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MQP Level 3

Instructions for Structural Analyses

This document provides instructions and guidelines for structural analyses and structural analysis reports. These instructions give:

- Requirements for performing structural analyses.
- Requirements for reports that document structural analyses.
- Guidance for how to comply with the requirements listed above.

Associated with this document are:

- A template for structural analysis reports
- Checklists for:
-- Reviewers
-- Independent Peer Reviewers
--Technical Checkers

The QA requirements given in the Procedure for Analyses and Calculations MQP document are implemented in this document.

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Change Log			
Instructions for Structural Analyses (35BVV3)			
Version	***Latest Status***	***Issue Date***	***Description of Change***
v0.0	In Work	21 Dec 2009	
v1.0	Signed	21 May 2010	First version.
v1.1	Approved	04 Jun 2010	Reference to the Magnet Structural Design Criteria has been changed to https://user.iter.org/IDM/Pages/DocumentSystem.aspx?uid=2NEA7A In the review scope of N. Taylor: The word "sufficient" was replaced with "adequate". The check of section 2.4 was removed. Typing mistakes pointed out have been corrected. The reviewers and approver specifications were made consistent with the sign-off specification for the ITER project, see section 2.4.
v2.0	Revision Required	24 Feb 2017	A major update to comply with the current requirements for MQP documents.
v2.1	Approved	19 Dec 2017	1. Technical requirements and guidance have been moved from the main body to appendices. 2. References have been split into References and Applicable Documents. 3. Reviewer checklists have been split into one for Reviewers and one for Independent Peer Reviewers. 4. The lists of checks performed by reviewers and technical checkers have been updated. An appendix has been added to define in detail what each check covers. 5. Chapters have been added to cover Workflow and Links with Other Processes. 6. The template for Structural Analysis Reports has been updated and uploaded as a stand-alone document in IDM. 7. Minor clarifications and improvements have been implemented throughout the document to address comments from reviewers to the pervious version.
v2.2	Signed	25 Mar 2020	As per approved MQP doc request https://user.iter.org/?uid=YQSXGS the changes are: The document was changed in the context of the IO Re-organization.
v2.3	Approved	16 Jun 2020	Under same doc request some minor changes are made as: Implemented comments from Eric Thomas on v2.1, namely: - Added reference to ITER_D_2NCULZ - §A.1.2: Rephrased the requirement to allow for non-approved (but still frozen) geometries. - §A.4.7.2: Priority is given to DET as a method to track the geometry used in the analyses.
v3.0	In Work	16 Dec 2020	As per approved MQP doc request https://user.iter.org/?uid=4AGYG2 the document has to be reviewed by DAs in order to be included in MPA.
v4.0	Signed	18 Dec 2020	As per approved MQP doc https://user.iter.org/?uid=4AGYG2 the document has to be reviewed by DAs in order to be included in MPA.

Table of Contents

1 Purpose

This document provides instructions and guidelines for structural analyses and structural analysis reports. These instructions give:

- Requirements for performing structural analyses.
- Requirements for reports that document structural analyses.
- Guidance for how to comply with the requirements listed above.

Associated with this document are:

- A template for structural analysis reports [8].
- Checklists for:
    - Reviewers [5]
    - Independent Peer Reviewers [6]
    - Technical Checkers [7].

The QA requirements given in the Procedure for Analyses and Calculations MQP document [1] are implemented in this document.

2 Scope

This document applies to the ITER Organization (IO) involved in the performance of structural analyses and calculations. It also applies to Domestic Agencies (DA) or external contractors who are asked to perform analysis or calculation tasks for the ITER project, see [1]. The rules governing the propagation of the requirements specified in these Instructions to external contractors or interveners are specified in [10], and shall be followed.

Thermal analysis is outside the scope of this document. However, this document does mention temperature, as it is often an input parameter in structural analysis.

These instructions cover the activities associated with planning, preparing, technical checking and reviewing, issuing, and revising structural analyses and calculations.

These instructions apply to the development of structural analyses and calculations of ITER Systems, Structures and Components (SSCs) of any Quality Class (QC). The instructions are mandatory when any of the following apply to a structural analysis or calculation:

- They are required or planned to be retained as a design verification and validation.
- They are required to document that an existing, modified, or proposed SSC will meet design or operational requirements.
- They constitute alternative calculations (see definition) for completing design verification of an SSC.
- They are required by other ITER procedures.

This process is not mandatory for preliminary or scoping calculations that are to be superseded by later analyses. For preliminary or scoping calculations, the Quality Assurance (QA) requirements shall be defined on a case-by case by the Analysis Coordinator, see [1] for the definition of the role of the Analysis Coordinator.

These instructions do not cover spot-checking or surveillance activities on Protection Important Activities (PIAs). Requirements for these activities are specified in [1].

This level 3 MQP document is generated from the level 2 MQP "Procedure for Analyses and Calculations" [1] in the scope of the process "Software Control and Model Development".

3 Definitions and acronyms

3.1 Definitions

Term	Definition
Computational model	The numerical implementation of the mathematical model, usually in the form of numerical discretization of the geometry, solution algorithm, and convergence criteria.
Conceptual model	The collection of assumptions and descriptions of physical processes representing the solid mechanics behaviour of the reality of interest from which the mathematical model and validation experiments can be constructed.
Discretization	The mapping of a continuous structure into discrete counterparts as it is done with a FE mesh.
Error	A recognisable deficiency in any phase or activity of modelling or experimentation that is not due to lack of knowledge, e.g. choosing an incorrect material property for use in the computational model, programming errors.
Margin	In these instructions, margin is defined as the difference in percent between the calculated result quantity $R_{calculated}$, e.g. membrane stress, and the allowable $R_{allowable}$: $\text{margin}\,[\%] = \frac{R_{allowable} - R_{calculated}}{R_{calculated}} \cdot 100\%$ In some calculations involving complex load combinations, different definitions of margin may be more appropriate.
Mathematical model	The mathematical equations, boundary values, initial conditions and modelling data needed to describe the conceptual model.
Structural analysis	The computation of deformations, internal forces, and stresses under consideration of physical laws and through the application of mathematical equations. It incorporates the fields of mechanics and dynamics as well as the failure theories of materials.
Uncertainty	A potential deficiency in any phase or activity of the modelling, computation or experimentation process that is due to inherent variability or lack of knowledge. Uncertainty can be as quantified as follows: $uncert.\,[\%] = \frac{R_{correct} - R_{calculation}}{R_{correct}} \cdot 100\%$ However, since a "correct" result in the ideal sense is not usually available, a result with an insignificant error can be considered correct.
Validation	The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the mathematical model. Validation is based on comparisons between numerical simulations and relevant experimental data.
Verification	In these instructions, verification is the process of determining that computational model accurately represents the conceptual model. Note that this definition is slightly broader than the ASME V&V definition, where verification is the process of determining that a computational model accurately represents the underlying mathematical model and its solutions [14].

Table 1 - Definitions.

The list of definitions used in this document is given in Table 1. These definitions supplement those in [1] where definitions are given for alternative calculations, analyses, calculations, calculation software, deliverables, independent calculations, independent peer reviewer, reviewer, technical checker, and technical checking.

3.2 Abbreviations

The list of abbreviations used in this document is given in Table 2. For a complete list of ITER abbreviations see ITER_D_2MU6W5 - ITER Abbreviations.

2D	Two-dimensional
3D	Three-dimensional
BC	Boundary Condition
CAD	Computer Aided Design
DET	Data Exchange Task
DoF	Degree of Freedom
EM	Electromagnetic
EPNS	Environmental Protection & Nuclear Safety
IDM	ITER Document Management system
INB	Installation Nucléaire de Base
IO	ITER Organization
FE	Finite Element
MQP	Management and Quality Program
PD	Plant Description, ITER_D_2X6K67
PIA	Protection Important Activity
PR	Project Requirements, ITER_D_27ZRW8
QA	Quality Assurance
QC	Quality Class
RO	Responsible Officer of the system, section leader or division head
SRD	System Requirement Document
SSC	System, Structure and Component
V&V	Verification and Validation

Table 2 - Abbreviations.

4 Applicable documents and References

4.1 Applicable Documents

[1] Procedure for Analyses and Calculations. 22MAL7.
[2] Instructions for the Storage of Analysis Models. U34WF3.
[3] Software Qualification Policy. KTU8HH.
[4] Order dated 7 February 2012 relating to the general technical regulations applicable to INB – EN. 7M2YKF.
[5] Reviewer Checklist for Structural Analyses. RYATXV v2.0.
[6] Independent Peer Reviewer Checklist for Structural Analyses. VQVFEN v1.0.
[7] Technical Checker Checklist for Structural Analyses. TK33SU v2.0.
[8] Template for Structural Analysis Reports. VQVTQW v1.0.
[9] Guideline-Framework Instruction for Safety Demonstration Art 3.8 INB Order. PQT8AC.
[10] Provisions for Implementation of the Generic Safety Requirements by the External Interveners. SBSTBM.

4.2 References

[11] Benchmark of Different ANSYS Shell Elements for Bending Stress Results. 2N5PU7.
[12] Procedure for the Preparation, Review and Approval of SRDs. 25DSU2.
[13] IO Generic Template. 34BAZX.
[14] ASME V&V 10-2006 – Guide for Verification and Validation in Computational Solid Mechanics.
[15] ASME V&V 10.1-2012 – An Illustration of the Concepts of Verification and Validation in Computational Solid Mechanics.
[16] ISO 16454-2007(E) Space systems - Structural design - Stress analysis requirements.
[17] Guideline for identification of the Protection important activities (PIA). SBYJXD.
[18] Quality Classification Determination. 24VQES.
[19] Load Specifications (LS). 222QGL.
[20] Procedure for ITER CAD Data Exchanges. 2NCULZ.

5 Basic Principles

The management requirements for structural analyses are those defined in [1]. Technical requirements for structural analyses are defined in Appendix A, and shall be followed.

6 Workflow

The workflow for structural analyses is defined in [1].

7 Responsibilities

General roles and responsibilities for analysis and calculations are defined in [1]. In this document the roles and responsibilities are defined for analyses conducted under different arrangements, for example:

- ITER Task Agreements (TAs) or Procurement Arrangements (PAs).
- Direct IO or DA contracts.
- Performed by IO or DA staff.

The requirements and responsibilities listed in [1] shall be applied to structural analyses and the associated reports. Additional clarifications on the roles and responsibilities for structural analyses are given in this chapter.

Document [1] defines the roles and responsibilities of the IO Responsible Officer, IO Analysis Coordinator or Requester, Contract Manager, Performer's Manager or Supervisor, Performer, Reviewer or Technical Checker, and of the Independent (Peer) Reviewer for all different types of Analyses and Calculations in general. The following chapter re-call some of them or further clarifies the specific roles within the context of the Structural Analysis process.

7.1 Performer

The performer executes and documents the analysis or calculation in accordance with these Instructions.

7.2 Approver of Analysis Report

The approver of the structural analysis report in IO IDM shall:

- Ensure that the performer, reviewers and technical checker are Suitably Qualified and Experienced Persons (SQEP).
- Ensure that any software tools are properly qualified.
- Ensure that the purpose and scope of the document are fully met.
- Ensure that the reviewers and technical checker fulfil the scope of their review.
- Ensure that the review has been exhaustive and certified. The review has included all necessary actors and interfaces, and covered all relevant aspects in relation to the purpose and scope of the analysis task. As a minimum this includes the reviews specified in Section 7.3.

7.3 Reviewers of Analysis Report

This section lists the minimum points that must be reviewed for structural analysis reports. The points are assigned to Reviewers, an Independent Peer Reviewer and a Technical Checker, see [1] for definitions. The outcomes of the reviews shall be stored in IO IDM as specified in Chapter 8.

To reduce the workload of the reviewers of the structural analysis report it is required to specify the scope of review of each reviewer. This scope can be defined either in the report itself, or else be done directly in IO IDM.

For the reviews defined in Subsections 7.3.2, 7.3.3 and 7.3.4, the use of different checklists may be used if these checklists are agreed in writing with the entity in the IO responsible for these Instructions. Based on the present IO organisation, the responsible entity is the Integrated Engineering Analysis Section of the Central Integration Office. A prerequisite for the use of alternative checklists is a demonstration that the alternate checklists are at least as comprehensive as the ones given in these Instructions.

7.3.1 EPNS Review

Analyses that are classified as Protection Important Activities (PIA) shall be reviewed by a member of the IO Environmental Protection & Nuclear Safety (EPNS) Division. The IO EPNS reviewer shall check that:

- safety requirements from the INB Order dated 7 February 2012 [4] are implemented and respected,
- the analysis method is consistent with the safety demonstration,
- the codes and calculation tools are consistent with the safety demonstration.

Guidelines for the identification of PIAs and quality classification determination are provided in [17] and [18] respectively.

7.3.2 Reviewers

The checks listed in Table 3 shall be performed. The review may be performed by a single Reviewer or be split between two or more Reviewers.

The requirements listed Table 29 shall be followed when performing a review. The outcome of the review shall be recorded using the template in [5].

