Structural Analysis and Verification Guidelines

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1 Purpose and Scope

The Cherenkov Telescope Array Observatory (CTAO) is constituted by a set of telescopes with imaging cameras and other instruments built and installed at two different sites with the aim of performing gamma ray observations. These telescopes with their cameras and other systems are provided to CTAO by various scientific institutes as in-kind contributions and require project-wide uniform structural design and verification methods.

This document summarizes the basic principles, rules, procedures and boundary conditions for structural verification of CTAO structures, namely telescopes structures camera and auxiliary instrumentation and other equipment fixed to the ground. The term “structures” refers to all load carrying elements, the failure of which could result in safety critical situations. Structural failures may be caused by different mechanisms not limited to the excessive loads and stresses but also due to fatigue and buckling among others. Structural verification must be done for each structural element according to its specific relevant possible mechanism of failure.

Facilities and civil buildings are not object of this document because they are to be designed and built according to building construction codes in force at the two CTAO sites.

Performance issues are not the main subject of this document, but the mathematical models and outcomes of structural analyses can be used in the verification process of relevant performance requirements, like for instance deformation of the mirror surface and misalignment of mirror facets and camera due to change of elevation, temperature variations, and other loadings.

It is noted that for what concerns specific analysis requirements, this document is largely based on the ESO Engineering Analysis standard [RD01].

1.1 Prerequisites

The principle of structural verification herein reported are largely based on Eurocode Norms. The general assumptions behind the Eurocode Norms and in particular [AD01] is that the structures will be designed, manufactured, assembled by experienced and skilled personnel and that during all execution of the work adequate quality control is applied. Similarly, the construction materials are selected and certified according to standards. It is also assumed that the structure will be adequately maintained and used in accordance with the design assumptions at the basis of its design during its entire projected life.

1.2 Verification of Structural Design Process

Implementation and verification of the structural requirements should be ideally following this process:

1. Sizing of the preliminary design by analysis indicating the adequate load paths, geometry and materials suitable to ensure that the final design intended for manufacturing, will meet the relevant requirements / regulations.
2. Development tests where data serving as input to the analyses are not validated or where analysis methods are not considered reliable or accurate. Such tests shall be closely correlated with the corresponding analyses and shall be performed on materials and / or components as needed.
3. Justification of the final design shall be performed prior to manufacturing, by demonstrating that the design intended for manufacturing fulfils all relevant requirements / regulations, by preparation of analyses and reports, subjected to an external design review.
4. Proof tests may be necessary on components or assemblies, whenever data, material or physical properties are subject to uncertainties and workmanship errors that can exceed the tolerances.

5. Qualification tests may be needed to support the design prior to serial production.
6. In case of design changes, the verification process shall be repeated to the extent needed and the design changes shall be traced.

The present documents is mainly dedicated to the step 3. above, whereby for specific items the steps 4 and 5 are also considered (section 8).

2 Related Documents

2.1 Applicable documents

The applicable documents herein form a part of this document and are applicable to the structural verification of CTA structures. In case of conflict, they have precedence over the guidelines herein.

AD01	Eurocode 0: Basis of structural design EN 1990:2002
AD02	Eurocode 1: Actions of Structures, all parts, EN 1991
AD03	Eurocode 3: Design of Steel Structures, all parts EN 1993-1
AD04	Eurocode 8: Design of structures for earthquake resistance, EN 1998 part 1: General rules, seismic actions and rules for buildings
AD05	Eurocode 9: Design of Aluminum Structures EN 1999, part 1-1 and 1-3
AD06	Jama Database for Environmental requirements
AD07	CTAO - South Seismic Risk Specification, CTA-SPE-SEI-400000-0001-1c
AD08	CTA Environmental Ranges for the CTA Sites, SYS-REQ/161123 ver. 05, 2017-04-5

2.2 Referenced Documents

The documents below provide additional background information to the present guidelines.

RD01	NASA Goddard Space Flight Center, Finite Element Modeling Continuous Improvement (https://femci.gsfc.nasa.gov/index.html)
RD02	VDI 2230, Systematic calculation of high duty bolted joints – Joints with one cylindrical bolt
RD03	VDI-2014 Part 3, Development of fibre-reinforced plastics components analysis
RD04	Advanced Optics, TIE-33 Bending strength of optical glass and ZERODUR, Dec. 2015
RD05	ESO Engineering Analysis Standard, ESO-191642, version 2

3 Definitions and Principles

3.1 Definition of Structures

This document distinguishes between two different types of structures, for which different methodology of structural verification can be used. These are:

Primary Structure:
For the purpose of this document a Primary structure is a mechanical structure connected to the ground. Therefore, a primary structure is subjected to seismic loading. The primary structure supports secondary structures. A typical example of a primary structure is a Cherenkov telescope structure.

Secondary Structure:
For the purpose of this document a secondary structure is a mechanical structure supported by the primary structure. Therefore dynamic loading coming from the ground cannot be applied directly to the secondary structure but is subjected to the loading transmitted by the primary structure. A typical example of a secondary structure is a Cherenkov camera, a mirror segment, or an electric cabinet.

3.2 Definitions based on Eurocode

Action / Load:
set of forces and/or imposed displacements acting on the structure. In formulas, actions / loads are indicated with the letter "**F**".

Action Effect:
effect of actions on structural members (e.g. internal force, moment, stress, strain) or on the whole structure (e.g. deflection, rotation). In formulas, action effects are indicated with the letter "**E**".

Characteristic Value of Actions
The characteristic value of an action (F_k) is its main representative value and shall be specified as a mean value, an upper or lower value, or a nominal value, which does not refer to a known statistical distribution, according to [AD01].

Design Criteria:
quantitative formulations that describe the conditions to be fulfilled for each limit state.

Design Situations:
sets of physical conditions representing the real conditions occurring during the execution and use of the structure, for which the design will demonstrate that relevant limit states are not exceeded. The design situations are divided in four classes:

- **Persistent:** relevant during a period of the same order of the life of the structure (normal conditions).
- **Transient:** under temporary conditions, but with an high probability of occurrence.
- **Accidental:** under exceptional conditions which are not part of the normal design condition, such as in case of impact.
- **Seismic:** situation caused by an earthquake.

Design Value of an Action / Design Load:
value obtained by multiplying the representative value by a factor *("partial factor")* covering the uncertainty of the action. In formulas, design values of actions are indicated with the letter "$\mathbf{F_d}$".

Design Value of a Material / Product Property:
value obtained by dividing the characteristic value by a safety factor, or, in special circumstances, by direct determination.

Limit State:
state beyond which the structure no longer fulfils the relevant design criteria.

Margin of Safety (MS)`; the reserve factor diminished by 1, which expresses the margin of load or stress capability. Fulfilment of strength requirements is achieved for margin of safety $\geq$ 0.

Reserve Factor (RF): the stress (or load) ratio divided by the applicable safety factor. Fulfilment of strength requirements are achieved for reserve factor $\geq$ 1.

Serviceability Limit State (SL)
state which corresponds to conditions beyond which specified service requirements for a structure or structural member are no longer met.

Stress (or Load) Ratio:
the inverse of utilization, namely the ratio between the allowable stress and the stress resulting from the applied actions defined in a load case.

Ultimate Limit State (UL):
state associated with collapse or with other similar forms of structural failure.

Utilization: the ratio between the applied stress and the allowable stress (resistance of material), indicating the utilization of the material under an applied load.

3.3 Principles of Limit State Design

3.3.1 Eurocode Principle

A degree of loading or other actions imposed on a structure can result in a limit state, beyond which the structure does not fulfil any longer its design criteria, such as durability (fitness for use) and structural integrity. Limit states are conditions of potential failure or permanent deformation not resulting in failure but irreversible without replacing the degraded unit. Therefore, limit state design involves verifying that relevant limit states are not exceeded in any design situation, which shall be specified to encompass all conditions that can reasonably be foreseen to occur during the construction and use of the structure.

