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	CLIENT:		SHEET 1 of 16
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DENGE	TITLE: GUIDELINES FOR STRUCTURAL DESIGN AGAINST BLAST LOADS		INTERNAL ESUP

INDEX OF REVISIONS

REV	DESCRIPTION AND/OR REVISED SHEETS
0	ORIGINAL
A	REVISED WHERE INDICATED
B	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	04/29/2024						
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APPROVAL	BX65	CMYR	CYEL						

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1. INTRODUCTION

The main objective of the blast assessment of offshore structures is to assess the main safety functions and identify and mitigate vulnerable components or structures that could lead to personnel life/safety incidents, environmental releases and facility damage when exposed to blast scenarios.

This document presents the preliminary guidelines and methodology for the blast structural analysis used in structural assessment to blast accidental condition of offshore structures. The presented methodology is based on the following methods commonly used for the blast structural analysis:

- Strength level analysis;
- Ductility level analysis.

The analyses described in this technical specification address the behavior of the structure during accidental limit states. Post-blast assessment shall be performed in order to evaluate the possibility of reuse of the structure after a blast event, considering buckling and high deformation of structural components. Post-blast 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 blast structural 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] API RP 2TOP – Topsides Structure – 1st Ed. – 2019;
[9] DNV RP C208 – Determination of Structural Capacity by Non-linear FE analysis Methods – 2013;
[10] DNV OS C101 – Design of Offshore Steel Structures, General (LRFD Method) – 2023;
[11] ABS Guidance Notes on Accidental Load Analysis and Design for Offshore Structures – 2013;
[12] DR-ENGP-M-I-1.3 – Safety Engineering Guideline;
[13] I-ET-3000.00-5400-98G-P4X-003 – Fire Propagation and Smoke Dispersion Study;
[14] Design of Blast-Resistant Buildings in Petrochemical Facilities, 2nd Edition, ASCE- 2010;
[15] DNVGL RP C204 – Design against accidental loads –2017;
[16] ISO 19901-3 – Petroleum and natural gas industries — Specific requirements for offshore structures — Part 3: Topsides structure – 2024;
[17] I-ET-3000.00-5400-98G-P4X-001 – Explosion Study;
[18] API RP 2FB – Design of Offshore Facilities Against Fire and Blast Loading – 1st Ed. – 2006.

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. BLAST STRUCTURAL ASSESSMENT INPUT

The blast structural assessment consists of five primary inputs:

i. Blast scenario definition;
ii. Ignition position and blast load direction;
iii. Structural configuration;
iv. Material properties;
v. Applied loading;
vi. Critical structural items.

4.1. BLAST SCENARIO DEFINITION

The blast scenarios, defined according to the blast simulation results obtained with 3D Computational Fluid Dynamics (CFD) from the Explosion Risk Analysis shall be considered as input for the blast structural analyses.

For the detailing design phase, the design overpressures shall be obtained considering the 3D CFD simulation results from the corresponding Explosion Risk Analysis study. The resulting design overpressures shall be used to verify the adequacy of the structure to comply with the adopted criteria.

4.2. IGNITION POSITION AND BLAST LOAD DIRECTION

The actual position of the ignition point has a strong influence on the resulting explosion overpressure. Besides defining the blast wave direction, its position is important also due to the fact that the pressure magnitude decreases with the distance to the ignition point.

In order to account for the overpressure changes due to the ignition point position, the following positions shall be considered for the ignition point whenever possible to occur:

- Outside the module at portside;
- Outside the module at starboard;
- Outside the module at aft;
- Outside the module at forward;
- Inside the module;

For each position of the ignition point mentioned above, inside as well as outside the module, changes in the ignition point elevation and direction shall also be considered to generate the possible blast loads in the structure. Due to low confinement, ignition point above module upper deck might be disregarded. Examples of blast ignition points located outside the module structure are shown in Figure 1. Blast wave loads due to elevation changes in ignition positioned at portside are shown in Figure 2. Ignition point between hull main deck and module production deck causing upwards pressure on module production deck shall also be considered.

Permeability or obstruction of the structure might be considered to simulate the respective blast load effects on the structural elements. The permeability factor might me estimated based on the 3D model views and shall be documented on the design document, if used.