Check ID	Check
R1	Report title, format and metadata
R2	Abstract, purpose and scope
R3	Scope of reviewers
R4	Definitions and abbreviations
R5	Units
R6	Geometry (excluding applicability)
R7	Applicability of geometry [1]
R8	Material properties (excluding applicability)
R9	Applicability of material properties [1]
R10	SDCs (excluding applicability)
R11	Applicability of SDCs [1]
R12	Loads (excluding applicability) [2]
R13	Applicability of loads [1]
R14	Conceptual model and analysis methodology
R15	Description of FE analyses (only applicable for FE analyses)
R16	Hand calculations (only applicable for hand calculations)
R17	Results
R18	Verification of FE analysis (only applicable for FE analyses)
R19	Conclusions
R20	References

Table 3 – Minimum checks to be performed by Reviewers.

7.3.3 Independent Peer Reviewers

The checks listed in Table 4 shall be performed by the Independent Peer Reviewer. Note that the list of checks is identical to that for Reviewers, except that there are no checks on the applicability of the geometry, material properties, SDCs or loads.

Also note that the requirement that check R12 be performed by the RO of the SLS of the SSC is only applicable to Reviewers, not to Independent Peer Reviewers.

The requirements listed Table 29 shall be followed when performing an independent peer review. The outcome of the review shall be recorded using the template in [6].

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[1] Checks concerning applicability shall be performed by the RO of the SSC.

[2] This check shall be performed by the RO of the SLS of the SSC. It is also recommended that the RO of the SLS checks how the loads are applied to the FE model (part of R15).

Check ID	Check
R1	Report title, format and metadata
R2	Abstract, purpose and scope
R3	Scope of reviewers
R4	Definitions and abbreviations
R5	Units
R6	Geometry (excluding applicability)
R8	Material properties (excluding applicability)
R10	SDCs (excluding applicability)
R12	Loads (excluding applicability)
R14	Conceptual model and analysis methodology
R15	Description of FE analysis (only applicable for FE analyses)
R16	Hand calculations (only applicable for hand calculations)
R17	Results
R18	Verification of FE analysis (only applicable for FE analyses)
R19	Conclusions
R20	References

Table 4 – Minimum checks to be performed by Independent Peer Reviewers.

7.3.4 Technical Checkers

The checks listed in Table 5 shall be performed by the Technical Checker:

Check ID	Check
TC1	Conceptual model and analysis methodology.
TC2	Mathematical model.
TC3	The analysis model is properly stored in the analysis database.
TC4	The model in the database matches the report.
TC5	The results of the model in the database match the description in the report.
TC6	Analysis results are reasonable, and hand calculations are correct.

Table 5 – Minimum checks to be performed by Technical Checkers.

The requirements listed in Table 30 shall be followed when performing a technical check. The outcome of the review shall be recorded using the template in [7].

8 Link with Other Processes

The links with other processes are defined in [1].

9 Outputs

Structural analysis reports shall be titled such that the scope of the analysis (Component, PBS, loads and failure modes) is described as well as possible within the confines of a reasonable number of characters.

Structural analysis reports that follow these instructions shall be uploaded in IO IDM as document type "Calculations" (Analysis and Calculation report following MQP procedure 22MAL7). Records of structural analyses that are outside the scope of these instructions shall not be uploaded as document type "Calculations". This is important, as it allows the project to determine which analysis reports can be used for design verification and validation purposes, see Chapter 2.

General requirements for the storage of analysis reports are given in [1].

All analysis models that support the analysis report shall be uploaded to the IO Analysis Model Database in accordance with [2]. If calculations are performed using software such as Excel or Mathcad, the relevant spreadsheets or worksheets shall also be uploaded to the analysis model database.

The following templates shall be used for documenting reviews and technical checks, unless otherwise agreed, see Section 7.3:

- Checklist for reviewers of structural analysis reports [5].
- Checklist for independent peer reviewers of structural analysis reports [6].
- Checklist for technical checkers of structural analysis reports [7].

Completed checklists shall be uploaded to IO IDM in a manner that makes it impossible to modify them at a later stage in an untraceable manner. The way that IO IDM is currently implemented, that excludes uploading the checklists as 'attachments' to the report. It is recommended to upload the checklists as attachments to 'comments'. If completed checklists are uploaded to IO IDM as stand-alone documents, they shall be uploaded as document type "Checklist for Analyses/Calculations" (Checklist for calculations, completed in accordance with MQP level 3 instructions made applicable by MQP procedure 22MAL7). Links shall be made from the analysis report to these checklists, thereby making it possible to identify that the review has been performed.

Appendix A Technical Requirements

The general requirements for analyses are given in [1]. The following chapter provides more specific requirements for the structural analysis domain.

Appendix A.1 Requirements for all Types of Structural Analyses

Appendix A.1.1 Conceptual Model and Analysis Method

The chosen conceptual model shall represent the physical reality sufficiently accurately to cover the intended purpose of the analysis. In order to do so it is necessary to have a clear definition of the intended use of the model.

Appropriate analysis method(s) shall be used. Note that hand calculations and finite element analyses are valid analysis methods, so long as they are used in an appropriate manner and domain.

Appendix A.1.2 Geometry

Analyses shall be based on geometry that is referenced through a frozen version of the CAD models consistent with the current design of the SSC. The uncertainty in the geometry, e.g. due to tolerances, shall be considered.

Analyses performed during or after the construction phase shall consider any relevant non-conformances.

Deviations from the current design geometry shall be justified. The quantitative effect of the deviations on the results shall be estimated, and considered in the conclusions of the analysis

Appendix A.1.3 Material properties

The analysis shall be based on referenced material properties that are consistent with the procured materials. The analysis shall also consider the uncertainties in material properties. A practical way of ensuring this during the design phase is to reference and use the minimum and/or maximum values specified in the applicable Structural Design Criteria.

Appendix A.1.4 Loads

All input loads used for analyses shall come from the relevant approved Load Specification.

Where there are uncertainties in the input data, the input data shall be considered in a conservative manner. This may require that more than one calculation is performed.

Appendix A.1.5 Units

All analyses shall be performed using S.I. base and derived units. The only exception to this rule is that degrees Celsius may be used instead of Kelvin. The table below lists the most common units used for structural analyses.

Quantity	**Unit name**	**Unit symbol**	**In SI base units**
Length	Meter	m[3]	
Mass	Kilogram	kg	
Time	Second	s	
Temperature	Kelvin	K	
	Celsius	°C	
Acceleration			m/s^2
Angular acceleration			rad/s^2
Angular velocity			rad/s
Density			kg/m^3
Energy, Work	Joule	J	N·m
Entropy			N·m/K
Force	Newton	N	$kg{\cdot}m/s^2$
Frequency	Hertz	Hz	1/s
Moment			N·m
Second moment of area			m^4
Power	Watt	W	N·m/s
Pressure	Pascal	Pa	N/m^2
Stress	Pascal	Pa	N/m^2
Young´s Modulus	Pascal	Pa	N/m^2
Thermal flux density			W/m^2
Velocity			m/s

Table 6 – List of S.I. Units

Appendix A.2 Additional Requirements for Finite Element Analyses

Appendix A.2.1 Software Package

Any software package used to perform FE analyses shall be validated. The software package shall be used in its validated domain.

If a validated Finite Element software package has non-negligible uncertainties when used properly, the uncertainties shall be covered either by performing sensitivity studies or by applying a suitable safety factor to the results.

[3] In ITER the reference unit of length is [m]. All FE models shall be made with lengths being defined in meters rather than for example mm. This simplifies the integration of different models, as well as the exchange of models between different IO divisions and IODAs. A standard unit of length also reduces the risk of mistakes which may occur when material properties are transferred between FE models with different units.

Appendix A.2.2 Coordinate systems

The global coordinate system for FE models shall have its positive z-axis pointing vertically upward. For equipment located in the Tokamak Complex it is recommended to use the ITER Tokamak Global Coordinate System, since it simplifies the possible integration of the FE model in a higher level model. In case this requirement causes particular disadvantages in the performance of the analysis a different origin may be chosen. One or more local coordinate systems may also be used.

Appendix A.2.3 Element Types and Shapes

The choice of element types and shapes shall be justified.

The choice of element type is partly a question of the geometric simplification that is introduced, e.g. beam, shell or solid elements. Such choices are justified as part of the justification of the conceptual model. However, the choice of element types is also a question of the assumptions that underpin each element type and its options.

Many FE elements have limits to the shape they can have whilst giving reliable results. The documentation for FE codes usually comes with definitions of acceptable shape criteria, such as Jacobian ratios. The software itself also usually comes with shape checking tools that check if the FE mesh respects these criteria. Shape checking shall be performed. If poor quality elements have been identified by the check, their use shall be justified.

Appendix B.5 gives some guidance on the choice of element types and shapes.

Appendix A.2.4 Solution Settings

The solution settings chosen for the analysis shall be documented and justified. Appendix B.8 gives some advice on this topic.

Appendix A.2.5 Verification

The accuracy of the results obtained with the FE model shall be verified by the performer of the analysis. The mandatory verifications listed here are partly based on [16]. The verification listed in Appendix B.12 is recommended when thermal expansion is relevant.

The results of these verifications of the FE model shall be reported in the analysis report. Appendix B.4 gives some background information on the necessity of the requirements.

Appendix A.2.5.1 Numerical Code Verification

The purpose of code verification is to check whether in the FE software the solution algorithms are correctly implemented. This is typically done by the software vendor for commercial software. Analysis software and its installation of the computer used for the analysis shall be qualified according to [3].

Appendix A.2.5.2 Mass Check

A mass check is only required if inertial effects are relevant to the analysis. This is the case in analyses that consider acceleration (e.g. gravity), transient analyses and modal analyses.

The total mass, centre of gravity, and second moments of inertia are usually calculated by default by FE codes. They are usually given in the general analysis output associated with the solution phase. The total mass, centre of gravity and if possible the inertia of the FE model shall be documented and compared to the values listed in the system load specification. Significant differences have to be explained, as such differences usually indicate modelling errors.

Appendix A.2.5.3 Gravity Load Check

A gravity load check is only required if gravity is part of the load case considered in the analysis. However, the usefulness of a gravity check is more general, and it is therefore recommended the check is always performed, especially for analyses involving inertial effects.

In a verifying analysis only gravity acceleration shall be applied to the final FE model. It shall be checked whether the reaction forces on the constraints of the FE model correspond to the weight of the FE model. In case the FE model has more than one constraint it shall be checked whether the distribution of the reaction forces is roughly consistent with the centre of gravity of the FE model.

Appendix A.2.5.4 Structural Load Check

The purpose of this check is to verify that the intended loads are applied correctly (magnitude, direction, etc.).

It shall be checked whether the total reaction forces and moments on the supporting constraints correspond to the total applied structural loads. This verifying analysis shall be static to prevent that dynamic effects influence the results. In case the FE model has more than one constraint it shall be checked whether the distribution of the reaction forces is reasonable.

If loads are transferred from other models (e.g. from electromagnetic, global dynamic or CFD models) the resulting reaction forces and moments from the different models shall be compared.

When complex structures made of several sub-structures are considered, the resulting forces and moments shall be checked for each sub-structure. The point(s) considered for the calculations of the moment(s) shall be reported.

In the special case that the applied structural loads cancel each other out, e.g. internal pressure in pressure vessels or restrained thermal expansion, it shall be verified that the magnitude of the applied loads is approximately correct. One or more simple hand calculations usually accomplish this purpose, e.g.:

- The circumferential membrane stress in a pipe due to internal pressure can be calculated by hand and compared to the analysis result.

- The magnitude of applied pretension in bolts shall be verified. Based on the preload and the cross-sectional area of the bolt, the pretension can be calculated by hand. This can then be compared to the stress in bolt calculated by the FE analysis.
- The internal strain energy in the model (calculated by the FE code) can be compared to the work done by the external loads.

Appendix A.2.5.5 Contact Check

This check is only required if contact elements are used.

It shall be demonstrated that the behaviour of the contact elements is as intended. In order to reduce the probability of such errors, it is recommended that the guidance in Appendix B.9 is followed.

Appendix A.2.5.6 Damping Check

This check is only required if structural damping is used, typically for dynamic analyses.

It shall be demonstrated that damping has been applied as intended. Appendix B.11 gives some guidance for the use of damping, and how its application can be verified.

Appendix A.2.5.7 FE Mesh Discretization

A common cause of poor accuracy in FE models is insufficient mesh density. The FE code does not warn the user of inaccuracies due to too coarse a mesh. The mesh density shall therefore be justified, and the sensitivity of the results to the mesh density shall be considered in the interpretation of the results. Several methods exist for this, but Appendix B.3 gives some guidance in this regard.

Appendix A.2.5.8 Comparison with Alternative Results

A verification of calculated results with alternative calculations shall be performed for every FE analysis. Alternative results can be obtained with any of the following methods:

- A hand calculation (usually the analytical result of a simplified conceptual model).
- The same analysis performed with a different, already verified FE model that is validated to be suitable for the analysis task.
- By performing a comparable FE analysis independently (or referring to a previous independently performed analysis). Being performed independently includes that it is performed by a different structural analyst based on comparable input data such as geometry, material properties, and loads. The FE mesh, the boundary conditions, and load application must be created anew, and the element types, real constants, and solution settings must be chosen anew, i.e. not copied from the original analysis. Also the conclusions must be drawn independently from the independent analysis results.