Verifications are performed using structural models and load cases, the details of which are established from three basic variables: actions, material properties, and geometrical data of the structure. Actions are classified according to their duration and combined in different proportions for each design situation (section 5).

In accordance with Eurocode two different types of damage limit states are considered in the requirements of the CTAO project namely:

- Ultimate Limit State (UL), or Collapse Prevention Limit (CPL). This limit state is concerned with the safety of people and the safety of the structure against collapse. In the case of building and civil structures as generally considered by Eurocode, collapse is prevented, but it may not be possible to maintain the structures in operation if this state is reached.
- Serviceability limit state (SL). This limit state is concerned with the functioning of a structure and the possibility to keep the structure in service, with no repair or with some minor degree of repair. Any damage which may have occurred shall not prevent the further use of the structure.

Structural failure may be generated by various failure mechanism, like loss of equilibrium, excessive deformation, deflection or rupture, transformation of structural member into a mechanism, fatigue and brittle failure.

3.3.2 CTAO Application of the Limit State Design

The Ultimate Limit State as defined in Eurocode does not guarantee the possibility to further use the equipment. In fact the objective is protection against loss of equilibrium and collapse, which may have been avoided, hence protecting the safety of people, but the extent of the suffered damage may make any repair impossible or not affordable to the project. This could be the case if the Ultimate Limit State definition of the Eurocode would be applied to a major earthquake (NCR type) as defined in [AD07].

However, as outlined in Section 4.2.4 of [AD07], CTAO require that the observatory can be operational after an earthquake, although considerable repair activity and downtime may be necessary before operation can restart in the case of major earthquakes. This needs to be considered when performing the verification according to Section 7.

3.4 Reliability Differentiation

Actions and resistance are subject to uncertainties. For instance, while permanent loads like gravity are well understood, environmental loading are of statistical nature. Scatter in material properties and construction tolerances in structural members may occur. The Eurocode uses the method of partial factors based on probabilistic concept of structural reliability, which can be regarded as the complementary to the probability of failure.

Consequence classes are defined depending on the consequences of failure or of malfunction of the structure. For CTAO a consequence class CC2 is used[1]. This corresponds to the (medium) reliability class RC2 to which corresponds a probability of failure of 7.23e-5 [2] in 50 years. To achieve certain reliability level a specific multiplication factor is used in load combinations for persistent design situations. For the class CC2 the multiplication factor is 1.0. Furthermore, considering the consequences of earthquakes, this corresponds to the Importance Class II for telescopes[3] as reported in [AD07]. Hence the following applies:

Eurocode	Section /Annex	Variable	Class
EN 1990-1 [AD01]	Annex B3, Table B1	Consequence Class	CC2
EN 1998 -1 [AD04]	Section 4.2.5, Table 4.3	Importance Class (Telescope)	II

Note:
The consequence class CC2 implies as well the specific design supervision DSL2 (independent verification of design) and inspection level IL2 (normal inspection level) during execution.

3.5 Material Properties

The materials used in structures shall be well defined and characterized to ensure that the predictions are reliable. Reliable sources for material data are standards like *MIL-STD*, *DIN*, *LN*, *EN*. General literature data are often related to typical properties that do not clearly identify the conditions of the materials (e.g. as resulting from heat treatments). Where material properties are not well defined and proven, they shall be validated by test, especially when such materials are used in highly stressed and in safety critical areas. These tests shall follow standardized procedures performed under specified conditions that shall be described in the reports. Conversion factors shall

1 Eurocode 0 EN 1990, Annex B3 [AD01]
2 This value is a theoretical value which does not take into account human errors.
3 The importance class I can be used for LIDAR and less important equipmernt as spelled in Section 6.3.4.

be applied where it is necessary to convert the test results into values which can be assumed to represent the behavior of the material in the structure. Where such tests are not considered, material properties shall be generously de-rated, for instance the maximum allowable stress in glass components shall be 10 MPa unless a detailed evaluation of surface characteristics and statistics is applied. If needed, materials shall be corrosion protected, to ensure that they will not become a safety risk due to the action of corrosion and ageing. This shall include corrosion effects caused by mating of dissimilar materials.

For primary structures the use of ductile materials (such as structural steel S235 or S355 according to the European Standard EN 100025-2) is preferred since such materials can re-distribute stress by yielding and indicate by plastic deformation potential rupture long before this will occur. Brittle materials, including high strength steels, shall be avoided because they are usually sensitive to shock loads and they will rupture, in case, suddenly and without any indication.

For glass and ceramics, the lack of ductility results in very low failure strains. The large scatter observed in component testing is primarily caused by the variable severity of flaws distributed within the material or flaws extrinsic to the material volume. The different physical nature of the flaws results in dissimilar failure response to identical external loading conditions. Due to the random distribution of flaws the failure of a complex structural part can be initiated also outside the point of highest stress. Determination of design allowable for glass and ceramics requires a probabilistic approach, covering all size effects.

Functional equipment often requires specific materials. In such case, it shall be made sure that the stress will be low enough to exclude any safety risk. Special safety factors shall be applied for critical material as outlined in section 7.3.1, herein.

4 General Verification Requirements

4.1 General

According to Eurocode [AD01-AD05] the structures of the elements constituting the CTAO, whose failure could result in damage of the structure, surrounding structures or injury of personnel shall be structurally verified by analysis. In addition, the CTA project requires performing analysis to ensure that the specified performance of the system are met.

The type of analysis which is considered is generally linked to the status of the project.

- **During the Conceptual Design Phase:** The analyses done at conceptual design level are generally done in the initial phase of the project when potential solutions are investigated, and the initial layout and preliminary sizing[4] of the system is defined. Feasibility studies are performed on the adopted baseline.
- **During the Detailed Design Phase[5]:** These are the analyses which are done to demonstrate the validity of the design of the structure adopted for the construction of the final product of the CTAO Observatory. These analyses are of two types:
  - Performance verification analysis: these are analyses which are needed to verify certain technical or scientific performance of the components of CTAO.
  - Safety Verification analysis: This type of analysis is performed to show compliance with structural codes in force and CTAO regulations which are associated to the structural safety of the element.

Notes:

I. In the case of performance verification analysis certain requirements herein specified can be deviated, if allowed by the review process of CTAO. Generic quality and accuracy check related to modelling must be applied.

II. In the case of structural safety verification, the requirements herein shall be applied in their entirety. The requirements herein do not waive the obligation to fulfill the valid structural code and national standards by the designer.

Engineering analysis can be based on classical analytical methods or on numerical techniques such as Finite Element Methods (FEM). FEM computation is the method to be applied for the verification of complex structural assemblies. Structural FEM models shall be prepared for determining the action effects on all complex structures, such as telescopes, and auxiliary instruments. These models shall represent the mass distribution, stiffness, damping characteristics, and load paths of structures so that assessment of stresses, interface forces, and other effects and performances can be performed.

A FEM model shall be prepared to allow simulations required for:

- evaluation of deformations due to static loads (including temperature) and dynamic loads (including dynamic wind loads and drive chain dynamics);
- determination of loads and stress of structural members due to static loads (including gravity, quasi-static drive forces, wind loads and temperature) and dynamic loads (including dynamic wind loads and seismic loading);
- Analysis of the various failure modes which applies to the structure (ultimate stresses, buckling, fatigue, fragile rupture…).

[4] The design process may have an intermediate Phase like the Preliminary Design Phase in which the structural sizing is determined.

[5] CTAO has decided to close the detailed design phase of products with a Critical Design Review (CDR). Therefore, for the purpose of this document the CDR represents the end of the detailed design Phase and the final design of the product is verified.

In general, FEM modelling is limited to primary structural elements and important secondary structural elements. Fasteners are often not modelled by FEM in order to minimize the effort, but whenever their performance is safety-critical they shall be analyzed by other methods, for instance by classical analytical methods.

4.2 Alternative Structural Verification Methods

In special cases, the structural verification can be performed or supplemented by different methods.

