PETROBRAS	TECHNICAL SPECIFICATION	Nº I-ET-3010.00-1300-140-P4X-005
	CLIENT:	SHEET 1 of 12
	PROGRAM:	
	ÁREA:	
DP&T-SRGE	TITLE: GUIDELINES FOR STRUCTURAL ANALYSES FOR CRYOGENIC PROTECTION DESIGN	NP-1 ESUP

INDEX OF REVISIONS

REV	DESCRIPTION AND/OR REVISED SHEETS
0	ORIGINAL
A	REVISED WHERE INDICATED

	REV. 0	REV. A	REV. B	REV. C	REV. D	REV. E	REV. F	REV. G	REV. H
DATE	07/24/2020	04/22/2021							
DESIGN	ESUP	ESUP							
EXECUTION	CYMQ	CYMQ							
CHECK	BX75	BX75							
APPROVAL	BX65	CMYR							

INDEX

1. INTRODUCTION

This document presents the methodology for the structural redundancy analyses used in design of cryogenic protection of structural members of offshore platforms. The presented methodology is based on nonlinear collapse analyses in order to assess the redundancy of the structure.

In order to perform the structural analyses with the methodology presented in this document, a safety study must have been performed indicating the region and structural elements that are subject embrittlement due to low temperatures for the possible accidental scenarios.

The main objective of the analyses presented in this document is to provide the information if the low temperature scenarios are able to cause the impairment of the structure. For the cases where the impairment frequency of the main structure is above the tolerable levels, mitigation with the use of cryogenic protection shall be presented to avoid the structural impairment.

The analysis presented in this technical specification addresses the behavior of the structure during accidental limit states. Post-accident assessment shall be performed in order to evaluate the possibility of reuse of the structure after the accidental event, considering changes in the material mechanical properties as well as in its metallurgical structure. Post-accident assessment methodology is not within the scope of this document.

The content indicated hereafter does not exclude the provisions by the Classification Society (CS), also to be complied with. Any unfavorable deviation between the information provided by this document and the Classification Society rules must be reported to PETROBRAS.

2. REFERENCES

This section presents the documents that will be necessary as references for the structural collapse analyses.

2.1. DESIGN DOCUMENTS

[1] STRUCTURAL REQUIREMENTS;
[2] PRIMARY STRUCTURES DRAWINGS;
[3] SECONDARY STRUCTURES DRAWINGS;
[4] GENERAL NOTES FOR STRUCTURES;
[5] WEIGHT CONTROL REPORT;
[6] GENERAL ARRANGEMENT;
[7] METOCEAN DATA;

2.2. RULES, CODES AND STANDARDS

[8] EN1993-1-2 – Eurocode 3 – Design of Steel Structures – Part 1-2: General Rules and Rules for Buildings – 2005;
[9] API RP 2FB – Recommended Practice for the Design of Offshore Facilities Against Fire and Blast Loading – 1st Ed. – 2006;
[10] EN1993-1-1 – Eurocode 3 – Design of Steel Structures – Part 1-1: General Rules – Structural Fire Design – 2005;
[11] DNV RP C208 – Determination of Structural Capacity by Non-linear FE Analysis Methods – 2013;
[12] DNV OS C101 – Design of Offshore Steel Structures, General (LRFD Method) –2011;
[13] ABS Guidance Notes on Accidental Load Analysis and Design for Offshore Structures – 2013;
[14] DR-ENGP-M-I-1.3 – Safety Engineering Guideline;
[15] I-ET-3000.00-5400-98G-P4X-005 – CO2 High Content Gas Leakage – Embrittlement Study;
[16] Guidance Notes for Risk Base Analysis: Cryogenic Spills, August 2015, Lloyd's Register.

3. UNITS

The International System of Units (SI) shall be adopted for the analyses presented in this document. Decimals multiples and fractions of the following units are used:

- Length: meter (m)
- Mass: kilogram (kg)
- Force: Newton (N)
- Stress: Pascal (1 Pa = 1 N/m^2)
- Time: second (s)
- Angle: degree (º)
- Temperature: degree Celsius (ºC)

4. STRUCTURAL ASSESSMENT INPUT

The structural assessment considers the following inputs:

i. Low temperature scenario definition;
ii. Structural configuration;
iii. Material properties;
iv. Applied loading;
v. Critical structural items.

4.1. LOW TEMPERATURE SCENARIO DEFINITION

The low temperature scenarios, obtained in the safety studies according to [15], shall be considered in the structural consequence analyses. The structural elements subject to temperature that might lead to steel embrittlement shall be obtained considering the simulations of CO_2 leakage performed in the safety studies. The structural behavior shall be assessed for all accidental scenarios that might cause steel embrittlement.