All methods have in common that the results are obtained in an alternative way that bypasses possible sources of error and uncertainty in the FE analysis.

In case more than one type of result is intended to be obtained by the structural analysis, alternative results may be required for each type of result.

Appendix A.3 Additional Requirements for Hand Calculations

An essential part of a hand calculation is the justification of the conceptual model that the hand calculation is based on, see subsection Appendix A.1.1.

The estimated accuracy of the hand calculation must be stated, along with the consequently chosen uncertainty factor. Note that no uncertainty factor is required when the hand calculations are performed following ‘Design by Formula’ structural design criteria.

All equations used in the calculation shall be shown. A reference shall be given for any non-trivial analytical formulas used. To improve the clarity it is recommended to use an equation editor. Equations shall be referenced, for example using the format below:

Second moment of area *I* can be calculated as in **(Eq. 1)** and **(Eq. 2)**:

$$I = \frac{bh^3}{12} \qquad \textbf{(Eq. 1)}$$

$$= 2.554 \times 10^{-6}\ \text{m}^4 \qquad \textbf{(Eq. 2)}$$

where b = 1.135 m, the width of the cross-section
h = 0.03 m, the height of the cross-section

- In the first part the equation is given using symbols.
- The result shall be given including the unit.
- All symbols used in the equation shall be defined somewhere in the document.

Appendix A.4 Requirements for Structural Analysis Reports

This section covers the requirements for structural analysis reports. Analyses performed inside IO shall follow the template for structural analysis reports, [8]. This is based on the IO Generic Template for documents, [13]. DAs and subcontractors may use their own templates, but the reports shall contain all of the contents described in this section.

Structural analysis reports should be provided in Microsoft Word format (.doc or .docx) in order to facilitate revisions and updates. If final reports are provided in “pdf” format, the Word version shall be stored in IO IDM as an attached file.

It is recognised that structural analysis reports can serve a wide range of purposes, and that a fixed list of section headings is not always appropriate. The list of headings covered here is appropriate in most cases. If any of the sections listed here are not applicable for a particular report, the sections shall be included, along with the text “Not applicable” underneath it.
The author should add additional sections if these are required. This is especially the case when a single document reports about both seismic and structural analyses. In this case, the report template prescribed by the seismic MQP instructions can be merged to the one for structural analyses.

The headings in this section are capitalised to indicate that they correspond directly to headings in the template for structural analysis reports.

Appendix A.4.1 ABSTRACT

The abstract of the structural analysis report shall contain the following information:

- The ITER SSC to which the structural analysis is related.
- The assessed components or parts of the system. PBS codes should be used where practical.
- The type of failure modes that were assessed, e.g. buckling or fatigue, if applicable.
- The loads or load combinations that were considered in the structural analysis.
- Any recent significant changes of design, structural design criteria or load specification.
- A statement that the report was written following these Instructions, and that the loads applied in the assessments are consistent with the system load specification.

Appendix A.4.2 CHANGE LOG

This section is mandatory, unless changes are logged using the in-built feature in IO IDM.

This section contains a log of the changes made to the document between different versions. If changes are not logged directly in IO IDM, they can be logged using the format below.

Version	**Location**	**Change**
1.1	2.2	The following sentence was inserted: Masses are occasionally given in metric tonnes instead of kilos.
	Appendix A	The presentation of the stiffness and flexibility matrices was improved.
1.0		First version.

Appendix A.4.3 SCOPE OF REVIEWERS

The scope of the review shall be specified for each reviewer, allowing each reviewer to focus on his/her part. Chapter 7 defines the required reviewers and their scope. Additional reviewers can be added.

The scope of reviewers can be specified either in the analysis report itself or directly in IO IDM. The former is often necessary due to the character limits of the relevant fields in IO IDM. This section is mandatory, unless the scope of reviewers is specified directly in IO IDM. If the scope of reviewers is not specified directly in IO IDM, it can be specified using the format below.

Reviewer	**Scope of review**
J. Bloggs	Reviewer o R1. Report format. o R2. Abstract, purpose and scope. o …
J. Smith	Reviewer (Load Specification)

	o R12. Loads (excluding applicability). o Part of R15. The described application of loads to the FE model is consistent with the System Load Specification.

Appendix A.4.4 PURPOSE

This section of the report outlines the aim of the report.

Appendix A.4.5 SCOPE

This section should contain a description of the parts of the ITER Project to which the document applies. It may also be necessary to define areas where this document is NOT applicable. Applicability can typically be defined in terms of:

- Geometry – e.g. pressure vessel with its nozzle but not the connected pipe and its weld. PBS codes should be used where practical.
- Loads – e.g. only the category-I-to-IV loads specified in the SLS [x], without any Beyond Design Basis ones.
- Results – e.g. margins against code criteria for plastic instability. Service limits, buckling, fatigue and ratchetting are not covered.
- Context – e.g. Preliminary Design Review.

Appendix A.4.6 DEFINITIONS AND ABBREVIATIONS

This section shall contain lists of all definitions and abbreviations used in the document.

Appendix A.4.6.1 DEFINITIONS

This section is only required if certain terms have specific meaning in the context of this document, that is outside the normally accepted dictionary definitions. As an example, see Table 7.

Term	**Definition**
Computational model	The numerical implementation of the mathematical model, usually in the form of numerical discretization of the geometry, solution algorithm, and convergence criteria.
Validation	The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the mathematical model. Validation is based on comparisons between numerical simulations and relevant experimental data.

Table 7 – Definitions.

Appendix A.4.6.2 ABBREVIATIONS

All abbreviations and acronyms used in the report shall be listed in alphabetical order, e.g. as below:

BC	Boundary Condition
EM	ElectroMagnetic
FE	Finite Element

Table 8 – Abbreviations.

For a complete list of standard ITER abbreviations see: ITER_D_2MU6W5 - ITER Abbreviations.

Appendix A.4.7 UNITS AND INPUT DATA

Appendix A.4.7.1 UNITS

All units used in the analyses and the analysis report shall be listed. These units shall be S.I. base and derived units. Whilst FE models shall be always created using S.I. units, analysis reports may use standard S.I. prefixes to aid presentation. For example, whilst Young's Modulus in an FE model shall always be defined in Pa, the analysis report could list this parameter in GPa.

Appendix A.4.7.2 GEOMETRY

A figure of the geometry used in the structural analysis shall be shown, and the main dimensions relevant to the analysis indicated. Special attributes of the geometry that cannot be easily recognized in a figure and that are relevant to the analysis shall be described, e.g. clearance of pins or geometrical imperfections.

In case geometrical imperfections are considered in the analysis, which are not contained in the initial geometry but are imposed through a modification of the initial FE mesh (e.g. after a linear buckling analysis), these imperfections shall be described in the results section. The maximum magnitude(s) of the imperfections shall however be stated in this section.

The geometry used to build the geometry of the FE model must be unambiguously traceable. This can be achieved by:

- Providing references to the relevant approved CAD files, drawings or Data Exchange Task (DET) [20].
- Including a full set of dimensions and/or drawings in the analysis report.
- Attaching CAD files or drawings to the FE model in the ITER Analysis Model Database.

Appendix A.4.7.3 MATERIAL PROPERTIES

The physical material properties of the analysed SSC shall be listed here. These material properties shall be traceable, and consistent with the procured materials.

Material properties can be reported in tables like the ones below. It shall be clearly documented which parts are made from which materials. This can for example be done by adding a column to the table below. The link between materials and geometry can also be made in the preceding "Geometry" section.

Material designation	Property	Notation	Value	Unit	Source
X2CrNiMo 17-12-2 austenitic stainless steel plate (Grade 1.4404)	Young's modulus	E	200	GPa	[X] §A3.3S.22
	Poisson's ratio	ν	0.3	-	[X] §A3.3S.23
	Density	ρ	7930	kg/m^3	[X] §A3.3S.24
	Allowable stress for Class-1 components	S_m	127	MPa	[X] §A3.3S.43
16Cr–12Ni–2Mo Stainless steel type 316L - plate (UNS designation S31603)	Modulus of Elasticity	E	195	GPa	[Y] §II.D Table TM-1 Group G
	Poisson's ratio	ν	0.31	-	[Y] §II.D Table PRD High alloy steels (300 series)
	Density	ρ	8030	kg/m^3	
	Allowable stress for Class-1 components	S_m	115	MPa	[Y] §II.D Table 2A Line 36

Table 9 – Example table of material properties at 20°C. In this example, [X] is RCC-MRX 2015, [Y] is ASME BPVC 2015.

Appendix A.4.7.4 STRUCTURAL DESIGN CRITERIA

The design code applicable to the analysis of the system shall be stated here. This shall be consistent with the definition in the relevant SRD, in the section "Applicable Codes and Standards", see [12].

The rules and limits from the design code applicable to this structural analysis shall be extracted from the design code and summarized here. Since design codes are written in a very general manner, it is often difficult to comprehend how they apply to specific cases. It is therefore recommended to explain how the design code applies to the structural analysis.

The service limits of the system are usually not given in the design code but are listed in the SRD or another related document. The corresponding reference shall be given and the service limits applicable to this structural analysis shall be listed, e.g. maximum service temperature, allowable displacements etc.

Appendix A.4.7.5 DAMPING

If damping is considered in a model, the level of damping shall be listed here. The level of damping shall be justified, for example by referring to the applicable SLS.

Appendix A.4.7.6 LOADS

All input loads used for analyses shall be listed here, with reference to the applicable System Load Specification. All loads shall be described clearly and unambiguously. Where there is uncertainty in the loads, these uncertainties shall be reported.

For transient loads the time functions of all loads shall be given either in form of a table or on a diagram that allows the identification of characteristic magnitudes of the load time functions. Loads that are shown graphically should also be defined numerically. Lengthy input may be put in appendices or in attached text files or spreadsheets.

Appendix A.4.8 METHODOLOGY

The principle of the analysis approach shall be described. This is especially important if the analysis involves multiple steps or different analysis types. An example of this would be using the results of a linear buckling analysis to determine a geometrical imperfection that is used as input for a non-linear buckling analysis.

The conceptual model shall be justified, in particular the inherent simplifications compared to the physical reality. Appendix B.2 gives some advice on this topic. Where simplifications, e.g. linear material properties, are allowed/required by the structural design criteria, it can simply be stated that the simplification is in accordance with the chosen design criteria.

It shall be justified that the analysis methods are used in their validated domains. If the analysis method is allowed/required by the structural design criteria, it can simply be stated that the method is in accordance with the chosen design criteria.

Sensitivity studies may be required if the conceptual model or analysis method cannot be justified by referring to the structural design criteria.

Appendix A.4.9 DESCRIPTION OF FE ANALYSIS

This section is mandatory if the report concerns an FE analysis. All subsections are mandatory, unless stated otherwise.

Appendix A.4.9.1 TYPE OF ANALYSIS

The type of analysis shall be stated, e.g. 3D static linear elastic analysis.

Appendix A.4.9.2 SOFTWARE PACKAGE

The name and version number of the software package used for the analysis shall be stated, e.g. "The FE analysis was performed using ANSYS 17.1 Mechanical APDL".

In case analyses are classified as PIA, the performer has to check that the software package is accepted as validated by the responsible entity in the IO safety department. Based on the present IO organisation, that is the EPNS Division. It shall be justified that the software package is used in its validated domain.

It shall be stated what uncertainties, if any, are associated with the use of the validated Finite Element software package for the reported analysis.

Appendix A.4.9.3 COORDINATE SYSTEM(S)

All coordinate systems used in the FE analysis shall be defined. This includes but is not limited to the following:

- Local coordinate systems that are used for boundary conditions and load application.
- Coordinate systems used for results.
- The global coordinate system in which the FE model geometry is created.

Appendix A.4.9.4 FE MATERIAL PROPERTIES

All material properties used in the FE model shall be listed. These may be different from the physical material properties, for example when ‘smeared’ material properties are used, or when material densities are modified to match masses listed in the System Load Specification. In case the physical material properties are used in the FE model it is acceptable to combine the requirements of this section with those of Appendix A.4.7.3, and report all of the required information in a single paragraph.

In case tuned densities are used, they should be compared to the theoretical values. Significant discrepancies should be explained, as they often indicate problems with the FE model.

Since material properties are usually temperature dependent, the assumed temperature(s) of the structure could be stated in this section.

Material properties can be reported in tables like the ones below.

Part	**Material number**	**Young’s modulus (GPa)**	**Poisson’s ratio ( )**	**Density (kg/m^3)**
Top lid	1	195	0.31	8600
Upper cylinder	2	195	0.31	8800
Lower cylinder	3	195	0.31	8430

Table 10 – Example table of material properties 1. Young’s modulus and Poisson’s ratio from [X], densities have been modified to ensure that the mass of each component matches the values given in the Load Specification [Y].