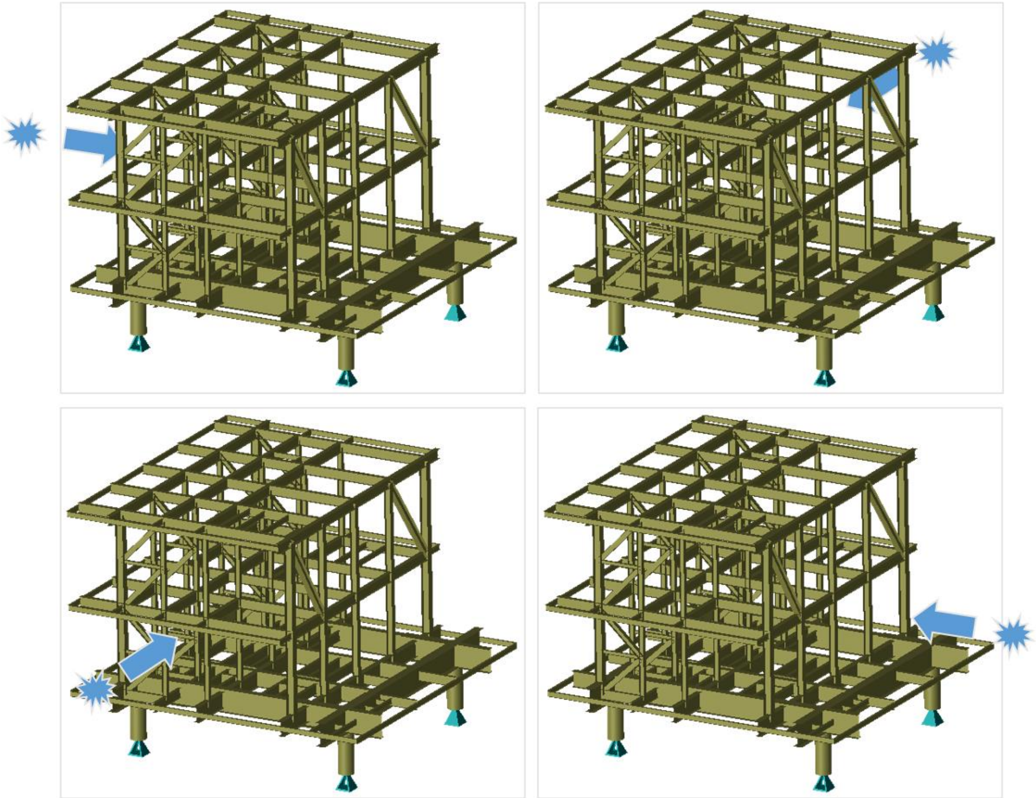

Figure 1 – Blast ignition points outside the module

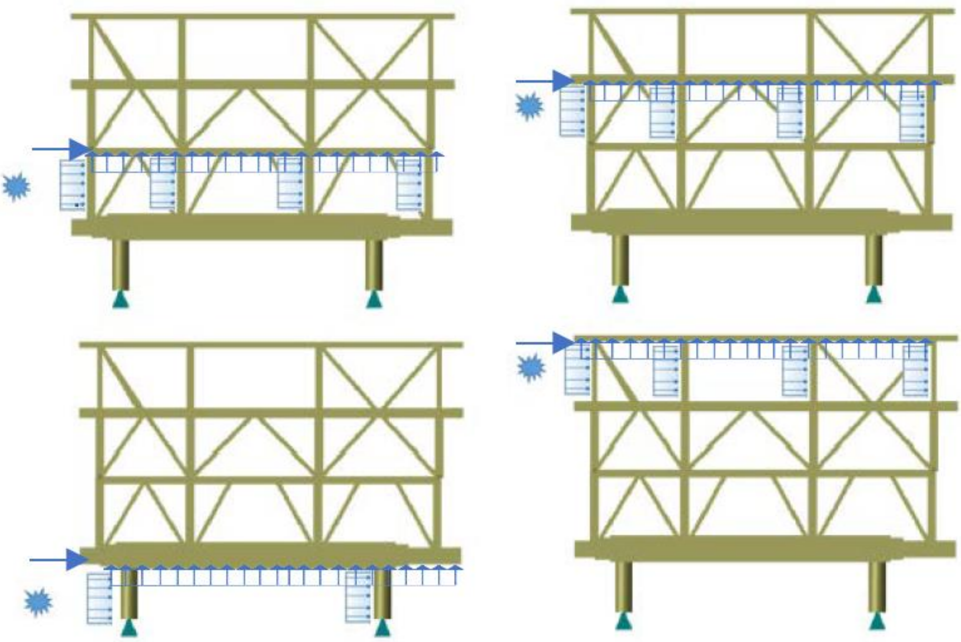

Figure 2 – Overpressures due to elevation change in ignition position outside the module at portside

4.3. STRUCTURAL CONFIGURATION

The structural geometry considers the facility topsides and equipment. The structural layout identifies the position of equipment and structural members relative to ignition points considered. This will influence the development of key factors pertinent to the acceptance criteria. The shape of the topside module where the explosion takes place, the degree of congestion, ignition location are important factors to be considered in the blast structural assessment. Structural redundancy, as load carried by collapsed members can be redistributed, as well as permeability, allowing the blast wave to travel through the space between the main structural elements, have a high impact on the overall structural integrity.

4.4. MATERIAL PROPERTIES

The materials are modelled with its 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 = 206 000 MPa or 210 000 MPa
- Poisson's Ratio: $\nu = 0.3$
- Density: ρ = 7 850 kg/m^3

Specifications referenced in the codes define minimum mechanical properties for various grades of material. In practice, the average yield strength of steel materials being installed is approximately 25% greater than the specified minimum values [14]. A strength increase factor is used to account for this condition and its recommended value is 1.10 for the structural steel [18]. Application of the recommended 1.1 factor is warranted for petrochemical facilities where it is desired to reduce conservatism and make use of the full available blast capacity [14].