4.2. STRUCTURAL CONFIGURATION

The structural geometry considers the unit general arrangement and individual member configurations. The structural layout identifies the position of equipment and structural members relative to the release locations considered. This will influence the development of key factors pertinent to the acceptance criteria (proximity to critical safety elements, personnel evacuation routes/muster areas, and degree to which structural damage can be tolerated). Individual structural member geometry definition is required to develop the individual structural member temperature profiles and the overall structural assessment. Utilizing the low temperature accidental event definition, with the individual member geometry (shape and critical cross-sectional dimensions) and relative position to the leakage source, it is possible to develop the temperature profile for the affected members during the accidental event.

4.3. MATERIAL PROPERTIES

The primary structural impact of the low temperature in structural steel is the embrittlement. The ductile to brittle transition temperature (DTBTT) of the adopted steel will govern the material behavior and shall be used in order to assess if brittle failure is possible.

Material test results shall be used to define the DTBTT of the adopted steel. In the absence of material tests, typical DTBTT of low carbon steel shall be adopted as -40 ºC [16]. The structural elements subject to temperatures below DTBTT shall be assumed failed.

An important parameter to assess if steel embrittlement is possible is the time to DTBTT. More refined methods with the use of thermal models might be used to estimate the steel temperature changes during the accidental scenario. In the absence of more refined methodology, the time to DTBTT might be considered instantaneous.

The materials are modelled with their properties at a reference temperature of 20 ºC, with the minimum yield strength presented at [1] and [10], according to the member and steel type (Rolled Profile, Welded Profile, Pipes, Plates). Some of the properties, at reference temperature of 20 ºC, are presented below:

- Young's Modulus: E = 210000 MPa
- Poisson's Ratio: $\nu = 0.3$
- Density: $\rho = 7\,850$ kg/m^3
- Coefficient of thermal expansion: $\alpha = 1.2 \times 10^{-5}$ / ºC

The stress-strain relationships from [11] shall be used in the nonlinear collapse analyses. The choice of the stress-strain curve shall take into account the material that the structure is composed of.

4.4. APPLIED LOADING

Structural loads to be considered in the models can be separated into several broad categories:

- Dead loads consist of structural members self-weight, non-modeled structural weights, miscellaneous items (such as electrical, instrumentation, safety, telecom), operating piping and operating equipment weights;
- Live loads (only at laydown and storage areas). Other live loads as well as environmental loads are not to be considered;
- Functional loads such as helideck and crane loads may be considered but typically only if pertinent to the accidental scenario identified.
- Hull deflections at static condition.

4.5. CRITICAL STRUCTURAL ITEMS

Among the inputs for the structural analyses is the definition of critical structural elements to evaluate the need of cryogenic protection:

- Primary structure (according to design documents);
- Secondary structural elements considered important;
- Secondary structure supporting important equipment;
- Secondary structure supporting piping (escalation);

The definition of the important equipment, secondary structure and piping support structures, as well as the structural performance criteria to be adopted for those elements supporting equipment and piping, shall be defined in a specific meeting with PETROBRAS and Designer’s representatives of the following disciplines: structures, process, safety, piping and equipment.

Item 4.3.2.1, from safety engineering guideline [14], shall be considered in the critical equipment/structure definition.

5. CRYOGENIC PROTECTION DESIGN METHODOLOGY

The cryogenic protection shall be designed considering all the possible CO_2 leakage scenarios that could lead to the embrittlement of the structure steel. The structural elements with temperatures of DTBTT or below shall be removed from the FE model and a nonlinear analysis shall be performed to check the structure has enough redundancy to absorb the loss of the structural members and prevent escalation according to the criteria from Section 6. In cases where the structure is not capable of complying with the adopted criteria, mitigation with the use of cryogenic protection shall be investigated and proposed. The validation step takes into account the presence of the designed cryogenic protection by considering the protected members intact. It shall be demonstrated that the structure is capable of complying with the criteria adopted with the use of cryogenic protection. . If the structure is capable of complying with the structural criteria, either with or without the use of cryogenic protection, the analysis is finished for the CO2 leakage scenario evaluated and the analysis shall be repeated for the remaining scenarios.

Once the assessment is complete for all CO2 leakage scenarios, the impairment analysis of the structure shall be performed according to Section 7.

The cryogenic protection design workflow, as considered in this document, is presented in Figure 1.