Material		Part	Material properties				
#	Name		Name	Notation	Value	Unit	Source
1	Stainless steel 304(L)	Top lid	Young's modulus	EX	195	GPa	[X] p.165
			Poisson's ratio (minor)	NUXY	0.31		[X] p.180
			Density	DENS	8600	kg/m^3	[X] p.201
2	Stainless steel 304(L)	Upper cylinder	Young's modulus	EX	195	GPa	…
			Poisson's ratio (minor)	NUXY	0.31		…
			Density	DENS	8800	kg/m^3	…
3	Stainless steel 304(L)	Lower cylinder	Young's modulus	EX	195	GPa	…
			Poisson's ratio (minor)	NUXY	0.31		…
			Density	DENS	8430	kg/m^3	…

Table 11 – Example table of material properties 2.

Appendix A.4.9.5 FE MESH

This section is mandatory, but the subheadings may change depending on the analysis software. It has to include a comprehensive description of the mesh used i.e. element shapes, order, formulation and settings.
Appendix B.15 gives some guidance on how to report the FE mesh.

Appendix A.4.9.6 BOUNDARY CONDITIONS

Each set of boundary conditions (BCs) shall be described, including degrees of freedom and the coordinate system. The BCs shall also be shown on a figure.

In case the BCs are not constant throughout the analysis, the changes shall be described.

Internal constraints (e.g. coupled equations) shall be described in this section Boundary Conditions or in a separate section. They shall also be shown in one or more figures.

Usually the boundary conditions of the structure under consideration represent either the surrounding structures or a part of the structure not represented in the FE model (e.g. in case of symmetric boundary conditions). Often the surrounding structures are assumed to have infinite stiffness (structural analysis), e.g. when applying fixed displacement constraints.

The basic principles of the constraints are part of the justification of the conceptual model, and should therefore be justified in section Appendix A.1.1. Such justification does not need to be duplicated here. This paragraph should focus on their implementation in the FE model, for example: The rotation and translation of surface X is restrained by setting all Degrees of Freedom (DoFs) of all nodes of the surface to zero.

Appendix A.4.9.7 LOAD APPLICATION

This section covers how the defined loads are applied to the FE model.

Note that the loads applied to an FE model may be different from those defined in the Loads section (Appendix A.4.7.6). An example of this could be the internal pressure applied to a moderately thick pressure vessel modelled using shell elements at the mid-plane. In this case it may be appropriate to reduce the element pressure based on the ratio of mid-plane to internal radii, such that the hoop stresses are calculated correctly.

Appendix A.4.9.8 SOLUTION SETTINGS

The solution settings shall be listed and justified. Some examples of how solution settings can be reported are given in Appendix B.8.

Appendix A.4.10 RESULTS

- All results values shall be given with their units (including graphs and contour plots). Clear titles shall be given when presenting graphs.
- All relevant results to meet the scope of the structural analysis shall be given. In case a large number of similar results are calculated it may be more practical to present some results either in appendices or in attached spreadsheets.
- In case an uncertainty factor is applied to the results to account for the uncertainties of the structural analysis, it is recommended to give in the Results chapter the result value found in the analysis excluding the uncertainty factor. The uncertainty factor should however be mentioned. It is recommended to apply the uncertainty factor to the results in a separate section or in the conclusions.
- Results shall be given corresponding to the design criteria. For example if the failure is membrane plus bending stress, peak stresses are not required.
- When giving reaction forces or moments the direction of a positive reaction force shall be specified or shown in a figure, unless it is obvious. As the direction is dependent on the component the load is acting on, the latter shall be specified. For example "forces applied by component X to the supporting structure".
- The point of summation of moments shall also be explicitly stated.
- The coordinate system used for the results shall be specified.
- If modal damping is used for response spectrum or mode-superposition transient analyses, the damping ratio for each mode shall be reported.

For each type of result (e.g. buckling load factor, maximum displacement, etc.) the result values that are most critical - due to the related load case or the associated location in the structure - shall be compared to the relevant structural design criteria.

Appendix A.4.11 VERIFICATION OF THE FE ANALYSIS

This section is mandatory if the report concerns an FE analysis. The results of all of the checks listed in Sub-section Appendix A.2.5 and applicable to the structural analysis shall be reported here.

A comparison shall be made between the results of the FE analysis and those of the alternative calculation(s), see paragraph Appendix A.2.5.8. An example of how this could be presented is shown below:

Type of Result	Result of this analysis	Result of independent assessment	Difference	Reference
Circumferential	55 MPa	60 MPa	9 %	

membrane stress in pipe due to internal pressure				
End deflection of structure due to gravity	9.8 mm	11.0 mm	11 %	

Table 12 – Example of how the results of an FE analysis could be compared to results from alternative calculations.

The reference can be another document, or a different section in the analysis report, e.g. in case of a hand calculation.

Appendix A.4.12 CONCLUSIONS

- The conclusions shall summarize the most significant findings, and be comprehensible for persons familiar with the design and loads of the system, with an engineering background but not necessarily with expertise in structural analyses.
- The scope of the structural analysis should be recalled before writing the conclusions.
- The result values given in the conclusions shall consider the uncertainty of the structural analysis. Appendix B.4 gives some advice on this topic.
- Results for which the FE model cannot meet accuracy requirements shall either not be reported or be marked as "preliminary" or "best estimates".
- Result values shall not be given without a judgement. Rather than an absolute judgement (e.g. "the design criteria are met") it is recommended to make quantitative judgements, e.g. the margin to the structural design criteria.
- If appropriate, recommendations for improvements of the structure can be given in the conclusion chapter or in a separate chapter.

Appendix A.4.13 REFERENCES

- All documents that are referenced by the analysis report shall be listed here.
- References shall be stored in IO IDM or be publically available (e.g. design codes or engineering handbooks).
- References shall be approved.
- References to IO IDM documents shall include the version numbers.
- An approver and at least one reviewer must be assigned to a reference.
- It is recommended that use is made of the cross-reference or bibliography capability in MS Word.

Appendix A.4.14 APPENDIX A

Appendices can be included if appropriate.

Appendix B General Guidance and Advice

This document is not intended to be a manual for how to perform structural analyses. Nonetheless, this chapter contains some advice and guidance on the topic. The chapter does not introduce any compulsory requirements.

Appendix B.1 General Starting Tips

Before starting any analysis, it is useful to create a plan for the analysis. Such plans are usually written by the performer of the analysis. All information required to start the analysis is gathered, and the whole sequence of tasks up to the approval of the analysis report is planned. The plan is then presented to the Technical Responsible Office for discussion and agreement. This reduces the probability of misunderstandings and wasted effort.

In particular, the following points are worth considering before analyses are started:

- Identify purpose and scope:
  - It is recommended to discuss early with the author of the structural integrity report the desired outcome of the structural analysis and its possible extension following the first results. The section "Scope" of the analysis report should be written as early as possible.
  - Awareness of the assessed failure mode(s) as well as of the applicable structural design criteria usually helps in the preparation of the analysis process as the required results become clear.
- Identify Suitably Experienced and Qualified Persons to perform and review the analyses. Both managers and performers must understand that this is a requirement, not a ‘nice-to-have’. Respecting this requirement from the start of the analysis process typically saves time in the long run.
- Identify inputs:
  - Verify the maturity, state, and correctness of the geometry that the analysis is based on.
  - Ensure that the material properties are according to those referenced in the system specification (e.g. SRD).
  - It is recommended to discuss early the status of the system load specification with its author. The purpose of this is to ensure that:
    - All necessary loads and Boundary Conditions (BCs) are specified before the structural analysis is performed.
    - The performer has interpreted the Load Specification correctly.

    Moreover, if loads are likely to change in the future it is usually also time-saving to identify this at the start of the analysis process.
- Estimate likely results:
  - Before starting the analysis it is good practice to make an estimate of the expected results. This exercise usually helps to understand the structural behaviour of the structure and to focus the attention to the essential points. It also helps to prevent gross mistakes in the analysis. It is not required to report this initial estimate.
- Reporting:

- Make a prediction of the type and format of the results presented in the analysis report. Doing this before starting the analysis process helps to ensure that the analysis plan does not overlook any tasks.
- A template for structural analysis reports is available in [8]. It is strongly recommended to use this template, but the structure of the document may be modified to account for the particularities of the analysis (see Appendix A.4).

Appendix B.2 Justification of Conceptual Model

The physical principles adopted in the conceptual model generally idealize and hence simplify the physical reality. Such simplifications include, amongst others:

- The application of fixed displacement constraints. Here the stiffness of the surrounding structure is assumed to be infinite. This includes displacements imposed on the boundaries of submodels.
- Parts or the entire model are assumed to have linear or constant material properties, e.g. those parts are assumed not to yield or their properties are assumed not to be dependent on temperature.
- When beam or shell theory is used it is typically assumed that that the cross section remains plane. Deformation due to shear may or may not be taken into account.
- When hinges are assumed, the resisting moment at the hinge is often assumed to be negligible.
- When a structure is assumed to act as a truss, the elements in the truss are usually assumed to transfer axial forces but no bending moments.
- The application of loads in an idealised manner, e.g. point loads or uniform pressure distributions.
- The manner in which structural damping is considered.

In particular the most important simplifications that the chosen model contains shall be listed. Examples include:

- Simplifying assumptions related to contact, e.g. uniform friction coefficient, thermal contact conductance independent of contact pressure, corrected contact geometry.
- Neglected nonlinearities, e.g. small gaps, damping, the application of the load to the initial undeformed structure, linear isotropic material properties.
- Neglected dynamic amplification.
- Neglected geometrical imperfections and tolerances (e.g. use of nominal dimensions).
- Neglected thermal expansion.
- Neglected or simplified loads, e.g. radiation heat, dead weight or coolant or hydrostatic pressure.
- Simplified mass distributions, for example by assuming that mass is located at a single point.
- Structural elements of the model assumed to have infinite stiffness, e.g. when linking the degrees of freedom of two non-coincident nodes with constraint equations.
- Geometric simplifications, e.g. neglected holes, chamfers, fillets.

Justification shall be given for each simplification or assumption. Short, logical arguments are often sufficient to meet this requirement, but sensitivity studies may be necessary in some cases. Examples justifications could include:

- Non-consideration of fillets: The effect of the fillets is only to reduce peak stresses, which are not within the scope of this analysis. Their contribution to the global stiffness of the structure is negligible and beneficial.
- Consideration of a part A as a point mass element: The single mass element representing part A has the same influence on the intended results of this analysis as a detailed model of part A would have since the intended results are not from within part A or near the interface between part A and the rest of the system.

Appendix B.3 Mesh Discretisation

With the exception of stress and strain at geometric discontinuities, results of FE analyses usually tend toward the correct value as mesh density increases. To verify that the mesh density is sufficient it is suggested to obtain results for several different mesh densities. Based on such sensitivity analyses it is usually possible to determine what uncertainty is associated with mesh discretisation. One method for doing this is Richard extrapolation, with ASME V&V 10.1 giving a good example, see [15].

Beyond that, this section also contains some guidance for minimum mesh densities and related uncertainty factors. The given recommendations are based on the experience with ANSYS FE models, but other FE codes will tend to require similar mesh densities.

Note that the verification of the mesh density cannot be avoided even if the recommendations given in this section are followed. It remains the responsibility of the performer to verify the FE model. Such benchmarking always requires the generation of multiple meshes with different mesh densities. Different uncertainty factors than those given here may be applied if justified by an appropriate benchmarking of the mesh density, which shall be reported in the analysis report.

Appendix B.3.1 Fillets

When calculating peak stress in a fillet, it is recommended that a minimum of 6 nodes should lie on a 90° fillet line. Table 13 gives an indication of the uncertainty in the peak stress in a fillet as a function of the number of nodes on the fillet line. However, as the uncertainty is a function of several parameters these value should only be taken as an indication.

Number of nodes on the fillet line	6	8	12	16
Minimum uncertainty factor	1.5	1.25	1.15	1.07

Table 13 - Approximate uncertainty factors on peak stress in a fillet as a function of mesh discretisation.

It is also possible to calculate peak stresses in fillets by multiplying the linearized stresses by a stress concentration factor. This approach usually requires fewer elements in the FE model.

Appendix B.3.2 Shell Type Structures Modelled Using Solid Elements

When modelling shell type structures using solid elements, and stress results are required, it is recommended that at least four nodes should be used though the thickness of the shell. It is also recommended that least twelve nodes should be used between two locations where the bending moment is zero (l_{field}), see Figure 1.

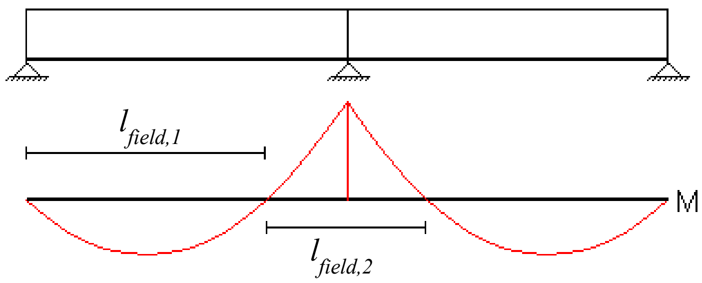


Figure 1 - Definition of l_{field}, distance between two locations where the bending moment is zero.

Appendix B.4 Analysis Verification and Accuracy of Results

Having selected and justified the conceptual model and analysis method, the accuracy of the results obtained with an FE model shall be verified by the performer of the analysis. Generally speaking, determining whether or not the FE model accurately represents the conceptual model is done in two ways:

- Eliminating characteristics of the FE model that could cause imprecision or errors in the results.
- Comparing obtained results from the FE analysis with those from alternative calculations.