To incorporate the effect of material strength increase with strain rate, a dynamic increase factor is applied to static strength values. DIFs are simply ratios of dynamic material strength to static strength and are a function of material type as well as strain rate as described above. DIFs are also dependent on the type of stress (i.e. flexural, direct shear) [14]. The dynamic strength is determined by multiplying the static strength (increased by the strength increase factor) by the DIF. The dynamic increase factors are shown in Table 1.

Table 1 – Dynamic increase factors

Material	Yield stress Fy (MPa)	Tensile Strength (MPa)	Strength Increase Factor (SIF)[1]	Dynamic Increase Factor (DIF)[2]			Overall increase factor (SIFxDIF) for material dynamic strength for Blast	Yield stress applied for dynamic strength in Blast analysis (MPa)
				Bending / Shear	Tension / Compression [3]	Ultimate Stress		
Structural Steel (Fy ≤ 345 MPa)	345	490	1.10	1.29	1.19	1.10	1.31	452
Steel Pipes 415 MPa (Topsides and MSM tubulars, API 5L X60)	415	520	1.00	1.19	1.10	1.00	1.10	457
Steel Pipes 360 MPa (Flare tubulars API 5L X52)	360	490	1.10	1.29	1.19	1.10	1.31	452[4]
Plates and Welded Plate Girders 390 MPa (AH/DH/EH40)	390	510	1.00	1.19	1.10	1.00	1.10	429
Rolled sections 355 MPa (AH/DH/EH36)	355	490	1.10	1.29	1.19	1.10	1.31	452[4]

(1) As per [14], TABLE 5.A.1

(2) As per [14], TABLE 5.A.3.

(3) Tension/Compression DIF is conservatively applied as an overall factor for DIF.

(4) Strength value for materials with Fy ≤ 360MPa is limited with respect to the increase factor for the steel grade 50ksi (Fy = 345MPa). SIF factor is modified to limit.

Dynamic increase factors for steel member connections can be conservatively ignored [14].

4.5. APPLIED LOADING

Loads are separated into two categories for the blast events:

i. Blast pressure and drag loads;
ii. Structural loads.