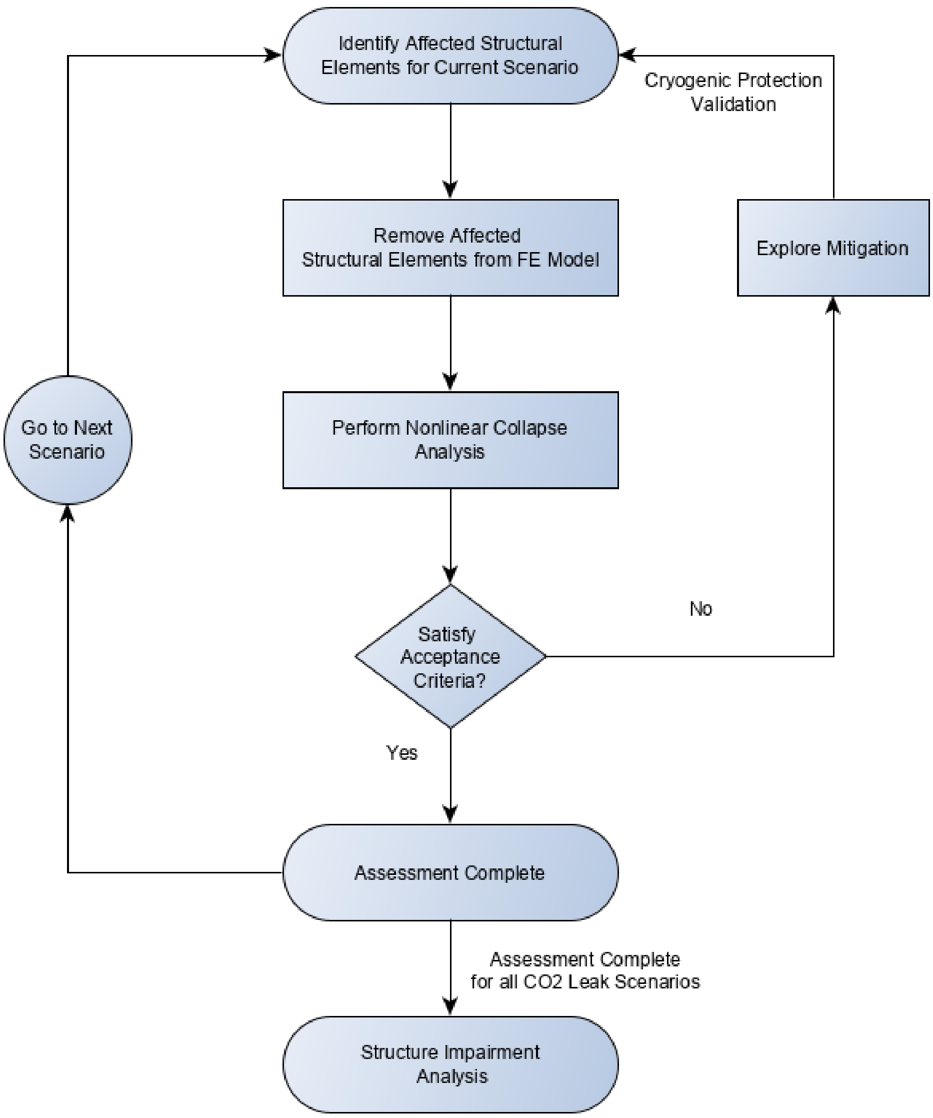

Figure 1 – Cryogenic protection design workflow

6. STRUCTURAL COLLAPSE ANALYSIS

6.1. INTRODUCTION

The structural analysis used in the cryogenic protection design is a progressive collapse analysis method that allows for load redistribution as individual members fail due to the increase of the structural loads. The members subject to temperatures of DTBTT or below are removed from the finite element (FE) model and the load redistribution utilizes alternative load paths to compensate for the lost members. Cryogenic protection might be required in order to prevent escalation although other mitigation options might also be considered.

The model for assessing the mechanical response shall take account of:

- the combined effects of mechanical actions and geometrical imperfections;
- the stress strain relationships of the material, as in [11];
- geometrical non-linear effects;
- the effects of non-linear material properties, including the unfavorable effects of loading and unloading on the structural stiffness;
- the effects of thermally induced strains and stresses both due to temperature reduction and due to temperature differentials, if relevant.

The model shall be suitable to represent all failure modes that are intended to be checked by the analysis. It should be made clear in the report which failure modes the model will adequately represent and which failure modes are excluded from the analysis. The failure modes excluded from the analysis shall be prevented or explicitly checked by other methods [11].