The purpose of the verification of the FE model is two-fold. The first is to ensure that there are no errors in the analysis. In this sense, errors are deficiencies in any phase or activity of modelling or experimentation that is not due to lack of knowledge.

The second purpose of the verification process is the quantification of the maximum expected uncertainty associated with the different types of results that are intended to be obtained with the FE model and, if applicable, the different types of loads. Note that in FE analyses, the uncertainties in local stresses, strains and other element results are often much larger than the uncertainties in global displacements or temperature distributions.

It is common practice to apply an uncertainty factor to the obtained results to account for possible uncertainties in the input data or the conceptual model. The accuracy requirement for the FE model depends on the intended use and usually requires engineering judgement. A general rule is that the required accuracy is the minimum accuracy for which meaningful conservative results can be obtained through the application of a defined uncertainty factor.

As stated in Appendix A.4.12, the result values given in the report shall consider the uncertainty of the structural analysis. It may be that the accuracy goal is met only partially, e.g. for certain types of loads or for certain types of results only.

Errors and uncertainties in FE results can occur due to a number of causes and it is the duty of the performer to prevent errors and keep uncertainty to an acceptable level. Since it is often difficult to exclude all possible sources of errors and quantify all uncertainties in an FE analysis, results from FE analyses shall be verified by comparing them with results from an alternative calculation.

The purpose of these requirements is to support the performer to produce reliable results by excluding certain well-known sources of errors in FE analyses. Individual checks may be dropped if the consequent effects on the analysis results are quantified and considered in the analysis conclusions. Engineering judgement combined with the results of the verification checks can be used to determine the uncertainty in an analysis.

Note that compliance with the verification requirements does not release the performer from his/her responsibility to report correct and reliable results.

Appendix B.5 Element Types and Shapes

One cause of wrong results is use of inappropriate element types or element shapes. This section gives some guidance for common pit-falls to avoid.

- Using shell and beam elements often means that the effective length of structural elements is overestimated. For example, in a shell model of a building, the length of a slab between two walls would typically be measured from mid-plane to mid-plane. This would overestimate the length of the span by the width of the wall. Beam and shell elements are therefore most appropriate in slender structure. A good rule of thumb is that structures with slenderness ratios over 20 should be modelled using shells or beams.
- When using shell and beam elements the performer should be aware of whether or not shear deformation is likely to be important, and whether or not the element formulation includes shear deformation. Shear deformation can usually be ignored in slender structures.
- Many FE codes struggle to give accurate results when using linear (i.e. without mid-side nodes) degenerate (e.g. triangular or tetrahedral) elements.
- In ANSYS, the shell element type SHELL181 typically needs a very fine mesh to converge to the correct solution for bending stress. However, this will become apparent during a mesh-sensitivity study. SHELL281 has been found to require a much smaller number of nodes to reach the converged solution. A study highlighting this problem can be found [11].
- In solid models, parabolic tetrahedra, parabolic hexahedra and linear hexahedra are roughly equivalent terms of the solution accuracy that can be achieved for a given number of DoFs. Linear tetrahedra tend to perform less well.

Appendix B.6 Boundary Conditions

The choice of BCs is linked to the conceptual model and its justification. The following points are a few examples of potential issues with BCs

- The use of rigid links between nodes (in ANSYS e.g. CP or CERIG) that are based on degrees of freedom whose direction does not follow the deformation of the structure is generally not appropriate in large-deformation analyses. If such links are used in large-deformation analyses, their use shall be justified.

- Unless there is a specific requirement to have free rigid body motion it should be verified that all parts of the structure are globally constrained in all degrees of freedom. Problems with under-constrained models are usually spotted during the gravity and structural load checks described in Paragraphs Appendix A.2.5.3 and Appendix A.2.5.4.
- Inappropriate BCs are a common source of unrealistic thermal stresses. Therefore, when assessing thermal stresses in a local model, care has to be taken to avoid restraining displacements in all directions if a structure is in reality free to expand.

Appendix B.7 Load Application

When loads are applied through nodal forces or nodal heat fluxes the nodal forces applied to each node should normally only be identical in case the element surface or element volume related to each involved node is equal. In case a surface pressure is applied through nodal forces, edge nodes are often loaded with half the force, corner nodes with a quarter of the force on internal nodes. Similarly, mid-side nodes in quadratic elements do not have the same stiffness as the nodes at the apices.

When pressure loads are applied, care should be taken to consider the real area of application, and not only the modelled area. This can be important if relatively thick structures are modelled using shell elements, or if pipes are only partially modelled.

In non-linear structural analyses with large deformation, care should be taken to ensure that the direction of application of load remains appropriate as the structure deforms.

Appendix B.8 Solution Settings

Solution settings can have significant effect on analysis results. It is therefore important for the performer to understand these effects and control their impact on the analysis results. This section highlights some common issues:

- Many FE software packages offer several different solver types (e.g. sparse, preconditioned conjugate gradient) for both shared memory and distributed memory solvers. These vary in robustness and solution speed. The performer needs to be able to determine which solver is most applicable for a particular task.
- The solution settings cover whether or not non-linear geometry is assumed.
- In transient analyses, the following settings are important:
  - The size of the time step shall be verified. A good rule of thumb for implicit solvers is that the time step shall not be longer than 1/20th of the period of the highest natural frequency important to the results of the analysis.
  - Whether loads are ramped or stepped.
  - Whether the analysis is fully transient or mode-superposition transient.
- In non-linear analyses, results are often sensitive to the convergence criteria. In ANSYS, this is especially true when friction is present. In this case it is recommended to run analyses with two different sets of convergence criteria (e.g. CNVTOL) to verify that the convergence criteria are suitable.

Some examples of how solution settings can be reported are given below, valid for both ANSYS APDL and Workbench:

Static analysis (the non-listed solution settings are left at their default values):
- Automatic time stepping: Program controlled
- Solver type: Sparse direct
- Weak springs: Off
- Large deflection: Off

Modal analysis (the non-listed solution settings are left at their default values):
- Maximum modes to find: 150
- Solver type: Direct (Block Lanczos)
- Frequency range minimum: 0 Hz
- Frequency range maximum: 50 Hz

Dynamic analysis (the non-listed solution settings are left at their default values):
- End Time: 1 s
- Automatic time stepping: On
- Initial time step: 0.01 s
- Minimum time step: 0.01 s
- Maximum time step: 0.2 s
- Solver type: Sparse direct
- Weak springs: Off

Appendix B.9 Contacts

It is not uncommon for incorrect contact properties (standard, rough, frictionless, etc.) to be set by mistake, especially when multiple contact surfaces with different properties are specified. In addition, it is quite common for contact pairs to 'miss' each other due to inappropriate pinball settings or too-coarse time step. To minimise the probability of these errors, it is recommended to:

- Check the contact status (open, closed, sliding, etc.) of each contact pair at significant steps throughout the analysis.
- Check that the contact stiffness is reasonable. It should be borne in mind that the default contact stiffness values chosen by FE software are often not appropriate. Whilst it is relatively simple to determine what the contact stiffness is in an FE model, it is often difficult to know whether or not it is appropriate without real-world tests. If contact stiffness has a significant impact on the result of the FE analysis it may be necessary to either perform a sensitivity study or experimental validation. In cases where the analysis is used to calculate stresses due to imposed displacements (e.g. thermal) it is often conservative to minimise contact penetration by maximising the contact stiffness. The penetration at contacts should therefore be plotted and reported in the results section of the report to show that it is reasonable.
- Check that the shear stress in a contact pair is consistent with the normal stress and the coefficient of friction.
- Note that Ansys Workbench offers a checking tool for contacts based on constraint equations (multi-point constraint formulation) or beams. Those can be plotted by selecting the *Graphics* tab after selecting the *Solution* object. This is very useful to check whether a proper pinball radius has been selected.

Appendix B.10 Natural Frequencies

In case of a modal analysis the main vertical natural frequency can be estimated if the elastic displacement Δ (in meters) due to standard earth gravity is known. The main natural frequency in Hz is approximately:

$$F(Hz) \approx \frac{1}{2 \cdot \sqrt{\Delta(m)}} \quad \textbf{(Eq. 3)}$$

Appendix B.11 Damping

Choosing an appropriate value of damping is very important in dynamic analyses. Suitable damping values can vary depending on the type of component, the materials used and the severity of the load. The damping values for most ITER systems are defined in the ITER Load Specifications, [19].

In case α and β structural damping is used, the chosen values of α and β can be justified by comparing the desired damping ratio with the effective damping ratio for the significant modes of the structure. This is often best achieved in a tabular format. Using plots similar to the one below can also be very helpful, perhaps adding in the main modes and their effective modal mass. The values of the frequencies ω_1 and ω_2 should be given. These are the frequencies for which the effective damping ratio is equal to the desired one.

If α and β are used to simulate a constant damping ratio, care must be taken to avoid overdamping significant modes.

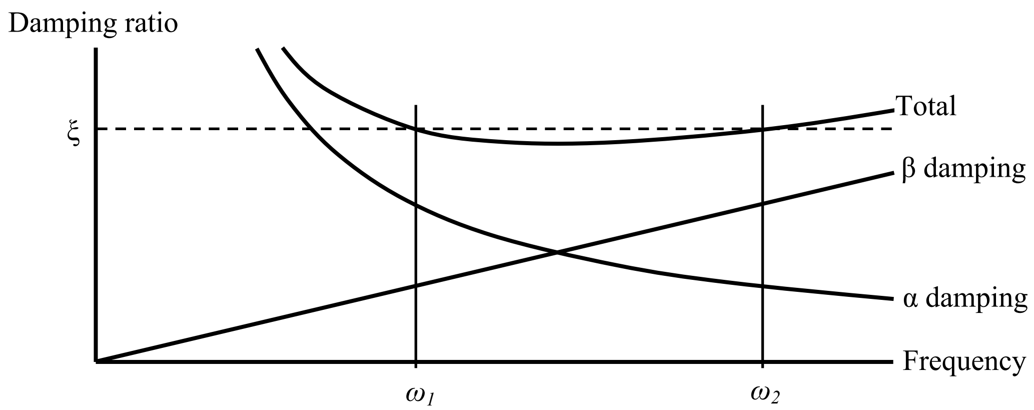


Figure 2 - Raleigh damping.

The most appropriate manner of checking that the intended damping has been applied correctly varies depending on the nature of the model and the type of analysis. However, looking at the response of a model to a simple load is often helpful. One example of this is the decaying response to an applied step function of acceleration. Looking at relevant transfer functions may also give a good indication that damping has been applied correctly.

Appendix B.12 Unintended Internal Stiffness Check

The purpose of this check is to identify any unintended rigid links between nodes. The check is conducted by applying a uniform temperature of 100°C to all parts of the model. Uniform material properties are applied to the whole model, with Poisson's ratio of 0.3 and a thermal expansion coefficient larger than zero. All support constraints are removed, except for one single node which is constrained in all degrees of freedoms. It is recommended to check that all resulting stresses are negligible.

Appendix B.13 Use of Figures and Plots

Figures can be a very useful way to communicate. However, it is worthwhile for the performer to be conscious of what the purpose of each figure is, and then satisfy him or herself that the relevant figure serves the intended purpose. The following suggestions may be helpful:

- If the report compares results from different contour plots, it is usually easier for the reader if the same contour definitions are used in all of the plots.
- Text in the plot should have an appropriate size.
- The resolution/compression should be appropriate. For example, if the purpose of the plot is to show the details of a mesh, the mesh should be clearly visible in the plot.
- It is usually easier for the reader to understand plots of mesh or geometry if the image is orientated such that the vertical axis is pointing upwards.

Appendix B.14 Internal References

If the report is written using Microsoft Word it is strongly recommended that the in-built cross-reference function is used for references to Tables, Figures, Sections, References, etc. This makes it less likely that internal references become incorrect as the report is written and updated. It also allows readers to navigate the report more easily.

For references to external documents, i.e. like those made in Chapter 4, several suitable features are available in MS Word. It is recommended to make use of one following:

- Numbered list.
- Bookmarks.
- Bibliography.

Appendix B.15 Mesh reporting

Some examples are given below of how to report details of an FE mesh, for some of the most common software packages within IO.

Appendix B.15.1 FE MESH (for ANSYS APDL)

Appendix B.15.1.1 OVERVIEW

A description of the FE model is given in this section, along with pictures of the FE mesh. Several figures may be necessary to show all relevant details. An example overview table of the FE mesh is shown in Table 14.

The summary of the shape check performed on the FE model shall be reported here.

Parts	Element Properties in ANSYS					Number of elements
	ETYPE	ENAME	REAL	MAT	SEC	
Inner cylinder of top lid	85	SHELL63	809	1	1	720
Base section cylinder	88	SHELL181	1	88	88	576
UCTS inner mass	1022	MASS21	1022	1	1	1

Table 14 – Overview of the element types and attributes used in the analysis (APDL example).