Blast loads will be based on information from the previously developed blast scenario definition for a given event. The blast loads will include the effects of both overpressure and drag. The blast overpressure will be defined by its distance from the ignition source, the blast exceedance curve (peak overpressure exceedance), and a pressure curve, as shown in Figure 3. The drag loads are derived based on the pressure and gas flow velocity associated with the blast as well as the drag coefficients for the structure and equipment present.

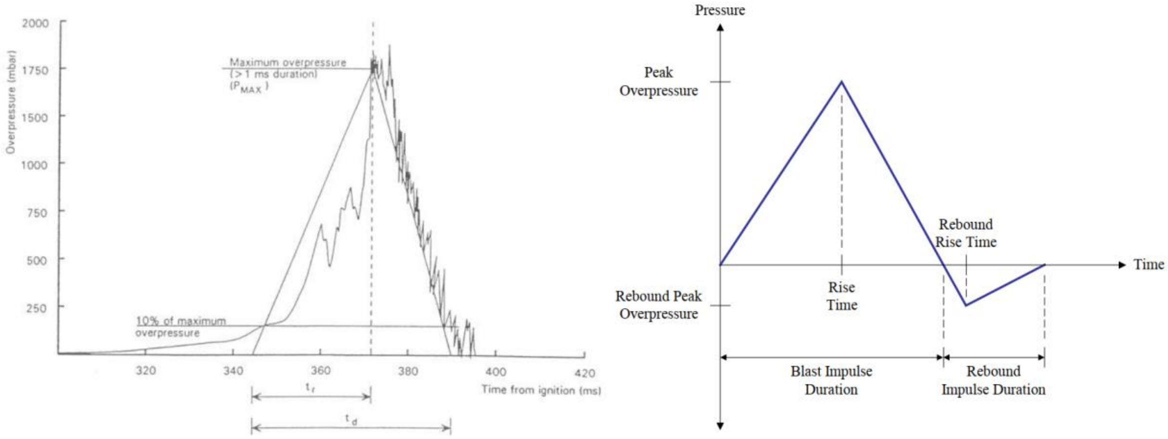

Figure 3 – Derivation of simplified pressure-time profile

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 at 75% of their maximum design values (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 blast scenario identified.
- Hull deflections at static condition.

4.6. CRITICAL STRUCTURAL ITEMS

Among the inputs for the structural analyses is the definition of critical structural:

- 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 [12], shall be considered in the critical equipment/structure definition.

5. BLAST STRUCTURAL ASSESSMENT METHODOLOGY

The blast structural assessment methodology presented in this document is based on the Recommended Practice API RP 2TOP [8] and ISO 19.901:3 [16]. There are two different assessment methods that shall be performed:

i. Strength level blast analysis;
ii. Ductility level blast analysis;

The strength level analysis is a linear elastic analysis (static or quasi-static) with code checks, which provides a way to ensure that the primary structure will remain elastic and not be permanently damaged by the explosion. If the strength level analysis fails to satisfy the performance criteria, blast mitigation and/or structural modification shall be considered.

The ductility level analysis assesses the structural response accounting for geometric and material nonlinearities. Explicit computer program checks should be performed to verify that the structural performance is within acceptable limits. This analysis is to ensure that the structure will not collapse and that no local collapse escalates the personnel health and safety or environmental risk exposure. If the ductility level analysis fails to meet the performance criteria, blast mitigation and/or structural modification shall be considered.

The blast structural assessment workflow, as considered in this document, is presented in Figure 4.

In order to start the blast structural assessment, the blast scenario overpressure shall be obtained. Once the blast overpressure is defined, the structure shall be assessed with the two methods:

1. strength level blast analysis.
2. ductility level blast analyses.

The structure and facility needs to be verified to meet the acceptance criteria defined in the respective sections of this document.

Ductility level blast analysis may be avoided if strength level blast analysis is performed with DLB level blast overpressure defined in item 6.1 and the structure is able to comply with the criteria presented in item 6.3.

