figure 14). After the tensile test, the graph in Figure 15 was produced.

Based on the graph, the value for the longitudinal modulus of elasticity was determined. The modulus of elasticity is obtained using the following formula:

$$\tan \beta = E_L \quad (13)$$

E_L – represents the longitudinal modulus of elasticity.



Figure 14. Test specimens after tensile testing

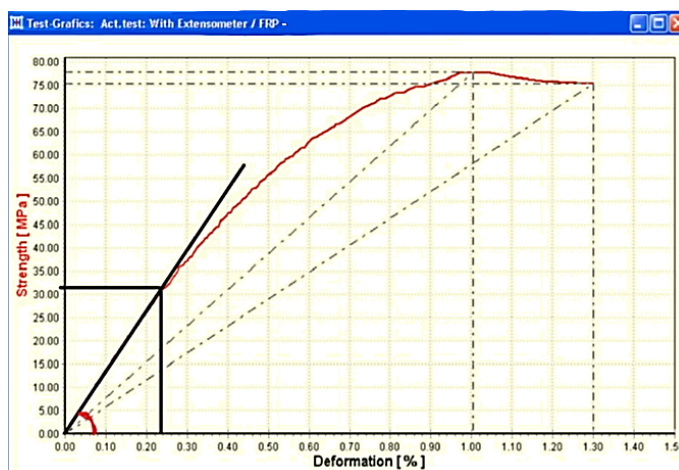


Figure 15. Test specimen

The table 1 shows the values obtained from the tensile test. After the bending test (the tested specimen are presented in Figure 16), the graph from Figure 17 was created. The table 2 shows the values obtained after the bending test.

Table 1. Experimental results of the tensile test

Sample no.	Deformation [%]	Tensile strength [MPa]	Deformation corresponding to linear behaviour [%]	Stress corresponding to linear behaviour [MPa]	Longitudinal modulus of elasticity [MPa]	Angle β
1	1.30	76	0.22	30	11590	89.995
2	1.26	83	0.25	25	12600	89.995



Figure 16. Test specimens after the bending test

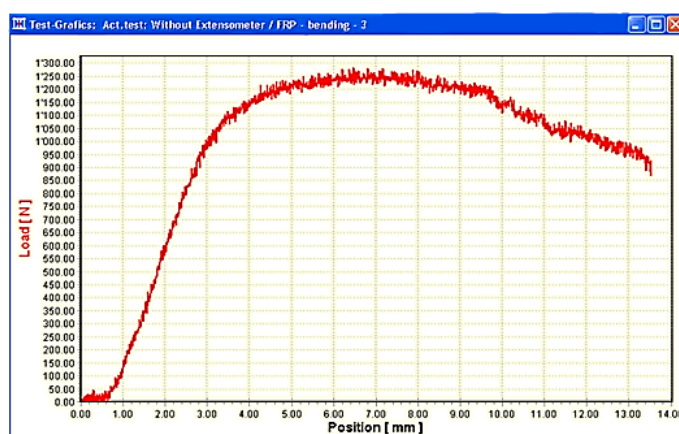


Figure 17. Test specimen 6

Table 2. Experimental results of the bending test

Sample no.	ΔL [mm] (Length)	(Force) [N]
1	4	1150
2	6	1300

EXPERIMENTAL EVALUATION OF MECHANICAL STRESSES M

Electrical tensometry is a method of indirectly measuring mechanical deformations using resistive transducers (strain gauges). These are attached to the material under stress and change their electrical resistance in proportion to the deformation, allowing the stress state to be evaluated using relationships from elasticity theory. Experimental stand for evaluation of mechanical stresses is presented in Figure 18. The characteristics of the strain gauges are:

- Resistance is $120 \Omega \pm 0.35\%$
- The K factor is $2.07 \pm 1\%$
- Transverse and longitudinal sensitivity is -0.1%

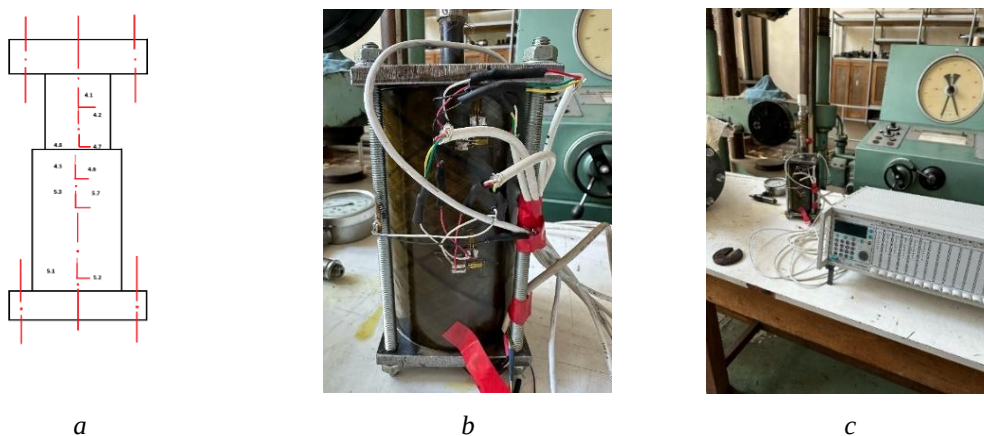


Figure 18. Experimental stand for evaluation of mechanical stresses:

a) 2D sketch; b) Strain gauges mounted on the pipe; c) Strain gauges and measuring device

Table 3 contains the values obtained after applying different pressures to the FRP material. In Table 4 are presented the results obtained from testing compared to 0.

Table 3. Results obtained from testing

Sample no.	MTR	Value [micron/m]									
		0 bar	2 bar	3 bar	5 bar	8 bar	9 bar	10 bar	15 bar	19 bar	22 bar
1	4.2	147.00	282.47	284.60	341.00	431.31	487.35	490.69	601.68	701.04	797.17
2	4.	109.15	155.80	156.44	175.43	205.60	266.00	226.72	266.25	303.47	339.39

Table 4. Results obtained from testing

Results obtained compared to 0									
	2 bar	3 bar	5 bar	8 bar	9 bar	10 bar	15 bar	19 bar	22 bar
1	133.47	137.60	197	284.31	340.35	343.69	454.68	554.04	650.17
2	46.65	47.29	66.28	96.45	116.85	117.57	117.1	194.32	230.24

Assessment of FRP pipe flexibility through modelling and analysis

The assessment of FRP pipe flexibility involves analysing material properties and stresses (pressure, temperature, external factors), followed by the calculation of flexibility coefficients. The system configuration is optimized through numerical modelling, targeting the positioning of supports and compensators. The design was verified according to ASME B31.3, including influences such as wind and earthquakes [16], [25], and the results are presented in Tables 5 and 6.

A technical report highlights the importance of choosing the right supports and compensators to limit excessive movement [17]. Recent advancements in CFRP pipe fabrication have been thoroughly documented, including improvements in lay-up precision and curing efficiency [18].

Table 5. Design data for the analysed lines

Lines	ND (NPS)	DT [°C]	DP [bar/g]	OT [°C]	OP [barg]	Mat.	S_r [mm]	c.a. [mm]	ν [-]	γ_{pipe} [kg/m ³]	α [°C ⁻¹]	E [N/mm ²]
ID3												
14-12-8	350	-					6.8					11141
9823024-	300	29/	0.05	42	0.02	FRP	5.9	1.1	0.3	1950	0.0	10992
01GRP0F	200	60					4.1				188	10894
F-GO												

Table 6. Calculation models

Analysis system	Lines	Calculation model
3	14-12-8 9823024-01GRP0FF-GO	ID-3 (identification number 3)

For group ID- Identification Number 3.

An overview of the calculation model is presented in Figure 19.

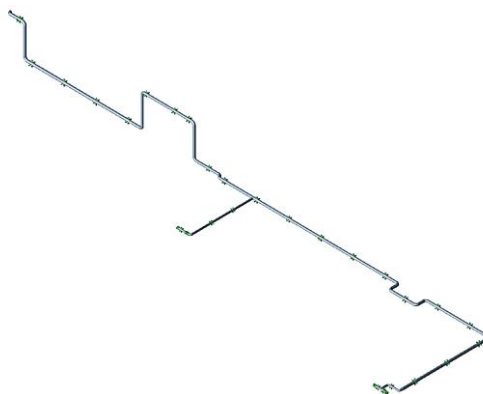


Figure 19. Overview (analysis model).

The Figure 20.a,b,c,d shows the isometrics related to the analysis model (with the corresponding supports). In the Table 7 are presented geometric and elastic characteristics related to the lenticular compensator.