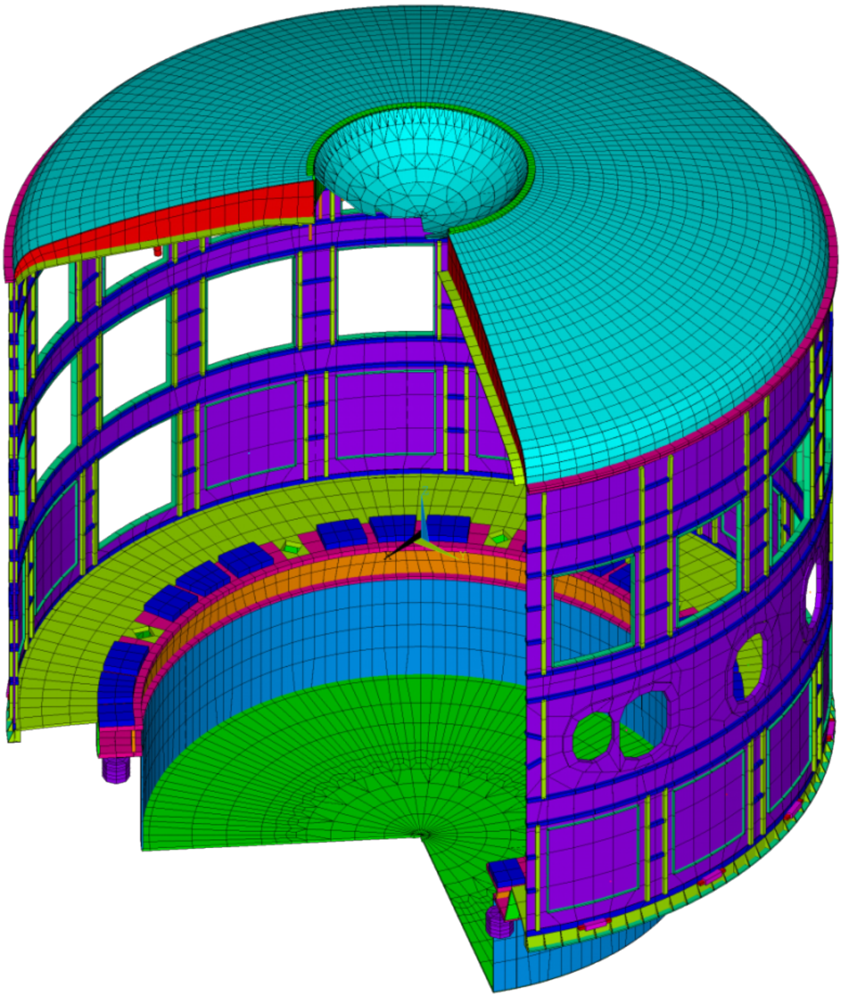


Figure 3 – Cut-away view of the mesh of the simplified Cryostat model.

Appendix B.15.1.2 REAL CONSTANTS

A suitable tabular format should be chosen to present relevant real constant parameters. Two examples are shown below.

Parts	Real number	Real 1	Real 2
		OD (m)	TKWALL (m)
Outer UCTS attachments	905	0.273	0.0254
Inner UCTS attachments and truss for outer UCTS attachments	909	0.114	0.0112

Table 15 - Real constants for elements of type PIPE16. Non-listed REALs are left at their default values (APDL example).

Parts	Real number	Real 1	Real 2	Real 3	Real 4	Real 5	Real 6
		MASSX (m)	MASSY (m)	MASSZ (m)	IXX (kgm^2)	IYY (kgm^2)	IZZ (kgm^2)
VVGS master node	120	0	0	0	0	0	0
UCTS inner mass	122	21903	21903	21903	452330	421175	828274

Table 16 - Real constants for elements of type MASS21 (APDL example).

Appendix B.15.1.3 SECTION PROPERTIES

A suitable tabular format should be chosen to present relevant section parameters. An example is shown below.

Parts	Section number	Width (m)	Height (m)
Toroidal ribs in lower cylinder	1017	0.244	0.021
Vertical ribs in lower cylinder	1021	0.021	0.601

Table 17 – Sections used for elements of type BEAM188, SUBTYPE = RECT. The number of cells along the width and height is set to the default value of 2. The section's centroid is offset to the beam node locations (default) (APDL example).

Appendix B.15.1.4 FINITE ELEMENT OPTIONS OR KEYOPTIONS

The element options or keyoptions shall be listed for every element type. This information can be listed in the 'Overview' table described in Paragraph Appendix B.15.1.1 if desired. An example is shown below.

Use of Elements	ETYPE	ENAME	KEYOPT(3)	KEYOPT(8)
Plate	53	SHELL181	2 - Full integration with incompatible modes.	2 - Store data for TOP, BOTTOM, and MID.

Table 18 – Keyoptions of SHELL181 elements. Non-listed keyoptions are left at their default values (APDL example).

Appendix B.15.1.5 CONTACTS

This paragraph is mandatory if contact elements are used in the FE model.

For every contact pair used in the analysis, the two associated parts of the FE model should be defined in the analysis report. The settings of each contact pair (keyoptions and real constants of contact element) should be listed here. It is recommended to show a figure of each contact pair, highlighting the geometry that is part of the contact. Examples of all this are shown below.

Use of Elements	Real number	Target elements		Contact elements	
		ENAME	ETYPE	ENAME	ETYPE
Contact between boss and insulation ring	58	TARGE170	59	CONTA174	58
Contact between boss and bolt	62	TARGE170	63	CONTA174	62

Table 19 – Contact pairs used in the model (APDL example).

Use of Elements	Real number	Real 3	Real 6
		FKN	PINB
Contact between boss and insulation ring	58	10	-0.10E-02
Contact between boss and bolt	62	$-1.34\cdot10^{12}$	-0.10E-02

Table 20 - Real constants for contact elements of type TARGE170 and CONTA174. Non-listed REALs are left at their default values (APDL example).

Contact element options		CONTA174 element type	
KEYOPT	**Description**	58	62
1	Element degrees of freedom	UX/UY/UZ	UX/UY/UZ
2	Contact algorithm	Augmented method	MPC algorithm
3	Contact stiffness units	F/(L^3)	F/(L^3)
4	Contact detection	Node: Normal from contact	Node: Normal from contact
5	Auto CNOF/ICONT adjustment	No auto. Adjustment	Close gap
6	Auto contact stiffness change	Standard	Standard
7	Contact time/load prediction	No predictions	No predictions
8	Asymmetric contact selection	No	No
9	Initial penetration/gap	Exclude	Exclude
10	Contacting stiffness update	Each iteration	Each iteration
11	Shell thickness effect	Include	Include
12	Behaviour of contact surface	Standard	Bonded (always)
15	Effect of contact stabilization damping	Active in 1st load step	Active in 1st load step
18	Sliding behaviour	Small sliding	Small sliding

Table 21 – Settings for contact element CONTA174. Non-listed keyoptions are left at their default values (APDL example).

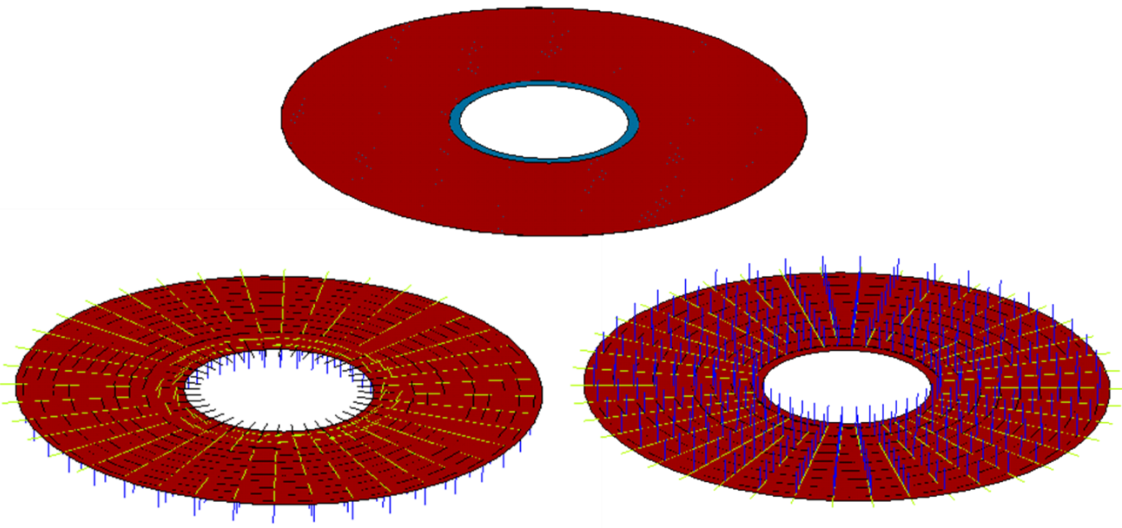


Figure 4 – Contact pair (top) with real constant 58 between boss and insulation ring. Standalone view of CONTA174 elements (bottom left) and TARGE170 (bottom right).

Appendix B.15.2 FE MESH (for ANSYS Workbench)

Appendix B.15.2.1 OVERVIEW

A description of the FE model is given in this section, along with pictures of the FE mesh. Several figures may be necessary to show all relevant details. An example overview table of the FE mesh is shown in Table 22. Parts shall be clearly and unambiguously identifiable, especially if the names in Workbench do not match the ones presented in the geometry section of the report.

The summary of the shape check performed on the FE model shall be reported here. An example is shown in Figure 6.

Parts	**Element Name**	**Number of elements**
Contacts	TARGE170	4930
Contacts	CONTA174	2456
Plate	SHELL181	10060
Bosses, bolts and insulation ring	SOLID186	15582

Table 22 – Overview of the element types used in the analysis (Workbench example).

Notes:

- Starting from version 19.0 of ANSYS Workbench, the number of elements of each type can be obtained under *Material and Element Type Information* option in the Solution Summary Worksheet. This can be displayed by either selecting the *Worksheet* button on the *Home* tab or by right-clicking on the *Solution* object and selecting the option *Worksheet: Result Summary*.

- The element name used for each body (either solid or shell/beam) can be displayed by plotting the *User Defined Result* defined by the expression *PNUMENAM*. An example of this plot is shown in Figure 5.
- A mesh check can be performed by plotting one or more element quality metrics:
    - Click the *Mesh* object in the Tree Outline.
    - In the Details View, expand the *Quality* folder.
    - For the *Mesh Metric* control, select the metric of interest from the drop-down menu. One example is shown in Figure 6.

A global picture of the mesh metrics can also be obtained by changing the *Display Style* of the *Mesh* object to the desired mesh metric (e.g. *Element Quality*). Particular attention should however be paid to the mesh quality inside solid elements since they are not visible from the exterior. Figures shall show the location of the worst elements and section plane may be used if those are inside a body.

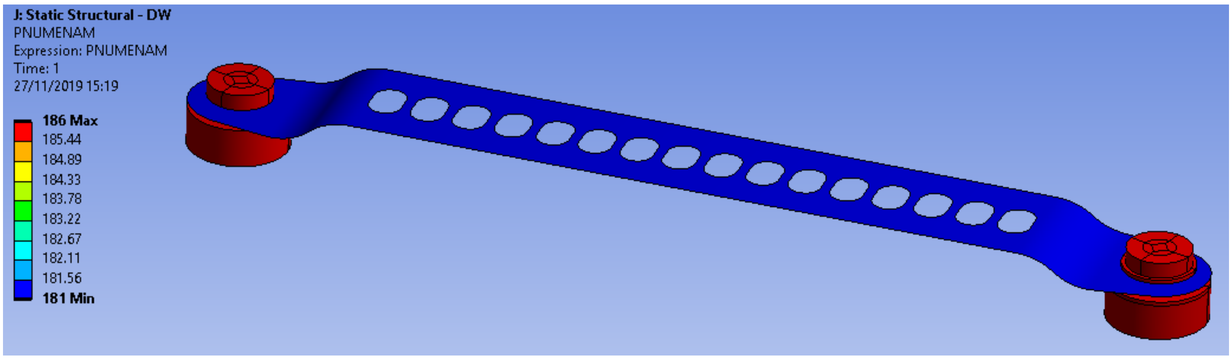


Figure 5 – Plot of user defined result PNUMENAM that shows the parts made of SOLID186 (186 in the legend) and SHELL181 (181 in the legend) (Workbench example).