6.2. ANALYSIS INPUTS

The nonlinear structural analysis performed considers the following inputs:

- Structural loads as defined at 4.4;
- The information about which structural element is assumed to be failed for the respective accidental scenario, as defined in 4.3;
- The respective stress-strain curves, as defined in 4.3;

6.3. ANALYSIS OUTPUTS

The results of the nonlinear analyses are the equivalent stresses, deflections and deformed shape of the structure. Based on this results, mitigation with cryogenic protection or other means shall be specified, when necessary, considering the design criteria specified in 6.4.

6.4. DESIGN CRITERIA

In the structural evaluation of an accidental CO_2 leakage event, the structure should be designed to meet specific performance criteria. These criteria should be selected to ensure that the consequence of the event is consistent with the risk level assigned in the risk assessment for that event. The performance criteria defined in this document shall be taken into account together with the criteria defined in the safety engineering guideline document.

The structural criteria to be used in the nonlinear analyses are the following:

- Global structure stability shall be preserved at the end of the mechanical load history ensuring that there is no sudden or progressive collapse of the overall topside structure.

- Any blast walls and fire walls shall remain in place without rupture or discontinuation of their supports; deformation of the wall shall be limited to avoid escalation.
- Safety critical elements (SCEs) that are designed to mitigate the effects of a major accident, such as those necessary for (a) the safe shut down of the installation, (b) personnel protection and escape, (c) fire protection, suppression and control, (d) communications, and (e) hydrocarbon containment including transport and storage; shall remain intact.
- Local buckling shall be prevented or considered accordingly.
- Critical deformation of structure to avoid damage to critical equipment and piping supports, as defined according to 4.5.
- The design shall take into account the ultimate limit state beyond which the calculated deformations of the structure would cause failure due to the loss of adequate support to one of the members [8].

6.5. VALIDATION STEP

A validation step shall be performed including the effects of the cryogenic protection in the structure (protected members considered intact) in order to ensure that the structural behavior of the protected structure is as intended. The cryogenic protection is considered adequate if the structure is able to comply with the criteria from 6.4.

7. STRUCTURE IMPAIRMENT ANALYSIS

After the workflow presented in Figure 1 is complete for every CO_2 leak scenario, a structure impairment analysis shall be performed in order to ensure that the impairment criteria is met.

The structure impairment analysis step accounts for the occurrence of failure of any structural member of the platform and is performed to assess the risk of structural failure due to accidental events. The expression structural failure is used here to indicate that the structure failed to comply with the design criteria adopted in 6.4, and is not restricted to structural collapse.

When it is identified, during the structural analysis step, that the structure needs mitigation by the use of cryogenic protection to perform within the allowable structural limits (6.4) for a specific accidental scenario, a failure is accounted with the frequency of occurrence of the accidental scenario in study. The total impairment of the structure due to the CO_2 leak accidental events should be lower than the limit value specified in [15]. If the total impairment of the structure is greater than the limit, passive cryogenic protection shall be applied to reduce the impairment of the structure to the limit value.

In order to choose the scenarios that will receive cryogenic protection, the scenarios shall be ordered as presented in [15] and cryogenic protection shall be applied to the accidental scenarios that are increasing the impairment of the structure, at the locations and quantities designed with the structural analyses described in this document.

8. DELIVERABLES

The final report with the results from the nonlinear structural analyses shall be delivered, containing the details of the structural models used, mechanical loads considered, boundary conditions, mesh sizes, element types, initial imperfections, material properties, resulting strains and stresses, deformed shape of the structure and other relevant information. The results shall be presented for all structural analyses performed, including the validation steps.

For each accidental scenario, it should be clear in the final report which structural members were considered failed and removed from the analyses.

A spreadsheet associating each structural scenario to the accidental scenarios evaluated shall be delivered. With this spreadsheet, it should be possible to identify the complete accidental scenario from [15], including location of the leak point (module, identification of the component origin of the leak), CO_2 content and pressure, direction of the leak, flow rate, occurrence frequency of the accidental scenario, leak cone geometry, distance to DTBTT and structural elements considered affected by embrittlement.

A spreadsheet with the results of the impairment frequency analysis described in 7 shall be delivered. This spreadsheet should contain data of all accidental scenarios analyzed, its occurrence frequency as well as the impairment frequency before and after the cryogenic protection recommendation. With this spreadsheet it should be possible to identify which accidental scenarios lead to the impairment of the structure after the nonlinear analyses and consequently lead to mitigation like need for cryogenic protection.