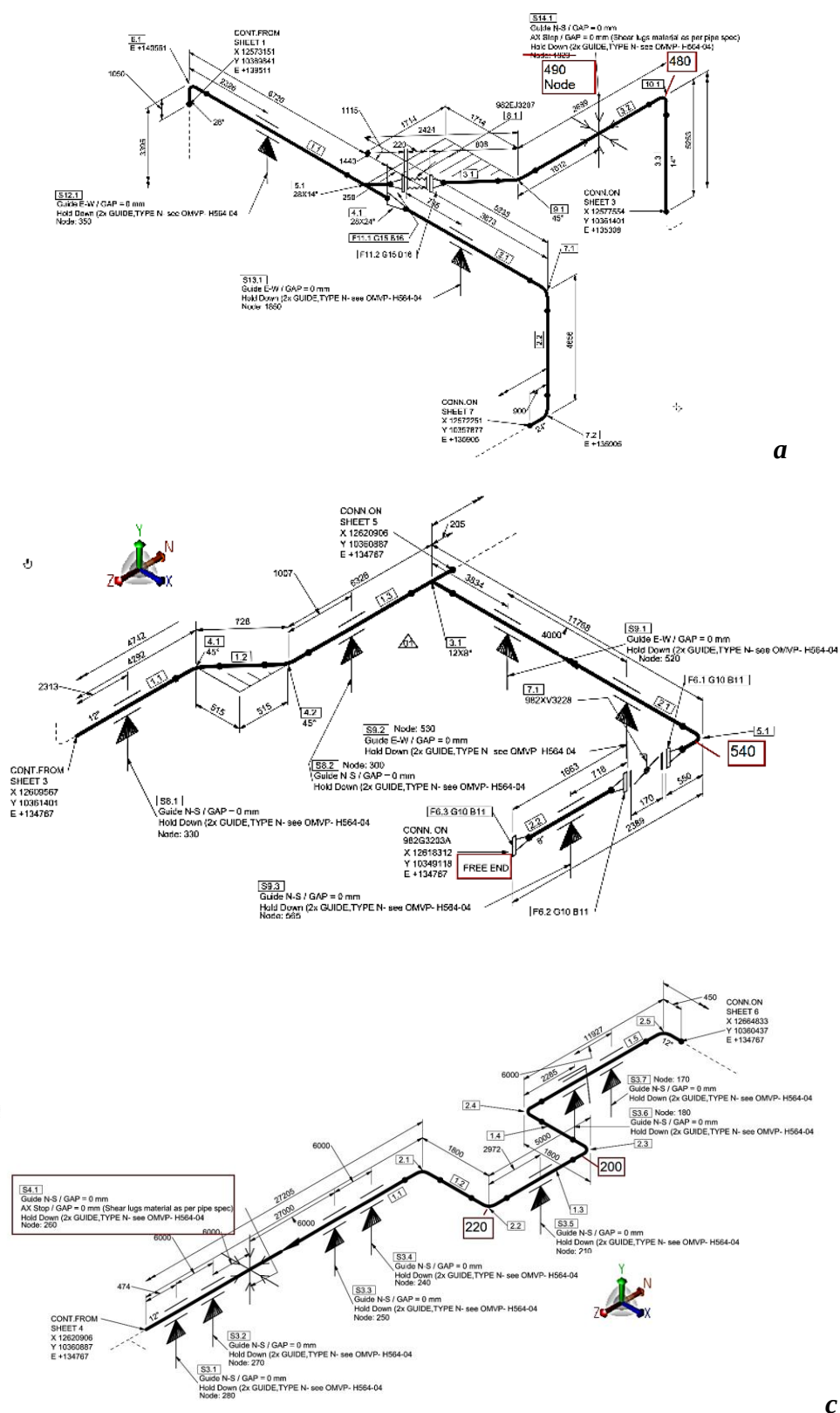


Figure 20. a, b, c Isometrics/supports for group ID-3.

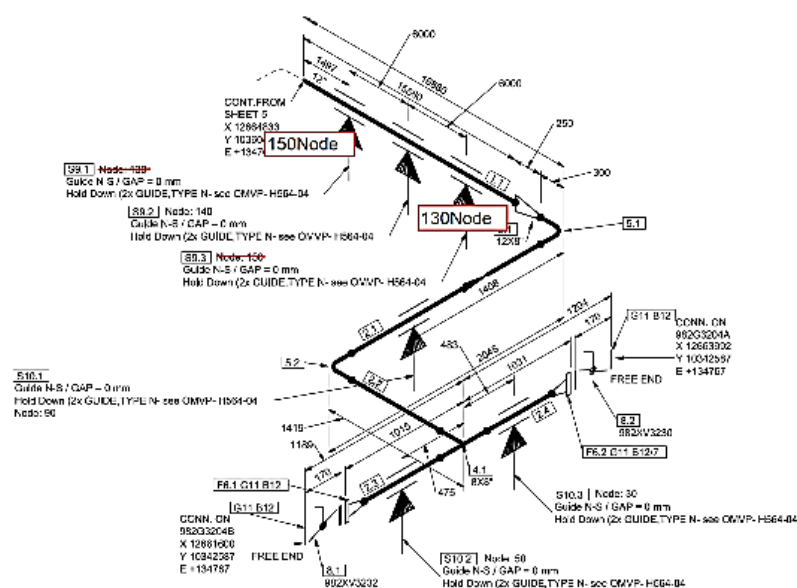


Figure 20. d Isometrics/supports for group ID-3.