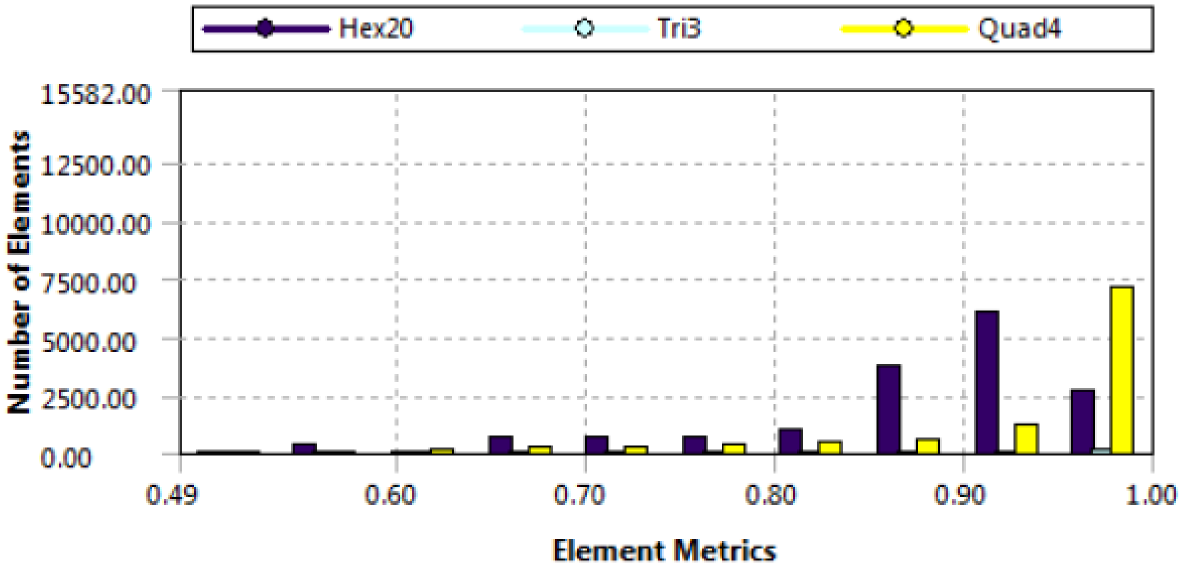


Figure 6 – Plot of Jacobian ratio at Gauss points (Workbench example).

Appendix B.15.2.2 FINITE ELEMENT OPTIONS

All the relevant element options shall be listed for every element type. This information can be retrieved from the automatic report generated by clicking the *Report Preview* option, selected from the *Tools* group or *Home* tab. Some examples of these tables are shown below. Note that another option for reporting some element properties is to plot them by changing the *Display Style* in the *Geometry* object to the desired element property (e.g. *Body Type*, *Shell Thickness, Material*).

If any APDL commands are inserted with the purpose to modify the mesh, these shall be mentioned here (see Table 27).

Line parts	Model type	Coordinate system	Offset type	Cross section
Toroidal ribs in lower cylinder	Beam	Local coordinate system 1	Centroid	LowerCylRib
Outer UCTS attachments	Pipe	Local coordinate system 2	Centroid	UCTS_outer

Table 23 – Element options for line bodies. Non-listed settings are left at their default values (Workbench example).

Cross section	Type	Area (m^2)	I_{yy} (m^4)	I_{zz} (m^4)
LowerCylRib	RECT	$5.124 \cdot 10^{-3}$	$1.8831 \cdot 10^{-7}$	$2.5422 \cdot 10^{-5}$
UCTS_outer	CTUBE	$1.9757 \cdot 10^{-2}$	$1.5298 \cdot 10^{-4}$	$1.5298 \cdot 10^{-4}$

Table 24 – Cross sections defined for line body elements (Workbench example).

Surface parts	Thickness (m)	Offset type
Outer_shell	$1.5 \cdot 10^{-3}$	Middle
Flange	$2 \cdot 10^{-3}$	Top

Table 25 – Element options for surface bodies. Non-listed settings are left at their default values (Workbench example).

Point masses	Coordinate System	X coord (m)	Y coord (m)	Z coord (m)	Mass (kg)	I_{xx} ($kg \cdot m^2$)	I_{yy} ($kg \cdot m^2$)	I_{zz} ($kg \cdot m^2$)	Behavior
Mass1	Global coordinate system	0	0	0.408	30.4	0	0	0	Rigid

Table 26 - Element options for point masses. Non-listed settings are left at their default values (Workbench example).

Use of Elements	ETYPE	ENAME	KEYOPT(3)	KEYOPT(8)
Plate	53	SHELL181	2 - Full integration with incompatible modes.	2 - Store data for TOP, BOTTOM, and MID.

Table 27 – Keyoptions of SHELL181 elements. Non-listed keyoptions are left at their default values (Workbench example).

Appendix B.15.2.3 CONTACTS

This paragraph is mandatory if contact elements are used in the FE model.

For every contact pair used in the analysis, the two associated parts of the FE model should be defined in the analysis report. The settings of each contact pair should be listed here. It is recommended to show a figure of each contact pair, highlighting the geometry that is part of the contact. This information can be retrieved from the automatic report generated by clicking the *Report Preview* option, selected from the *Tools* group or *Home* tab. Some examples of these tables are shown below.

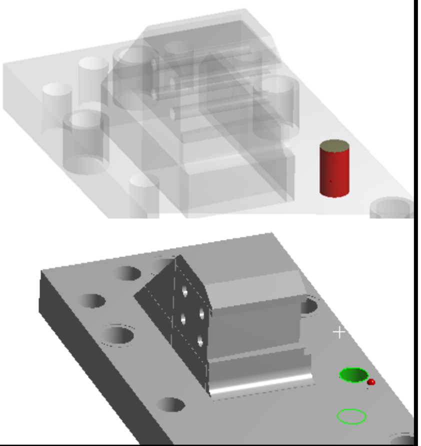
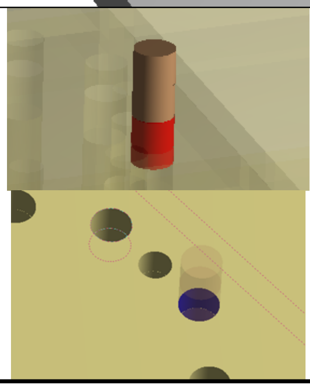
Contact pair	Type	Behavior	Formulation	Normal contact stiffness (GN/m^3)	Tangential contact stiffness (GN/m^3)	Figure
Shear pins-Female lug	Bonded	Auto asymmetric	MPC	Rigid	Rigid	
Shear pins-Embedded plate	Frictional (υ=0.1)	Auto asymmetric	Augmented Lagrange	1340	511	

Table 28 – Contact pairs used in the model. Non-listed contact settings are left at their default values (Workbench example).

Appendix C Completion of Checklists

The completion of Reviewer and Independent Peer Review checklists shall be performed following the requirements and guidance listed in Table 29.

Check	Requirements and Guidance
R1	**Report title, format and metadata.** The requirements of Appendix A.4 (not including sub-paragraphs) are met, including that: • IO analyses reports follow the template for structural analysis reports, [8]. Reports from DAs and subcontractors either follow the template, or contain all of the contents described in Appendix A.4. • Reports stored in IO IDM are in the Microsoft Word format (.doc or .docx). If not, a Word version is stored in IO IDM as an attached file. The following requirements of Chapter 8 are met: • The report is titled such that the scope of the analysis (Component, PBS, loads and failure modes) is described as well as possible within the confines of a reasonable number of characters. • Structural analysis reports that follow the Instructions for Structural Analyses are uploaded in IO IDM as document type “Calculations”. Records of structural analyses that are outside the scope of these instructions are not uploaded as document type “Calculations”.
R2	**Abstract, purpose and scope.** The requirements of the following paragraphs are met: • Appendix A.4.1. The abstract of the structural analysis report contains the following information: o The ITER SSC to which the structural analysis is related. o The assessed components or parts of the system. PBS codes should be used where practical. o The type of failure modes that were assessed, e.g. buckling or fatigue, if applicable. o The loads or load combinations that were considered in the structural analysis. o Any recent significant changes of design, structural design criteria or load specification. o A statement that the report was written following these Instructions, and that the loads applied in the assessments are consistent with the system load specification. • Appendix A.4.4. The “purpose” section outlines the aim of the report. • Appendix A.4.5. The scope defines the applicability of the report, typically in terms of geometry, loads, results and context.
R3	**Scope of reviewers.** The requirements of Section 7.3 and Appendix A.4.3 are met, including that: • For PIA analyses, a reviewer from EPNS has been assigned to perform at least all of the checks listed in Paragraph 7.3.1. • One or more Reviewers have been assigned that between them cover at least all of the points listed in Paragraph 7.3.2. • Where required by [1], an Independent Peer Reviewer has been assigned that covers at least all of the points listed in Paragraph 7.3.3. • A Technical Checker has been assigned to cover at least all of the points listed in Paragraph 7.3.4. • The scope of the review is specified for each reviewer, either in IO IDM or in the report itself.
R4	**Definitions and abbreviations.** The requirements of Appendix A.4.6 and Appendix A.4.3 are met, i.e. all definitions and abbreviations used in the report are listed, in alphabetic order.
R5	**Units.** The requirements of Appendix A.1.5 and Appendix A.4.7.1 are met, i.e. analyses are performed using S.I. base and derived units.

Check	Requirements and Guidance
R6	**Geometry (excluding applicability).** The requirements of the following paragraphs are met: • Appendix A.1.2, including that: o Analyses are based on geometry that is unambiguously traceable. Where relevant, the references are approved. o The uncertainty in the geometry, e.g. due to tolerances, has been considered. o Analyses performed during or after the construction phase has considered any relevant non-conformances. o Deviations from the current approved design geometry have been justified. o The quantitative effect of the deviations on the results has been estimated, and considered in the conclusions of the analysis • Appendix A.4.7.2, including that: o A figure of the geometry used in the structural analysis has been shown, and the main dimensions relevant to the analysis indicated. o Special attributes of the geometry that cannot be easily recognized in a figure and that are relevant to the analysis has been described. o The magnitudes of geometrical imperfections considered in the analysis through any modification of the initial FE mesh have been stated.
R7	**Applicability of geometry (*).** Analyses are based on applicable geometry, i.e. the current approved design.
R8	**Material properties (excluding applicability).** The requirements of the following paragraphs are met: • Appendix A.1.3, including that analyses consider the uncertainties in material properties. • Appendix A.4.7.3, including that: o The physical material properties of the analysed SSC are listed, and traceable to approved references. o It is clearly documented which parts are made from which materials.
R9	**Applicability of material properties (*).** Analyses are based on physical material properties that are consistent with the procured materials of the analysed SSC.
R10	**SDCs (excluding applicability).** • The requirements of Appendix A.4.7.4 are met, including that: o The design code applicable to the analysis of the system is stated. o The design code is consistent with the definition in the relevant SRD. o The rules and limits from the design code applicable to this structural analysis are extracted from the design code and summarized in the analysis report. o Relevant service limits applicable to the system are listed, and linked to approved references. • The SDCs are appropriate.
R11	**Applicability of SDCs (*).** Analyses are based on the applicable SDCs and service limits.
R12	**Loads (excluding applicability) (**).** The requirements of Appendix A.1.4 and Appendix A.4.7.6 are met, including that: • All input loads used for analyses are listed and described clearly and unambiguously. • All listed input loads come from the relevant approved System Load Specification. • Any uncertainties in the loads are reported, and considered in a conservative manner. • For transient loads, the time functions of all loads are given in the form of either a table or a diagram that allows the identification of characteristic magnitudes of the time functions.
R13	**Applicability of loads (*).** The approved System Load Specification on which the analysis is based is still consistent with the current design of the SSC.

Check	Requirements and Guidance

R14	**Conceptual model and analysis methodology.**
	The requirements of the following paragraphs are met:
	• Appendix A.1.1, including that:
	  o The chosen conceptual model represents the physical reality sufficiently accurately to cover the intended purpose of the analysis.
	  o Appropriate analysis method(s) are used.
	• Appendix A.4.8, including that:
	  o The principle of the analysis approach is described.
	  o The conceptual model is justified, in particular the inherent simplifications compared to the physical reality.
	  o Justification is provided that the analysis methods are used in their validated domains.

R15	**Description of FE analyses (only applicable for FE analyses).**
	The FE analyses well documented, and are an appropriate implementation of the conceptual model and analysis methodology. The requirements of the following paragraphs are met:
	• Appendix A.2.1 and Appendix A.4.9.2, including that:
	  o The name and version number of any software package used to perform FE analyses is stated.
	  o Any software package used is validated.
	  o It has been justified that software packages have been used in their validated domain.
	  o It is stated what uncertainties, if any, are associated with the use of the validated Finite Element software package for the reported analysis.
	  o If a validated Finite Element software package has non-negligible uncertainties when used properly, the uncertainties are covered either by performing sensitivity studies or by applying a suitable safety factor to the results.
	• Appendix A.2.2 and Appendix A.4.9.3, including that:
	  o All coordinate systems used in any FE analyses are defined
	  o The global coordinate system for FE models has its positive z-axis pointing vertically upward.
	• Appendix A.2.3, including that:
	  o The choice of element types and shapes is justified.
	  o Shape checking has been performed and reported. If poor quality elements have been identified by the check, their use is justified.
	• Appendix A.2.4, including that:
	  o The solution settings chosen for the analysis are documented and justified.
	• Appendix A.4.9 (excluding paragraphs covered above), including that:
	  o The type of analysis is stated.
	  o All material properties used in the FE model are listed
	  o A description of the FE model is given, including pictures of the mesh, and details of element properties (e.g. element types and options, real constants and section properties.
	  o Each set of boundary conditions (BCs) is described, including degrees of freedom and the coordinate system. The BCs are also shown on a figure. This includes contact definitions.
	  o In case the BCs are not constant throughout the analysis, the changes are described.
	  o Internal constraints (e.g. coupled equations) are described, and shown on one or more figures.
	  o The report describes how the defined loads are applied to the FE model. The described application of loads to the FE model is consistent with the System Load Specification.
	  o The solution settings are listed and justified.