Verification by similarity can be accepted when it can be shown that the design and application of the reference item is equal or more severe than that of the item to be verified. Verification by reviewing the design is limited to those items where compliance can be shown by comparison of design documentation, for instance dimensions on drawing with the corresponding design requirements.

Where analysis methods are not representative or where data are not available or where data are not considered reliable, tests shall be performed to substantiate assumptions and to demonstrate sufficient performance or load capability. This can be the case for:

- Testing certain components on shaking table to demonstrate their ability to sustain dynamic loading. A typical example can be an electrical cabinet to be verified against earthquake excitation (Section 8.1.1).
- Tests on representative structural samples. This is the case for instance for the verification of bonded joints based on adhesive like those of glued mirror pads (section 8.1.2.).

Prototypes shall be produced and tested to verify the functional and performance characteristics. The Prototypes shall be designed and built under the same stringent conditions as the operational units. In addition, lessons learnt from prototype manufacturing, assembly and test shall be transferred to and improved in the design of the operational units.

4.3 Reference Configuration & Structural Analysis Report

The structural verification process shall be related to a well-defined design or hardware configuration (corresponding to one of the development phases defined in section 4.1), to ensure that design changes and deviations of the hardware from the design can be traced and assessed with respect to performance and safety.

In particular, at the time of the Critical Design Review the design shall be frozen and any subsequent changes shall be adequately documented and assessed with respect to their impact on performance and safety.

The structural analysis shall be documented in a structural analysis report. Some reqiuirements on the structural report are provided in Annex 9.2.

5 Modelling and Analysis Requirements

5.1 Finite Element Modeling

5.1.1 Software packages

The structural design and verification processes shall be performed with an internationally recognized software package, with the provider certified *ISO 9001*.

The recommended software packages are *ANSYS* and *NASTRAN* since they are widely used and verified. Furthermore, there are means to translate their formats from one to the other.

In case other software codes are used it shall be possible to translate the original models in *ANSYS* or *NASTRAN* so to allow an independent verification, or separate independent verification of the modeling shall be performed (ex. eigenfrequency check).

All Finite Element Model shall be delivered to CTAO in an agreed format, allowing independent verification by CTAO. Verification will be based on total mass, moments of inertia, location of center of gravity, eigenfrequencies and deformation under static and dynamic loads.

5.1.2 Modeling Requirements

The structural model shall be adapted to the specific analysis being performed and provide accurate representation of displacement, stresses and eigenfrequencies, for the set of loading described in Section 6. In Appendix 9.1 criteria for model checking are provided.

Boundary conditions shall be properly represented in the model. Care shall be exercised not to over-constrain the structure under study by artificial elimination of degrees of freedom.

If relevant, tolerances shall be taken into account while modeling.

Non-structural members, which are not contributing to performance or overall dynamics and are not critical for safety, can be modelled by lumped masses or as distributed masses. This may include cat walks, electrical cabinets, lifting cranes, cooling equipment and others.

When such lumped masses have more than one connection point to the structure, care shall be taken not to artificially over-constrain the supporting structure, by using appropriate nodal connections and correct degrees of freedom. When the stresses in the attachment elements cannot be derived by the FEA, such elements (ex. bolts) shall be verified separately, either analytically or with dedicated modelling. This is the case for instance for electric cabinet and other appurtenances, normally mounted on telescope structures.

Degenerated elements (triangular, prism, tetrahedron, pentahedron) without mid-side nodes are to be avoided in stressed areas, and are in general not recommended.

Distributed masses which cannot be easily modelled, like cables, piping, paints, connections, welds, fasteners and similar shall be taken into account by increasing the masses of structural members. The baseline increase of mass property shall be 10%. Lower values can be used if analytically justified and ddcoumented.

For the lowest fundamental modes (lowest frequency modes with effective mass $\geq$ 10% of total mass, the eigenfrequency accuracy of the analysis shall be better than 95%.

5.1.2.1 Bonded Joints Modeling

The study of adhesive joints by FEA[6] shall be based on typically 3 to 5 modelled layers. The meshing shall be such that the aspect ratio (side/thickness) in the element is not larger than 10:1.

[6] Not a substitution for appropriate tests on samples.

At the boundary between adhesive and the structural material the elements shall have a size ratio less than 1.5. The computed stress shall be the element stress and not the nodal stress.

5.2 Analysis Requirements

5.2.1 General Requirements

The analyses to be performed based on Finite Element Analysis are:

1. Static stress analysis showing the fulfillment of the load capability of all structural members. The static stress analysis shall provide displacement component loads, stresses and margin of safety.
2. Modal Analysis for the verification of the eigenfrequencies, the modal participation factor and the mode shapes.
3. Earthquake analysis
4. Buckling analysis of structural members.
5. Fatigue analysis

Additionally, a harmonic response analysis may be needed for the determination of the open loop transfer function.

5.2.2 Static and Dynamic Analyses

5.2.2.1 Deformation Analysis

An analysis of static deformations shall be performed with the following objectives:

- to determine overall deformations and local deformations for verification of required clearance between parts, where applicable (example mirrors facets);
- to determine the relative displacement of optical components (defocus, decentr, tilt) and the deformation of the optical train for verification of the optical error budget.

The following outcomes of the deformation analysis shall be reported as a minimum:

- the maximum deformation of each investigated load case;
- an overall deformation plot of each load case.

Specific outputs shall be provided if required for assessment of clearances and for error budget assessment or for ray tracing analysis of telescopes, if relevant.

5.2.2.2 Stress Analyses

All load carrying structures shall be verified by stress analysis for their applicable sets of loadings. The sets of loading must be in accordance with [AD01], and specifically as defined in Section 6.

The type of analysis to be performed is dependent on the system under study and shall be identified upfront and documented in the analysis report considering the various mechanism of failure of the structure under examination (ultimate stress, buckling, composite material failure, fatigue, fracture and crack growth, adhesive bonding failure ….)

5.2.2.3 Buckling Analysis

The buckling analysis verification of primary structures shall be performed either:

- By global linear buckling (first order) analysis with a buckling safety factor $\geq$ 10, or

- in accordance with the requirements of AD03.

In case other verification methods are proposed, they should be agreed with CTAO.

5.2.2.4 Fatigue Analysis

Fatigue analysis shall be performed on structural members with varying loads and and whose failure represents a hazard. For this reason, the use of brittle materials is discouraged.

For steel and Aluminum material the methodology of [AD03] and [AD05] respectively, shall be applied. For other material relevant method may be applied (example crack growth in ceramic materials).

Alternative methods (example methods applied in aerospace industry) may be used prior agreement with CTAO.

5.2.2.5 Modal Analysis

Modal analysis shall be performed for CTA structures. The following applies:

- The relevant eigenfrequencies, the corresponding modeshapes and effective masses shall be analyzed and documented.
- The sum of the effective modal masses for the modes computed in a modal analysis shall amount to at least 90% of the total mass of the structure in each direction.
- The modelling mesh should be fine enough to resolve the highest modeshape of interest.

5.2.2.6 Harmonic Response Analysis

An Harmonic Response Analysis may be needed to determine the steady-state response (transfer function) of a linear structure to dynamic (harmonically varying) loadings in the frequency domain.

5.2.2.7 Time-history Transient Dynamic Analysis

The time history analysis technique is used to determine the dynamic response of a structure under the action of a time-dependent loading.

For a linear system a modal representation can be used in the simulation. In this case the modal selection shall exceed the relevant frequency range of the excitation by a factor ≥ 1.5

5.2.2.8 Damping

The following damping ratios shall be applied in the dynamic analysis:

- 0.75% for bolted or welded structures excited by very low vibration amplitudes.
- 1.0% for bolted or welded structures excited by low vibrations. This can be considered the case for earthquakes lower than Damage Limitation.
- 2% for bolted or welded structures excited by mid to high vibration amplitudes as for earthquake at or above Damage Limitation.

Where properly justified these values can be exceeded in agreement with CTAO. Typically higher values can be used (never exceeding 4%) when stress level in the steel structure is of the order of 0.5 yield stress or higher, or when air damping can contribute significantly to the overall damping.