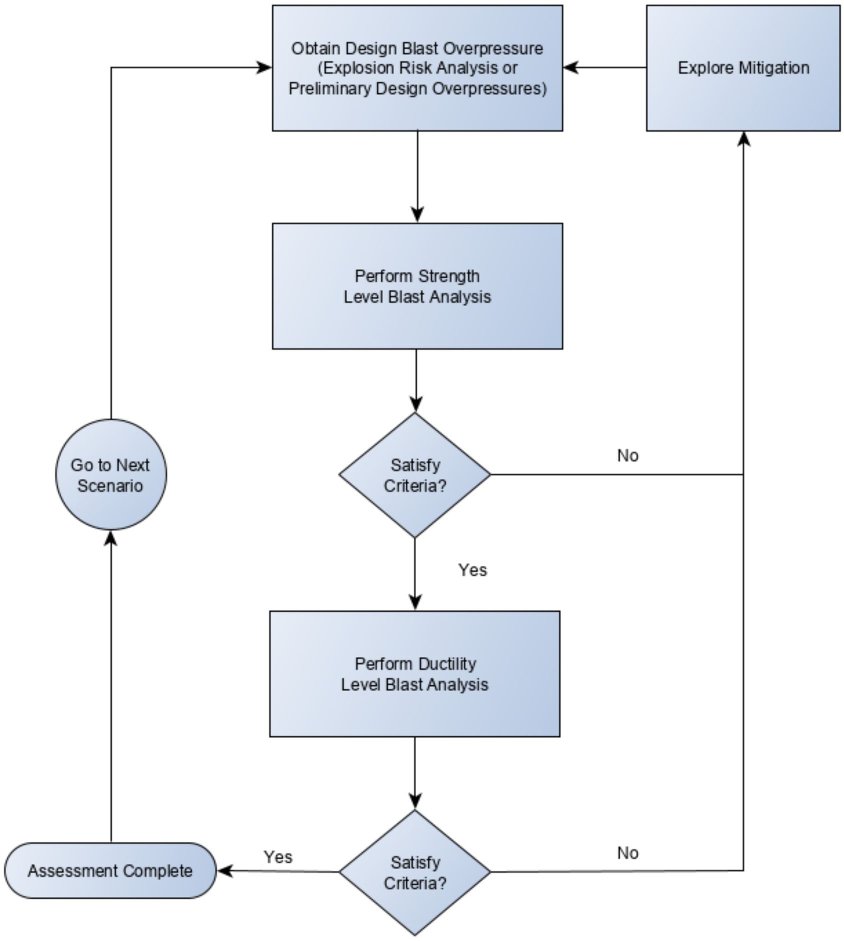

Figure 4 – Blast structural assessment workflow

6. METHODS FOR STRUCTURAL ANALYSIS

6.1. BLAST LOAD LEVELS

The blast assessment involves two event sizes:

1. Ductility Level Blast (DLB), a low probability high consequence event, associated with the annual occurrence frequency of 2.5×10^{-4}. For the main structure, the annual occurrence frequency of 1.0×10^{-4} shall be considered.
2. A higher likelihood but lower magnitude strength-level blast (SLB), associated with the annual occurrence frequency in the range between 1.0×10^{-2} [16] and 2.5×10^{-3}. The blast assessment should be performed using the SLB overpressure associated with the lowest occurrence frequency whenever possible. The minimum blast overpressure acceptable for the SLB is the blast overpressure corresponding to the annual occurrence frequency of 1.0×10^{-2}. The maximum SLB overpressure that the structure supports, within the frequency range above and without the need for mitigation shall also be defined.

In the absence of calculated pressures for the SLB level, the SLB overpressure can be taken as 1/3 of the DLB level blast overpressure.

6.2. DYNAMIC AMPLIFICATION FACTOR

Dynamic effects, where relevant, shall be captured by the chosen modeling technique. Any mass that is associated with in-place actions shall be included in a dynamic analysis. Dynamic amplification factor shall be considered in the blast structural assessment. For the ductility level blast, a non-linear dynamic finite element analysis might be performed, which evaluates the dynamic behavior of the structure and implicitly takes into account the dynamic amplification. For static or quasi-static analyses, the dynamic amplification factor shall be considered explicitly. Based on previous blast analyses, a DAF of 1.2 might be used. In case of equipment, DAF shall provided by vendor shall be adopted.