R16	**Hand calculations (only applicable for hand calculations).** The hand calculations are well documented, and are an appropriate implementation of the conceptual model and analysis methodology. The requirements of Appendix A.3 are met, including that: • All equations used in the calculation are shown. • A reference is given for any non-trivial analytical formulas used. • Equations are referenced • The result of calculations shall be given including the unit. • All symbols used in the equation shall be defined in the report.

Check	Requirements and Guidance
R17	**Results.** • Results are reasonable for the given inputs and assumptions. • The requirements of Appendix A.4.10 are met, including that: o All results are given with their units (including graphs and contour plots). o Clear titles and axis labels are given when presenting graphs. o All relevant results to meet the scope of the structural analysis are given. o Results shall be given corresponding to the design criteria. o When giving reaction forces or moments the direction of a positive reaction force shall be specified or shown in a figure, unless it is obvious. As the direction is dependent on the component the load is acting on, the latter shall be specified. o The point of summation of moments shall be explicitly stated. o The coordinate system used for the results shall be specified.
R18	**Verification of FE analyses (only applicable for FE analyses).** • Appendix A.2.5.1, including that analysis software and its installation of the computer used for the analysis shall be qualified according to [3]. • Appendix A.2.5.2, including that: o A mass check is performed and reported if inertial effects are relevant to the analysis. o The total mass, centre of gravity and if possible the inertia of the FE model is reported and compared to the values listed in the system load specification. Any significant differences are justified in the report. • Appendix A.2.5.3, including that: o A gravity load check is performed and reported if gravity is part of the load case considered in the analysis. o It has been checked whether the reaction forces on the constraints of the FE model correspond to the weight of the FE model. o In case the FE model has more than one constraint it has been checked whether the distribution of the reaction forces is roughly consistent with the centre of gravity of the FE model. • Appendix A.2.5.4, including that: o A static structural load check has been performed and reported, checking that the total reaction forces and moments on the supporting constraints correspond to the total applied structural loads. o In case the FE model has more than one constraint it has been checked whether the distribution of the reaction forces is reasonable. o If loads are transferred from other models the resulting reaction forces and moments from the different models have been compared. o When complex structures made of several sub-structures are considered, the resulting forces and moments have been checked for each sub-structure. o The point(s) considered for the calculations of resulting moment(s) are reported. o In the special case that the applied structural loads cancel each other out it has been verified that the magnitude of the applied loads, including bolt pretension, is approximately correct. o Appendix A.2.5.5, including that it is demonstrated that the behaviour of the contact elements is as intended. o Appendix A.2.5.6, including that it is demonstrated that damping has been applied as intended • Appendix A.2.5.7, including that: o The mesh density is justified, e.g. by means of a mesh sensitivity study. o The sensitivity of the results to the mesh density is considered in the interpretation of the results. • Appendix A.2.5.8 and Appendix A.4.11, including that the results of FE analyses have been verified by comparing them to those of alternative calculations.

Check	Requirements and Guidance
R19	**Conclusions.** • The conclusions are reasonable and representative of the outputs. • The conclusions properly meet (or cover) the scope and purpose. • The requirements of Appendix A.4.12 are met, including that: o The conclusions summarize the most significant findings, and are comprehensible for persons familiar with the design and loads of the system, with an engineering background but not necessarily with expertise in structural analyses. o The result values given in the conclusions consider the uncertainty of the structural analysis. o Results for which the FE model cannot meet accuracy requirements are either not reported, or marked as "preliminary" or "best estimates".
R20	**References.** The requirements of Appendix A.4.13 are met, including that: • All documents that are referenced by the analysis report are listed. • References are stored in IO IDM or are publically available. • References in IO IDM are approved. • References to IO IDM documents include the version numbers. • An approver and at least one reviewer must be assigned to IO IDM references.

Table 29 – Requirements for completion of Reviewer and Independent Peer Reviewer checklists.

(*) This check shall be performed by the RO of the SSC.

(**) On the Reviewer Checklist, this check shall be performed by the RO of the SLS. On the Independent Peer Reviewer checklist this requirement does not apply.

The completion of Technical Checker checklists shall be performed following the requirements listed in Table 30.

Check	Requirements and Guidance

TC1	**Conceptual model and analysis methodology.**
	The requirements of the following paragraphs are met:
	• Appendix A.1.1, including that:
	  o The chosen conceptual model represents the physical reality sufficiently accurately to cover the intended purpose of the analysis.
	  o Appropriate analysis method(s) are used.
	• Appendix A.4.8, including that:
	  o The principle of the analysis approach is described.
	  o The conceptual model is justified, in particular the inherent simplifications compared to the physical reality.
	Justification is provided that the analysis methods are used in their validated domains.

TC2	**Mathematical model.** The mathematical model is described properly, and is appropriate given the analysis methodology. This includes the: • Coordinate system(s) used. • FE material properties. • FE mesh. • BCs. • Load application. • Solution settings.
TC3	**The analysis model is properly stored in the analysis database.** The models are stored in the ITER analysis database, and respect the requirements of the MQP Instructions for the Storage of Analysis Models (ITER_D_U34WF3), including that they: • Include all files necessary to get the reported results (e.g. including macros & spreadsheets). • Are linked to the analysis report, and their metadata is filled properly. • Are stored in a sensible and organized folder of IO's Analysis Model Database. • Are in a ready-to-run state. The technical checker shall rerun the analyses to verify this. • Are commented/organised to be clearly and unambiguously understandable by a third party. Proper storage formats are used, i.e. that privileges robustness and exhaustiveness.
TC4	**The model in the database matches the report.** The geometry, mesh, element types, material and element properties, BCs and loads of the model in the database match the description in the report.
TC5	**The results of the model in the database match the description in the report.** Important results match those described in the report. Given that results are often not stored in the database this check may require rerunning the analyses, see TC3.
TC6	**Analysis results are reasonable, and hand calculations are correct.** • Results are reasonable for the given inputs and assumptions, i.e. no observations are made that indicate that there are errors in the analysis. • The analysis uncertainties are judicious. • The numerical evaluations of hand calculations are correct.

Table 30 – Requirements for completion of Technical Checker checklists.

Appendix D Compliance Matrix for Checking Requirements from [1]

The compliance matrix below demonstrates that all the requirements for checking of analysis reports required by [1] are covered by requirements given in these Instructions. In this table 'R#' means 'Reviewer check number #'; 'TC#' means 'Technical Checker check number #'. They correspond to the checks listed in Subsections 7.3.2, 7.3.3 and 7.3.4, which are propagated to [5], [6] and [7].

	Requirement from [1]	Covered by
Review / Technical Check	Check that the requirements defined in the specifications are met including the scope and purpose as defined in the technical specification.	A contractual issue, not in the scope of these Instructions.
	Check that the calculation model data appropriately reflect the geometrical data and interfaces of the object under investigation.	R6, R7, R14, TC1
	Check the basic approach, assumptions, subject-specific data (such as loads), and any equations or formulas applied are appropriate.	R8, R9, R12, R13, TC1
	Check that input data are consistent with requirements or validated by referenced sources.	R6, R7, R8, R9, R10, R11, R12, R13
	Check the calculations are mathematically correct.	TC6
	Check the requirements and acceptance criteria are appropriate and used correctly.	R10, R11
	Check the conclusions reached are reasonable and consistent with the analysis or calculation approach, assumptions, input, and acceptance criteria.	R17, R19, TC6
	Check that the software is validated for the scope and purpose of the analysis.	R15
Independent Peer Review	Design or analysis philosophy is sound	R14, TC1
	Structural system, materials, acceptance criteria, and other pertinent factors are considered.	R6, R7, R8, R9, R10, R11
	Analysis or calculation approach is reasonable and appropriate.	R14, R15, R16, TC1
	Inputs are reasonable and correct.	R6, R7, R8, R9, R10, R11, R12, R13
	Assumptions are reasonably substantiated and justified.	R14, TC1
	Mathematical formulations and/or computer models (see def.) are appropriate and contain sufficient detail.	R15, R16, TC2
	Outputs are reasonable for the given inputs and assumptions	R17, TC6
	Acceptance criteria used are appropriate.	R10
	Conclusions are reasonable and representative of the outputs	R19

Table 31 - Compliance matrix for checking requirements from [1].

Appendix E Compliance Matrix for INB Order [4]

The compliance matrix between these instructions and the INB order dated 7 February 2012 [4] is shown Table 32 and Table 33 below. By following these Instructions and the references in the table below, all requirements from [4] relevant to structural analyses are met.

For Article 3.8 of the INB order, the requirements have been taken from the summary table of [9], rather than directly from the INB order.

Article in [4]	Requirement	Covered by
2.2.1	Surveillance of external interveners. The operator informs all external interveners of the provisions required for implementing the Ministerial Order hereof.	Chapter 2, which states that the rules governing the propagation of the requirements specified in these Instructions are specified in [10].
2.2.2	The operator surveys external interveners.	Outside the scope of these instructions. The requirements for surveillance plans are defined in [1].
2.5.2.II	The protection-important activities are carried out in accordance with procedures and using means for meeting *a priori* the requirements defined for these activities and for the protection-important components concerned, and to ensure them *a posteriori*.	These Instructions represent the procedures that shall be followed to meet *a priori* the requirements for PIA analyses. The reviews required by Section 7.3 ensure *a posteriori* that analyses under direct control of ITER IO meet the defined requirements. The surveillance plans required by [1] ensure *a posteriori* that analyses performed by external interveners meet the defined requirements.
2.5.3	Each protection-important activity undergoes technical monitoring, to ensure that: the activity is carried out in compliance with the requirements defined for the activity and, if necessary, for the protection-important components concerned; appropriate corrective and preventive actions have been defined and implemented.	Subsection Appendix A.2.5, Section 7.3, the surveillance requirements defined in [1].
2.5.5	Protection-important activities, their technical monitoring and the checking and assessment actions are carried out by individuals with the appropriate skills and qualifications.	Section 7.2, the surveillance requirements defined in [1].

Article in [4]	Requirement	Covered by
2.5.6	Protection-important activities, their technical monitoring and the checking and assessment actions are documented and are traced to demonstrate *a priori* and to …	The *a priori* definition of PIAs is outside the scope of these Instructions. The surveillance requirements are defined in [1].
	… check a *posteriori* that they comply with defined requirements.	The reviews required by Section 7.3 ensure *a posteriori* that analyses under direct control of ITER IO meet the defined requirements. The surveillance plans required by [1] ensure *a posteriori* that analyses performed by external interveners meet the defined requirements.
	The documents and corresponding recordings are kept updated, are easily accessible and legible, protected, kept under appropriate conditions and archived for an appropriate and justified period of time.	Chapter 8.

Table 32 - Compliance Matrix for the INB Order [4], excluding Article 3.8.

Group	Requirement	Covered by
Input data	Use of referenced, updated and validated input data.	Appendix A.1.2 (geometry), Appendix A.1.3 (materials), Appendix A.1.4 (loads).
	Use of controlled assumptions.	Appendix A.1.1 (justification of conceptual model and analysis method).
	Assessment of the uncertainties in input data.	Appendix A.1.4 (loads).
Methods	Establishment of a range of assumptions and sensitivity studies when assumptions include uncertainties.	Appendix A.1.1 (justification of conceptual model and analysis method).
	Verification of the consistency with safety demonstration.	Subsection 7.3.1 (EPNS review).
	Establishment of a list of validated and appropriate methods.	Appendix A.1.1 (justification of conceptual model and analysis method).
	Use of methods in their validation domain.	Appendix A.1.1 (justification of conceptual model and analysis method).
	Verification of the methods consistency with safety demonstration.	Subsection 7.3.1 (EPNS review).
	Sensitivity studies to be performed for covering methods uncertainties or additional safety factor in the results.	Appendix A.1.1 (justification of conceptual model and analysis method). Appendix A.4.12
Codes and calculation tools	Establishment of a list of validated and appropriate codes.	Outside the scope of these Instructions.
	Use of methods in their qualification domain.	Appendix A.2.1 (software package).
	Verification of the methods' consistency with safety demonstration.	Subsection 7.3.1 (EPNS review).
	Sensitivity studies to be performed for covering code uncertainties or additional safety factor in the results.	Appendix A.2.1 (software package), Appendix A.4.9.1 (type of analysis).
Reports and results	All input data, methods, codes and their validity domain and uncertainties to be included.	Reporting of input data : Appendix A.4.7.2 (geometry), Appendix A.4.7.3 (physical material properties), Appendix A.4.7.6 (loads). Reporting of analysis method, including its validity and associated uncertainties: Appendix A.4.8 (methodology). Reporting of FE software packages, including their validity and associated uncertainties: Appendix A.4.9.2 (software package).
	Intermediate and final results to be expressed in international units.	Appendix A.4.7.1 (units).
	Sensitivity studies to be performed for covering uncertainties or additional safety factor in the results.	Appendix A.4.8 (methodology). Appendix A.4.12 (conclusions).
Acceptance criteria	The acceptance criteria to be substantiated and checked against potential safety limits and when applicable design margins brought by codes.	Appendix A.4.10 (results).
	Margins and safety factor to be expressed with regards to safety limits.	Appendix A.4.12 (conclusions).

Table 33 - Compliance Matrix for Article 3.8 of the INB Order, [9].