5.2.3 Thermal Analysis

The environmental temperature ranges do not completely describe the temperature of individual structural members, which can be affected by:

- solar irradiation;
- equipment thermal radiation to sky;
- convection and conduction.

Therefore, a thermal assessment is required for understanding if the thermal effects are negligible or if a more detailed thermal analysis is necessary to determine:

- temperatures as input to the stress analysis for the calculation of thermo-elastic stresses;
- compliance of equipment with enforced temperatures;
- calculation of deformation and misalignment of optical equipment.

For thermal analysis, there are the following options:

- analytical or numerical calculation or the temperature and heat fluxed using a lumped parameter thermal network;
- calculation of temperatures, heat fluxes and air flow by means of CFD analysis;
- detailed calculation of temperature gradients by FEA with input from lumped parameter calculations or CFD analysis.

5.2.4 Earthquake Analysis

5.2.4.1 Earthquake Analysis of Primary Structures

The analysis of Primary Structure shall be performed in accordance with requirements of [AD04]. This is for instance the case of telescope structures.

The Modal Response Spectrum analysis method can be applied if the structure behavior is linear. In case non-linear behavior is detected (example loss of prestress) and the behavior cannot be linearized, the time-history method shall be used.

In case of Modal Response Spectrum analysis, the modal combination shall be performed with the CQC (Complete Quadratic Combination).

When Secondary Structure(s) of significant mass with limited rigidity are mounted on the Primary Structure care shall be exercised during the modeling. Not only the attachment points between Primary and Secondary Structure must be properly modelled in terms of stiffness and degrees of freedom, but it may be needed to use more than one lumped mass (example: camera casing and focal plane) to have a proper estimation of key modes.

For simple Primary Structures (ex. LIDAR) the simplified method of Section 5.2.4.2.1. can be used, in agreement with CTAO.

5.2.4.2 Earthquake Analysis of Secondary Structures

This section provides instructions on how to perform earthquake analysis for subsystems and appendages which are connected to a Primary Structure and not directly to the ground (Secondary Structures).

In cases where the Secondary Structure is dynamically decoupled from the Primary Structure, the accelerations computed at the subsystem's with the earthquake analysis of the primary structure can be applied directly to the Secondary Structure in a quasistatic manner. In other cases, a resonant magnification effect between the Primary Structure and the Secondary Structure need to be considered or more accurate analyses procedures need to be applied.

- For the purpose of this specification a structure can be considered decoupled when its first frequency $f_{1S} \geq 5{*}f_p$ where f_p is the relevant mode of the Primary structure. In this case the simplified earthquake analysis method of Section 5.2.4.2.1. can be used. The input accelerations are those derived by the Response Spectra Analysis of the Primary Structure.

- In the cases where the first frequency 1.414 $*f_p < f_{1S} < 5*f_p$ a magnification factor shall be applied to the respective acceleration of the simplified earthquake analysis method of Section 5.2.4.2.1. according to the following table:

Frequency ratio	Acceleration Response Magnification Factor
1,414	2,00
1,50	1,80
1,60	1,64
1,70	1,53
1,80	1,45
1,90	1,38
2,00	1,33
2,10	1,29
2,20	1,26
2,30	1,23
2,40	1,21
2,50	1,19
3,00	1,13
4,00	1,07

Table 5-1: Acceleration response magnification factors for simplified earthquake analysis

- In the cases where $f_{1S} < 1.5 *f_p$ the simplified analysis method cannot be applied. In this case one of the methods of Section 5.2.4.2.2. below can be used, or a redesign of the Secondary Structure to increase its frequency is needed.

5.2.4.2.1 Simplified Earthquake Analysis Method

The static deformations and stresses shall be analysed by using the structural FE Model of the Secondary Structure.

The maximum action effect (A_{Ed1}, A_{Ed2} and A_{Ed3}) due to the three orthogonal seismic acceleration components shall be calculated with the Percentage Combination Rule:

The output of the seismic response spectrum analysis shall be processed according to stress analysis described in section 6.3.2. In addition, quasi-static accelerations shall be outputs to be considered in the stress analysis of dynamically decoupled mounted subsystems or equipment. A quasi-static analysis may be performed applying steady accelerations (Percentage Combination Rule) simultaneously along the three coordinate axes (x, y, z) by considering the following load combinations and all possible directions:

i. $A_{Ed1} = \pm F_{dx} \pm 0.3 \cdot F_{dy} \pm 0.3 \cdot F_{dz}$

ii. $A_{Ed2} = \pm 0.3 \cdot F_{dx} \pm F_{Fdy} \pm 0.3 \cdot F_{dz}$

iii. $A_{Ed3} = \pm 0.3 \cdot F_{dx} \pm 0.3 \cdot F_{dy} \pm F_{dz}$

where $\pm$ means “to be combined with”;

F_{dx}: design value of a seismic action (earthquake acceleration) in horizontal x-direction;

F_{dy}: design value of a seismic action (earthquake acceleration) in horizontal y-direction;

F_{dz}: design value of a seismic action (earthquake acceleration) in vertical z-direction.

The maximum design value of seismic action (A_{Ed}) is the worst case of all possible load combinations:

$$A_{Ed} = \max(A_{Ed1}, A_{Ed2}, A_{Ed3})$$

If the Secondary Structure is subject to different orientations, the earthquake analysis verification shall be performed for the various configurations, e.g. telescope altitude angles of 90º (Zenith), 45º and 0º (Horizon) as a minimum.

5.2.4.2.2 Detailed Earthquake Analysis Method

If a simplified analysis cannot be performed a more detailed analysis method is required. The following are descriptions of various detailed analysis methods which can be applied. The method a) and b) do not require the existence of earthquake accelerograms time-histories.

a) Modal response spectrum analysis of the assembly

In a seismic response spectrum analysis of the assembled models of the Primary Structure and the detailed Secondary Structure the entire model is loaded with the ground response spectra as defined in the appropriate Environmental Specification and fixed at the interface to the ground. The analysis requirements for the Modal Response Spectrum analysis are defined in section 4.3.3 of [AD04]. The modelling of the Secondary structure shall be accurate enough to well describe the dynamics of the main structural components.

b) Modal response spectrum analysis of the Secondary Structure

A seismic Response Spectrum analysis of the Secondary Structure applying appropriate *Floor Response Spectra* at the interface to the Primary Structure. The floor response spectra can be derived directly from the Modal Response Spectrum by specific algorithms. One example of such algorithm is *“Direct generation method for Floor Response Spectra” (Y. Yasui et al. SMIRT-12, Elsevier*). In this case the algorithm shall be approved by CTAO. The analysis requirements for the Modal Response Spectrum analysis are defined in section 4.3.3 of [AD04].

c) Non-linear time-history analysis of the Secondary Structure

In case time-histories are available for the primary structure a seismic a time-history input data at the interface of the Secondary Structure can be derived from the earthquake time history analysis of the Primary Structure and applied to the Secondary Structure. The analysis requirements for the time-history analysis are defined in section 4.3.3 of [AD04].

d) Non-linear time-history analysis of the complete Primary and Secondary assembly

In a seismic *time-history analysis* of the assembled models of the Primary Structure and the detailed Secondary Structure appropriate time-history input data *are applied* at the Primary Structure interface to the ground. The time-history input data can be derived from the specified acceleration Response Spectra defined in the appropriate Environmental Specification. The analysis requirements for the time-history analysis are defined in section 4.3.3 of [AD04].

By using the appropriate structural FE Model of the Secondary Structure, the static deformations and stresses shall be analysed for each of the specified design earthquakes.

5.3 Computational Fluid Dynamics Analysis

CFD analysis is a comprehensive tool for calculation of air flow and thermal analysis. In general, it requires a very accurate modelling and several analysis iterations. A trade-off can be reached if the CFD analyses are accompanied by analytical calculations that minimize the number of iterations. In case of analytical calculations conservative drag coefficients shall be selected.