Table 7. Geometric and elastic characteristics related to the lenticular compensator

Nominal diameter	Maximum displacement in the axial direction	Length	Weight	Flange		Bellows			Maximum displacement in the lateral direction	Axial stiffness	Transverse stiffness
				Collar diameter	Thickness of the corresponding flange	Outer lens diameter	Length between lenses	Effective diameter			
DN	Δx	BL	G	d1	C1	Yes	Lb	Ae	Δy	$C\Delta x$	$C\Delta y$
-	mm	mm	kg	mm	mm	mm	mm	cm^2	mm	N/mm	N/mm
350	124	220	36	415	26	409	132	1144	14	45	559

Analysis results

Flexibility evaluations based on seismic loading have their foundation in pioneering work on FRP displacement behavior and stress accommodation [22]. The maximum combined stress is compared with the permissible value, which is equal to 69.5% (as is presented in Table 8), being the permissible stress according to ISO 14692.

Table 8. Calculation model with stress summary for group ID-3

Node	Load cases	Stress value [N/mm ²]	Permissible value [N/mm ²]	Percentage difference [%]
530	UP	4.4	20	22
90	OPE	8	20	40.1
470	OPE+SEISM	13.9	20	69.5

UP – Unpressurized - Represents the base condition, likely including **dead weight (self-weight of the pipe)** and **thermal expansion** without internal pressure.

OPE - Operating Condition - simulates the **normal operating scenario**, which includes internal pressure, operating temperature, steady-state conditions.

OPE+SEISM - Operating + Seismic - Combines **normal operating loads** with **occasional seismic action** (earthquake scenario).

Figure 21 shows the most stressed area while in Figure 22 are shown nodes (areas) with maximum displacements. The maximum displacements calculated under design operating conditions are presented in Table 9.

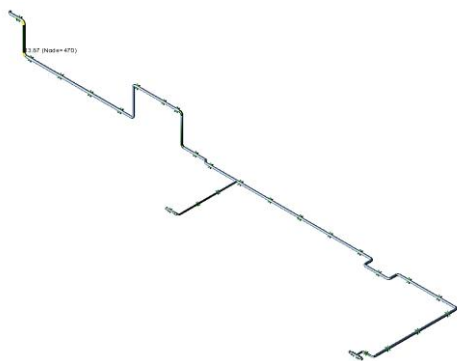


Figure 21. Most stressed area

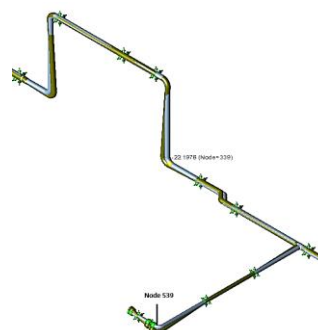


Figure 22. Nodes (areas) with maximum displacements.

Table 9. Maximum displacements under operating conditions at design conditions

Calculation Nodes	Load case	Global X [mm]	Global Y [mm]	Global Z [mm]
339	OPE (design)	-22.19	-7.11	1.02
335	OPE (design)	-21.78	-6.77	1.02
535	OPE (design)	1.01	-0.756	10.79

OPE = Operating Condition - Refers to the **steady-state condition** of the pipeline during regular operation: internal pressure is applied, operating temperature is reached, supports and constraints are active as designed

Evaluation of flange joint seals

The forces and moments acting on the flanges are shown in the Table 10.

Table 10. Maximum forces at flange joints during operation.

Node	Axial force N	Bending moment Nm
15	0	25
65	0	29
555	94	189
557	94	147

Mechanical performance of FRP flanges under bending and axial loads is a well-studied topic in modern pipe support design [23].

The analysis of flange joints under operational loads revealed that while most connections remain within safe mechanical limits, specific nodes exhibit significant axial forces and bending moments, highlighting the need for reinforced design measures in critical areas. [24]

CONCLUSIONS

FRP pipes offer superior resistance to corrosion and erosion compared to steel pipes, making them more suitable for use in aggressive environments. Determining permissible stresses requires detailed experimental data and compliance with ISO 14692. The components of FRP systems have variable mechanical properties, which complicates the modelling and analysis process. In above-ground applications, these pipes require denser support and an increased number of expansion compensators. Due to significant axial deformations under pressure, FRP pipes are more suitable for low-pressure regimes. The nomogram for allowable stresses was obtained through experimental tests and strain gauge measurements, allowing the mechanical behaviour to be evaluated. The study supplemented ISO 14692 with provisions from ASME B31.3 to cover occasional stresses, such as those caused by wind or earthquakes.

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