6.3. STRENGTH LEVEL ANALYSIS

The strength level analysis is a linear-elastic analysis of an equivalent static load corresponding to the blast overpressure that incorporates plastic code checks. The equivalent static load for the strength level analysis, P_{SLB}, is the peak overpressure considered from the strength level blast (SLB_{press}) scaled by a dynamic amplification factor (DAF):

$$P_{SLB} = DAF \cdot SLB_{press}$$

For the code check all load and material factors may be set to unity. If a WSD method is used then enhance the code allowable stresses by 1.67, which gives the allowable stress for a “yielding member” equal to the material guaranteed yield. The material yield can be enhanced by the strength increase factor according to Table 1. The allowable stresses can be increased by the dynamic increase factor according to Table 1. Then, the structural members are permitted to experience member utilization up to 1.0.

6.4. DUCTILITY LEVEL ANALYSIS

The nonlinear, elastoplastic method (ductility level blast analysis) shall be used to assess the structural response when exposed to a blast event while accounting for geometric and material nonlinearities. It is anticipated that standard code checks will not be applicable to this assessment and explicit checks shall be performed to verify that the structural performance is within acceptable limits. This type of analysis assumes the structure will undergo plastic deformation and acceptance criteria would be set using deformation limits, strain limits (i.e., steel rupture), potential for buckling, connection capacities, etc. Ultimately, the goal of the analysis is to ensure that the structure will not catastrophically collapse under the blast load and that no local collapse escalates the personnel health and safety or environmental risk exposure.

The following guidelines shall be followed when developing a DLB model:

- Mesh size shall be appropriate to capture global buckling effects (e.g., beam-column buckling);
- Section/material properties should be modified to properly account for the effects of local element buckling (e.g., local flange buckling in a deck beam). For some MDOF models, the mesh size may have to be fine enough to explicitly capture local buckling effects, but usually a global model is too large to allow for this level of refinement, therefore requiring additional checks;
- Material properties shall account for nonlinear material behavior with stress-strain curves from item 7.8 from [9];
- Geometric nonlinearities shall be captured (e.g., P-Delta effects);
- Strength increase factor should be used to account for the average or mean yield stress instead of the minimum specified yield stress;
- Strain-rate effects on the material yield may be considered as shown in Table 1
- Dynamic effects shall be accounted for;
- The nonlinear model used shall contain initial imperfections of sufficient magnitude to trigger critical local and global failure modes;
- In conjunction with the modelling of imperfections, it shall be ensured that the modelling of beams can allow torsional buckling behavior.

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

- Global structure stability shall be preserved at the end of the blast event 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 secondary structure shall avoid damage to critical equipment and piping supports, as defined according to 4.6.
- 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.

The main load-bearing primary structure which is one of the SCE and is fundamental to the support of the temporary refuge, the life boats and other components essential to the safety of the personnel shall retain sufficient integrity during accidental situations to provide:

- protection to personnel for a duration sufficient to effect their evacuation;
- protection to the environment for a duration sufficient to effect containment of hydrocarbon spillages from process equipment.

The criteria proposed in this section are based on performance and shall be complied with. In addition, for structural limits, the designer shall use the references from section 2 as guidance. Some structural limits are given below:

- Deformation limits: API RP-2TOP [8] section A.7.10.4.2.3;
- Strain Limits: API RP-2TOP [8] section A.7.10.4.2.4;
- Buckling: API RP-2TOP [8] section A.7.10.4.3.1, the effects of global member buckling in the global strength shall be captured by the model. Local buckling, not covered by the model, and its effects on global member bucking shall be addressed in accordance with recognized literature and Classification Society;
- Connection capacity: API RP-2TOP [8] section A.7.10.4.3.1, if not explicitly covered by the modelling technique, criteria shall be in accordance with recognized literature, provided that it is accepted by the Classification Society.

7. DELIVERABLES

The final report with the results from the blast structural analyses shall be delivered. The premises, model information, mechanical loads, load combinations, material properties, sectional properties, boundary conditions, dynamic amplification factors, dynamic increase factors, stress-strain curves, pressure-time curves and other relevant information regarding the structural analysis method performed shall be documented in the report. Code check settings and results as well as stress and strain plots shall be included in the reports if relevant to the chosen structural analysis method. Electronic model file shall be attached to the report.