The wind force acting on a structure is a function of the wind speed and the shape of the structure. Wind load may not be a significant concern for small, massive, low-level buildings, but it gains importance with large surfaces, height, the use of lighter materials and the use of shapes that my affect the flow of air. Fixings, aerodynamic profiles, and mass enhancement shall be considered to mitigate the wind effect whenever this can spoil the performances of the telescope / auxiliary instrument or even it can become a hazard for the structural integrity. Other effects that may need to be considered might include:

- jet streams that occur around the corners of the structure;
- resonances created by vortex shedding;
- through-flow that occurs in a passage through small gaps.

Wind speeds and characteristics presented in table 6.3.3.2 shall be considered for the determination of wind pressure. The resulting wind pressure shall be the input to the stress analysis. A check of the modelling of the turbulence shall be performed to validate the analysis by means of the dimensionless wall distance (y+) method.

6 Design Loads / Actions

Design loads (or actions) describe the force or pressure applied externally to the structural model that causes mechanical stresses, displacements, and deformations or simply accelerations. Excess load may cause structural failure, therefore structures shall be designed and built to be able to withstand all load types that they are likely to face during their working life.

6.1 Classification of Actions

Loads / actions are classified by their variation in time as follows:

6.1.1 Temporal classification

Permanent (G): loads that are relatively constant over time, including the self-weight of the structure, fixed equipment, and indirect actions caused by shrinkage and uneven settlements.

Variable (Q): imposed loads on structure, wind actions or snow loads.

Accidental (A): exceptional (short duration but significant magnitude) and rare loads as shocks, vibrations shaking or impact.

Seismic (E): effects resulting from earthquake events.

6.1.2 Spatial Classification of Actions

Loads may also be categorized by their variation in space as follows:

Concentrated (Points) Loads: single loads acting over a relatively small area (e.g. mirror actuator fixed point).

Distributed Loads: load exerted over a surface area or volume (e.g. weight on staircases and accesses).There are two types of distributed loads, hereafter described.

Surface Loads: are associated with actions such as wind pressure, and snow and ice weight. They are measured in force per unit area.

Volume Loads: are associated with own weight (gravity), inertial, centrifugal, and thermal effects. They are measured in force per unit volume.

Whatever their nature or source, distributed loads shall be converted to consistent nodal (element nodes) forces into the structural finite element model.

6.2 Permanent Loads

The following permanent loads are relevant for the structural verification process.

6.2.1 Gravity Load

The gravitational acceleration shall be assumed as 9.81m/sec. Where the relative direction of gravity changes, for example by change of the elevation angle of telescope, calculations shall be performed for a representative set of directions.

6.2.2 Settlement Load

The settlement load can occur in foundations, preloaded elements, threaded fasteners, and other structural members, by creep or yielding or environmental impact, e.g. absorption or release of humidity. Settlement shall be considered where applicable.

6.2.3 Preload:

Preloading of structural members shall be considered where applicable, for instance in prestressed members or pretensioned tether.

6.3 Variable Actions

6.3.1 Momentum by Azimuth and Elevation Drives

The load generated by the velocity (centrifugal force), acceleration or deceleration of azimuth and elevation drives (drive forces versus inertia forces and moment) as a function of the telescope / auxiliary instrument pointing direction. This includes positioning, fast positioning, tracking, parking, unparking and emergency stops. The relevant parameters are individual for each telescope. Corresponding data shall be derived from the selected kinematics, moved masses and drive forces of each drive.

6.3.2 Vibration and shocks

It is assumed that vibrations and shock are largely eliminated by specific design measure like drive oscillation monitoring, shock absorbers, speed limits when moving against stops and similar measures and are not occurring in a commissioned telescope. If not such effect have to be studied and considered in addition to the load combination provided in Section 6.4.

6.3.3 Environmental Loads and Actions

The environmental conditions at the CTA sites herein reported have been extracted from the requirement management system [AD06]and the [AD08]. The herein described environmental loads are relevant for the structural verification process.

6.3.3.1 Thermal Load

The applicable air temperature ranges are shown in table 6-1. The temperatures of telescopes / auxiliary instruments can be significantly different from the air temperature due to the action of solar radiation (maximum 1200 W/m^2) during the day and thermal radiation to cold sky (typical -50 °C if free of clouds) during the night. The resulting telescope / auxiliary instrument temperatures and gradients shall be determined by thermal analysis considering the relevant thermo-optical properties of exposed surfaces and dissipated power of these products, if relevant. As a rule of thumb, exposed surfaces with low thermal coupling to the main structure (e.g. reflector panels) can reach temperatures 30 °C beyond the ambient air temperature.

Temperature Ranges and gradients (both sites)		
Condtions	**Temperature**	**Gradient**
Operational air temperature[7]	-5 °C to +25 °C	0.05 °C/min
Survival air temperature	-15 °C to +35 °C	0.5 °C/min (over 20 min)

Table 6-1: Air temperature ranges applicable for the structural verification process.

6.3.3.2 Wind Load

The wind conditions reported in the table below shall be used for the verification of performances and the structural verification for ultimate cases:

[7] Operational performance is the one where the performance requirements must be fully met.

Maximum mean wind speed (V_m)		
Conditions	**North**	**South**
Maximum mean wind speed observation	36 km/h	36 km/h
Maximum mean wind speed repositioning	60 km/h	60 km/h
Maximum mean wind speed in SAFE state condition	120 km/h	100 km/h
Maximum gust speed (1 s) in SAFE state conditions[8]	200 km/h	170 km/h

Table 6-2: Wind speeds applicable for the structural verification process. (*): 10 minutes average.

- In the table above the mean speed refers to a 10 min average wind speed, measured at 10m above ground.
- The conversion from mean wind speed (averaged over time *T* = *1*0 min) to maximum wind speed, including gust (of duration *t*), is:

$$V_{gust} = V_m \text{ x } G\ (T, t)$$

$$G\ (T, t) = 1 + 0{,}42 \text{ x } I \text{ x } \ln{(T/t)}$$

- Where *G* is the gust factor and *I* is the turbulence Intensity.
- *I* is the turbulence intensity assumed at 25%[9].

[AD02] provides methods to determine the wind profile as a function of height (z) over ground. For simplicity, assuming that the terrain is Category III ([AD02], table 4.1, Z_{min} = 5m) the following can be used.

$$V = \frac{z}{5} V_m \quad \text{for z} < 5m, \quad V = V_m \text{ for } z > 5m$$

The model describing the wind dynamic characteristics is the Von Karman Power Spectral Density model, reported in Annex.

6.3.3.3 Snow Load

Snow can cumulate additional weight on structural surfaces. For horizontal surfaces and surfaces which are only slightly inclined the snow layers described in table 6-3 shall be assumed. Telescopes and auxiliary instrumentation will not be operated in case of snow, therefore this load is only to be considered in parking position and safe state.

Snow load ($\rho = 200\ kg/m^3$)		
	North	**South**
Maximum snow layer thickness in SAFE state condition	100 cm[10]	12.5 cm[11]

Table 6-3: Snow accumulation applicable for the structural verification process.

8 The wind gust values are under discussion and may be subject to a change request, resulting in a reduction of the gust wind speed.

9 The value of turbulence intensity expected by ESO is lower than 15% possibly affecting the value of 170 km/h, and therefore be considered in the above mentioned change request. At the time of the redaction of this issue a corresponding Change Request to B-ENV-0745 has not yet been prepared.

10 This value corresponds to the present requirement of Jama B-ENV-0520 [AD06], which considers that the 50cm thickness mentioned in [AD08] need revision.

11 In absence of speciifc data the Chilean norm NCh 431 is applied here, which foresees 25kg/m^2.

6.3.3.4 Ice Load

Ice can accumulate on structural surfaces. Structural beams of telescope and of auxiliary instrumentation shall be treated with special care, because a high ice layer can build up on the rear (downwind) side of the beams in specific wind conditions and also radial ice can be experienced. To cover these cases the application of radial ice in all wind exposed members shall be considered. Telescopes and auxiliary instrumentation will not be operated in case of ice, therefore this load is only to be considered in parking position and safe state.

The reference ice density is 900 kg/m^3 that is equivalent to 18 kg/m^2. In addition, fences with a small grid can be completely covered by a continuous layer of ice, so they shall be approximated as continuous surfaces.

Radial Ice ($\rho = 900\ kg/m^3$)		
	North	**South**
Maximum ice layer thickness in SAFE state condition	20mm	n/a

Table 6-4: Radial Ice accumulation applicable for the structural verification process.

Notes:

II. The 20mm layer is reported not to be sufficient for North in the Environmental range document. In particular, on certain surfaces the thickness of the "hard rime" deposited by the wind on the exposed surface can be considerably higher. It is noted however that in terms of mass a uniform radial ice thickness of 20mm represents a heavier condition than localized thickness of 200mm or even 300mm of ice of 800 kg/m3 density[12]. It is therefore suggested, for specific telescope elements known to be subjected to heavy accumulation of ice (example camera support structure) to perform localized analysis with thickness of ice on the top surface

II. For the CTAO South it is noted that icing in the form caused by icing rain storms has never been experienced even at the higher elevation of Paranal. Furthermore the Chilean Norm NCh431 foresees for that area only a snow load 25kg/m^2. Therefore, no additional load case needs to be computed beyond the snow load.

6.3.4 Seismic Action

Earthquake represents a major design driver for the CTAO-South, while the low seismicity at La Palma allows to neglect earthquakes. CTAO structures shall be designed and constructed to withstand the design value of a seismic action without collapse, and additionally also retaining the possibility to be put back in operation after repair. The specific earthquake requirements are detailed in [AD07]. Two reference earthquakes are considered for the CTAO-South in accordance with [AD04]:

- *The Damage Limitation Requirement (DLR)* earthquake corresponding to a seismic action with a probability of exceedance P_{DLR} = 10% within 10 years, corresponding to an earthquake with a return rate T_R = 95 years. This limit state is also referred to as a Serviceability limit state, which means that the structure has not yielded and retained its strength and stiffness.
- *The No-Collapse Requirement (NCR)* corresponding to a seismic action with a probability of exceedance P_{NCR} = 10% in 50 years, corresponding to an earthquake with return rate T_R = 475 years. This limit state is also referred to as a *Damage Control limit state*, which

12 Information from the document Site Proposal La Palma (La Palma as a candidate for CTA-North) dated 5 November 2014.

means that the structure has yielded to a certain extent, but the damage is contained so that the structure has retained its overall structural integrity (no local or global collapse) and has a minimum residual load bearing capability after the seismic event. Specifically, In the case of CTAO repair of the structure shall be possible which means that limited amount of plasticity in the structure is generated, sensibly less than what would be needed to avoid collapse.

Being the CTAO-South extended over various kilometers different elastic response spectra must be used at different locations depending on the soil conditions encountered (soft, medium and hard soil). The parameters for these two reference earthquakes in terms of elastic response spectra with 2% critical damping are given in [AD07].

- It shall be noted that in the case of telescope structures and cameras the importance class to be considered is Class II. As such the response spectra of [AD07] applies directly.
- In the case of auxiliary instrumentation as LIDAR and similar equipment the importance class Class I can be considered. In this case the NCR spectra to be used can be scaled by the factor $\gamma_I = 0.8$. This corresponds to verification against an earthquake with $T_R <$ 475 years.

As outlined in [AD07]] verification of telescopes shall be based on response spectra for 2% critical damping. The analysis shall be based on a seismic behavior factor *q=1* corresponding to a fully elastic behavior therefore neglecting dissipation by non-linear response (Section 4.2.5 of Eurocode 8 [AD04]).

6.3.5 Other Actions

6.3.5.1 Hail Action

Hail can be critical for local damages, for instance optical surfaces. Impact resistance of sensitive materials shall be checked, specifically for mirrors and other unprotected optical devices. The preferred verification method is based on prototype tests.

The impact of these actions shall be considered in the design verification for the relevant parts.

6.3.5.2 Loads imposed by maintenance activities

When designing working platforms, stairs, and gangways shall be designed to the following independent loads according to norm EN 14122 -2 (2016)

- distributed vertical force of 2 kN/m^2;
- single concentrated force of 1.5 kN on a surface of 200 × 200 mm^2;
- distributed horizontal force on railings of 1.5 kN/m.

If specific maintenance operations cause loading outside the envelope above, they should be verified as well.

6.4 Load Case Combinations for Verification of Structural Safety

Table 6-5 lists the necessary load cases for the structural verification of CTA telescopes and auxiliary instrumentation that behaves like a telescope (e.g. Lidar). The selection of these load cases has been done assuming that:

- observations will only be during night;

- Exceptional environmental events are predictable in time for bringing telescopes and auxiliary instruments into parking position and safe state;
- Earthquakes are not predictable, therefore can occur both in operational and in stow conditions.

Variables and parameters presented in the table 6-5are hereafter described.

A-Angle: azimuth angle.
A-Velo: actions initiated by azimuth angular velocity.
A-Acc: loads initiated by azimuth angular acceleration (azimuth drive).
E-Angle: elevation angle.
E-Velo: actions initiated by elevation angular velocity.
E-Acc: loads initiated by elevation angular acceleration (elevation drive).
T-Field: loads generated by temperature field.
Gravity: loads generated by static weight.
Wind: loads generated by wind pressure.
Snow: load generated by snow pressure.
Ice: load generated by the maximum specified ice layer.
Seismic: loads generated by seismic action.
V_{max}: maximum velocity.
A_{max}: maximum acceleration.
DLR (V): DLR vertical acceleration
DLR (H): DLR horizontal acceleration
NCR (V): NCR vertical acceleration
NCR (H): NCR horizontal acceleration.

Note: *DLR and NCR are equivalent to Operating Basis Earthquake (OBE) and Maximum Likely Earthquake (MLE) respectively, as often referred In previous CTAO documents.*

Different elevation angles shall be considered, as a minimum for parking position and elevation angles of 0 °, 45°, and 90°. The azimuth angle is relevant with respect to wind direction and horizontal direction of seismic ground acceleration. Both actions shall be applied in different orientations relative to the telescope / instrument, as a minimum for azimuth angles of 0°, 45°, 90°, 135°, and 180°. In case of critical conditions further refinement shall be considered.

The values given under “T-Field” are upper and lower levels of the air temperature. Temperature gradients as may result from wind, solar radiation or heat exchange with cold sky are to be determined accordingly and may need variation of additional parameters.

Table 6-5 contains the essential combinations of loads / actions, but further expansion of variables shall be evaluated, if appropriate. For a correct understanding of the severity of each load type, it is recommended to run each single load type separately before performing the load combinations.

The analysis effort can be minimized by creating envelope cases. If it can be demonstrated that different load types are not cumulating stress at the same locations, or actions do not occur simultaneously for example due to physical reasons, combinations can be omitted. Further reduction may be possible by removing loads with negligible stress contribution.

	DESIGN SITUATIONS			PERMANENT		INTRINSIC IMPOSED ACTIONS				ENVIRONMENTAL LOADS				SEISMIC ACTION	VARIABLE Parameter	LIMIT STATES
	Parameter id	**1**	**2**	**3**	**3a**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**		
	Parameter	**A-Angle [°]**	**E-Angle [°]**	**Gravity [g]**	**Preload [N]**	**A-Velo [° / s]**	**A-Acc [° / s^2]**	**E-Velo [° / s]**	**E-Acc [° / s^2]**	**T-Field [° C]**	**Wind [km / h]**	**Snow [kg / m^2]**	**Ice [mm]**	**Seismic [g]**	**Param. Id**	**Damage**
Site	**Operational State**															
Unit load cases (trade-off)																
N, S	O	0	0 to 90	1											2	
N, S	O,S	0	0		Preload											
N, S	O	0	0 to 90			v_{max}									2	
N, S	O	0	0 to 90				a_{max}								2	
N, S	O	0	0 to 90					v_{max}							2	
N, S	O	0	0 to 90						a_{max}						2	
N, S	O	0	0							+25						
N, S	S	0	0							-15						
N, S	O	0 to 360	0 to 90								36				1,2	
N	S	0	park									200				
S	S	0	park									25				
N	S	0	park										20			
S	O, S	0	0 to 90, park											DLR (V)	2	
S	O, S	0 to 360	0 to 90, park											DLR (H)	1,2	
S	O, S	0	0 to 90, park											NCR (V)	2	
S	O, S	0 to 360	0 to 90, park											NCR (H)	1,2	
Combined load cases for performance verification in Operational state																
N, S	O	0	0 to 90	1	Preload					-5 / +25					2,8	none
N, S	O	0 to 360	0 to 90	1	Preload						36				1,2	none
N, S	O	0 to 360	0 to 90	1	Preload					-5 / +25	36				1,2,8	none

DESIGN SITUATIONS				PERMANENT		INTRINSIC IMPOSED ACTIONS				ENVIRONMENTAL LOADS				SEISMIC ACTION	VARIABLE Parameter	LIMIT STATES
	Parameter id	1	2	3	3a	4	5	6	7	8	9	10	11	12		
	Parameter	A-Angle [°]	E-Angle [°]	Gravity [g]	Preload [N]	A-Velo [° / s]	A-Acc [° / s²]	E-Velo [° / s]	E-Acc [° / s²]	T-Field [° C]	Wind [km / h]	Snow [kg / m²]	Ice [mm]	Seismic [g]	Param. id	Damage
Site	Operational State															
Combined load cases for strength verification in Operational states (non safe configuration)																
N,S	O	0 to 360	0 to 90	1	Preload						50				1,2	none
N, S	O	0	0 to 90	1	Preload		± a_{max}		± a_{max}						2,5,7	none
N, S	O	0	0 to 90	1	Preload		± a_{max}		± a_{max}	-5 / +25					2,5,7,8	none
N, S	O	0 to 360	0 to 90	1	Preload		± a_{max}		± a_{max}		50				1,2,5,7	none
N, S	O	0 to 360	0 to 90	1	Preload		± a_{max}		± a_{max}	-5 / +25	50				1,2,5,7,8	none
S	S	0 to 360	0 to 90	1	Preload						36			DLR (V, H)	1,2	SL
S	S	0 to 360	0 to 90	1	Preload						36			NCR (V, H)	1,2	UL
Combined survival load cases for safety verification in safe state configuration																
N	S	0 to 360	park	1	Preload						120				1	none
N	S	0 to 360	park	1	Preload						200 (gust)				1	SL
N	S	0 to 360	park	1	Preload					-15	50	200			1	none
N	S	0 to 360	park	1	Preload					-15	120	200			1	SL
N	S	0 to 360	park	1	Preload					-15	120		20[13]		1	SL
S	S	0 to 360	park	1	Preload						100				1	none
S	S	0 to 360	park	1	Preload						170 (gust)				1	SL
S	S	0 to 360	park	1	Preload					-15	100	25			1	SL
South	S	0 to 360	park	1	Preload					-15 / +35	50			DLR (V, H)	1,8	SL
South	S	0 to 360	park	1	Preload					-15 / +35	50			NCR (V, H)	1,8	UL

Table 6-5: Unit load cases and combinations of load cases for the CTA telescopes and similar instruments.

13 See note in section 6.3.3.4.

7 Structural Verification by Analysis

7.1 General Requirements

Structural verification of Primary Structure shall be verified according to the methodology of Eurocode Norms, [AD01 to AD05] as per Section 7.2. In specific cases of simple Primary Structures and less important equipment (ex. Illuminator Lidars…) the simplified method of Section 7.3 may be applied.

For the verification of secondary structures, the simplified method of Section 7.3 can be used, if beneficial with respect the method of Section 7.2.

7.2 Structural Verification according to Eurocode

7.2.1 Partial Factors Method

The *Eurocode* has adopted a statistical approach for the superimposition of the various load types. The applicable document [AD01] specifies the partial factor method by providing a comprehensive definition of load cases and factors directly applicable to these loads considering the probability of their occurrence. It also distinguishes between *Serviceability Limit State* and *Ultimate Limit* State.

For the verification of the Ultimate Limit State, the method applies partial factors of safety differentiating between leading values and accompanying values of action.

For the Serviceability Limit State combination factors are provided to be applied to the characteristic values of actions.

Some requirements form Eurocode EN 1990 [AD01] are reported here, whereby in case of conflict the Eurocode takes precedence. It applies:

a) The fundamental combination of simultaneous loads that shall be used for persistent and transient design situations in case of Ultimate Limit State verification is as follows:

$$F_d = \gamma_G G + \gamma_p P + \gamma_{Q1} Q_{k1} + \sum_i \gamma_{Qi}\, \psi_{0i}\, Q_{ki}$$

with *i > 1*

b) CTAO has defined two seismic loading cases, NCR and DLR, to be verified against Ultimate Limit State and Serviceability Limit State, respectively. The combinations of actions is as follows:

$$F_d = G + P + A_{Ed} + \sum_i \Psi_{2i}\, Q_{kj}$$

with *i > 1*

In the above expressions:

“+” implies “to be combined with

F_d design value of the combination of actions;

G value of permanent action (e.g. weight);

P Preload actions (ex. cable prestress)

Q_{k1} characteristic value of the leading variable action (e.g. wind);

Q_{ki} characteristic value of an accompanying variable action (e.g. snow);

A_{Ed} design value of seismic action;

γ_G partial safety factor for the permanent action G;

γ_Q partial safety factor for variable action Q_k;

Ψ_{0i} factor for combination (rare / exceptional value) of an accompanying variable action (coefficient, $\Psi_{0i} \leq 1$);

Ψ_{2i} factor for combination (quasi-permanent value) of a variable action (coefficient, $\Psi_{2i} \leq 1$).

Notes:

- All survival load values must be understood as characteristics values according to section 4.1.2 of [AD01], hence as an upper value never expected to be exceeded.
- Each relevant load type shall become subsequently a leading variable to get all relevant load combinations.
- All other non-leading loads (accompanying action) shall be scaled using the factor for accompanying variables.
- The seismic loads, when considered, shall be the leading variable, never an accompanying variable.
- Seismic loading shall be verified both against Ultimate Limit state (NCR) and serviceability limit state (DLR).

The designer shall use in the load combinations the relevant factors in accordance with Annex A1 of [AD01]. Table **7-1**: reports recommended values of the partial safety factors and reduction coefficients for the combination of different actions / loads. These values can however be different in national codes.

Partial Factors and reduction coefficients									
Factor	**Gravity**	**Preload**	**A-Drive**	**E-Drive**	**Temp**	**Wind**	**Snow**	**Ice**	**Seismic**
Y(min)	1	1	0	0	0	0	0	0	0
Y(max)	1.35	1	1.35	1.35	1.5	1.50	1.50	1.50	1
Ψ_0					0.7	0.7	0.7	0.7	
Ψ_{2i}						0.2	0.2	0.2	

Table 7-1: Recommended partial factors and reduction coefficients applied for the combination of different actions / loads in the partial factor method.

7.2.2 CTAO Specific Ultimate Limit State Verification

As reported in section 3.3.2, the in the case of CTAO further use of the equipment must be guaranteed also after survival load cases have occurred. The verification of the survival load case is based on elastic analysis and verification against the yield stress. In Eurocode [AD04] this criterion is applied without a material safety factor (hence $\gamma_M = 1$)[14].

[14] For bolts and welds other material safety factors are recommended (γ_{M2} =1.25),

For this reason, if the yield stress is exceeded in the elastic analysis more sophisticated investigations are needed to assess the amount of plasticity in the structure and the associated consequences in terms of stability (amount of strain[15], plastic hinges, buckling under consideration of deformed geometry and failed structural members…).

These analyses shall also allow to globally estimate the structural damage to assess the effort for putting back in operation the structure. The effort to put back in operation shall conform to the requirements of [AD07] (CTAO-South Seismic Risk Specification), leading for earthquakes to specific interpretation of the limit state.

7.3 Simplified Structural Verification Method

7.3.1 Safety Factors

Sufficient load capability can be demonstrated by positive Margin of Safety as follows:

$$\text{Margin of Safety (MoS)} = \frac{\sigma_m}{\sigma * SF * SFM} - 1 \geq 0$$

where:

σ_m yield strength for ductile material, or ultimate strength for brittle material

σ maximum stress of individual load or of any applicable load combination (von Mises stress for ductile materials, maximum principal stress for brittle materials)

SF Stress Safety Factor

SFM Material Safety Factor

Alternatively the Reserve Factor can be used to demonstrate sufficient load capability as follows:\

$$\text{Reserve factor (RF)} = \frac{\sigma_m}{\sigma * SF * SFM} \geq 1$$

Also the Utilization can be used:

$$\text{Utilization (U)} = \frac{\sigma * SF * SFM}{\sigma_m} \leq 1$$

For the Load Safety factors the values of Table 7-2 shall be used:

Loading and conditions	Stress Safety Factor
Operational state, assembly phase	1.35
Safe state	1.35
Survival load cases	1.1

Table 7-2: Stress Safety factors for allowable stress

[15] Eurocode EN 1993 - 1-5, Annex C.8 Limit state criteria recommends a limiting 5% for the principal strain.

For the Material Safety Factors the values of Table 7-3 shall be used:

Material	Material Safety Factor	
	Yield	Rupture
Metal	1.1	1.5
Optical glass, glass-ceramics	n/a	2.0
Glue, adhesive	n/a	2.0
CFRP	n/a	2.0

Table 7-3: Applicable Material Safety factors for different types of materials.

7.4 Verification of Specific Materials / Items

7.4.1 CFRP Verification

In the case of CFRP the relevant failure mode shall be studied, considering all applicable relevant failure criteria (delamination, fatigue, gluing failure…) and considering the stress safety factor. For CFRP verification it is suggested to use the methodology of [RD04].

7.4.2 Glass Material

For glass ceramics material whose failure is based on crack growth the minimum baseline probability of failure shall be lower than 10^{-5} over the projected lifetime. The probability of failure shall be based on the Weibull statistical distribution, based on the parameters provided by the glass manufacturer. In case of material provided by Schott, the methodology outlined in [RD05] shall be applied.

7.4.3 Bolt Joints

Bolted joints shall be verified according to the guidelines of [RD03]

8 Structural Verification by Qualification Testing

8.1 General

As outlined in section 4.2 In specific cases structural verification can be obtained by testing prototypes or specific representative test specimens. In this case the verification is based on the qualification of items which are then procured and or manufactured accordingly. This shall be the case for instance the case for the items covered by point 8.1.1 below. The qualification activities may therefore lead to a specific certification.

In specific case test specimens are used proving that the design is adequate for the loads and the lifetime expected in conjunction with a specific manufacturing procedure, like in the case of adhesive joints under point 8.1.2 below.

Note: Structural verification by qualification testing is not necessarily limited to the cases specified herein, and can be extended if required of judged advantageous.

8.1.1 Electrical Cabinets

Electrical cabinets whose performance is critical for the case of recovering of a telescope to a safe state after a major earthquake (DLR, NCR) shall be:

- either bought according to Bellcore Zone-4 standards, or,
- if not bought according to the Bellcore Zone-4 standards they shall be checked against the actual acceleration expected at their location in case of earthquake. The actual accelerations shall be derived according to the procedure mentioned in Section 5.2.4.2.

In addition to the verification seismic resistance of the cabinet also the attachment points shall be properly verified for structural strength.

8.1.2 Adhesive Joints

The strength of adhesive joints like those used for gluing pads to glass mirrors shall be verified by appropriate test samples and/or prototypes.

The samples shall be representative of the final design adopted and consider the expected in-service conditions.

The test samples shall also be used to validate the manufacturing procedure associated to the gluing process (type of glue, thickness, application, layers, curing……)

9 Annexes

9.1 FE Modeling and Analysis Quality Checks

Each FEM structural model shall be checked with respect to the following parameters and characteristics, as a minimum.

Note: The source of this section is [RD05].

9.1.1 Model Accuracy Check

Model check		Requirement
1	Free nodes	Delete nodes in the model which are not connected to elements or constraint equations.
2	Free connections	Assure that elements in the model are properly connected by using free-edge check.
3	Coincident elements	Delete coincident elements (same node connectivity), if it is not intended.
4	Elements shape	Assure that plate element distortion (e.g. warping, aspect ratio, face angle, Jacobian Ratio) meets the recommended limit requirements.
5	Element normals	Assure that plate element normals of a component are oriented uniformly.
6	Model mass	Check if model's mass is reasonable and accurate and contains the margin as defined in section 5.1.2.
7	Units	Check consistency of units (dimensions, material properties, loads).
8	Constraints check	Check the adequacy of boundary conditions. Make sure their locations and DOFs are correct. Avoid incorrect over- or underconstraint system.
9	Material properties	Check whether material property values are correct and match the units used elsewhere. Check completeness of properties depending on the analysis type.
10	Element properties	Verify beam cross sections and area moment of inertias, plate thicknesses, mass and stiffness properties.
11	Dimensions	Ensure correlation between overall geometry and drawings / 3D CAD data.
12	Element selection	Select proper element type for the analysis.
13	Constraint equations	Cross check correct formulation of the constraint equations (CE, RBE and MPC). Avoid over-constraining the model with constraint equations.
14	Coordinate systems	Check the input and output coordinate systems applied.

9.1.2 Mathematical Model Checks

Model check		Requirement	Action / Criteria
15	Gravity load check	Verify that the model provides plausible displacements and reaction forces under unit gravity loading, applied separately along the three orthogonal Axes.	Check consistency of total mass, acceleration and total reaction force. Total reaction forces in other than loading direction should be zero.
16	Enforced displacement check	The unit enforced displacement and rotation check verifies that no illegal constraint (such as incorrect CE or RBE) is present in the model.	Constrain only a single node close to the center of gravity in all six DOF. The unit displacements and rotations should be applied to this node. The check shall be performed in all 6 DOF directions, one at a time. The model should move as a rigid body when it is translated by one unit or rotated one radian. The displacement results from the three translational load cases should be 1.0 along the input direction and zero in the other five directions. From the rotational load cases the rotation in the input direction should be 1.0 and the other two rotations should be 0.0. The element forces and nodal force balances should be close to zero.
17	Free-free dynamic	The free-free dynamics check verifies that the model moves as a rigid body when it is unconstrained. It also checks the stiffness matrix in terms of internal constraints, such as erroneously defined CE.	Perform modal analysis after all external constraints have been removed. The ratio between the first six frequencies and frequency of the lowest elastic mode shall be less than 1E-3. Additional rigid body modes should be justified case-by-case (e.g. free motor axis, mechanisms).
18	Conditioning check	The purpose of the conditioning check is to identify regions that can cause numerical rounding errors in the stiffness matrix and hence erroneous results.	The maximum stiffness ratio (ratio between highest and lowest stiffness coefficient values) of the model shall not exceed 10^{12} (goal 10^{8}).
19	Thermal-structural check	The purpose of the thermal-structural check is to verify that the model is well conditioned for the thermo-elastic analysis. This check should be performed on all models used for thermal distortion analyses.	The model must be iso-statically supported (e.g. all 6 DOFs constrained at one node). For this check all the material properties used in the model have been replaced with the same homogenous and isotropic ones. A uniform temperature increase must be applied to the model. The resulting displacements must comply with the theoretical displacements. The nodal forces balance and the resulting stresses should be close to zero, i.e. E=100 GPa, n=0.3, CTE=10^{-5} 1/K, dT=80 K,→ σ_{max}< 100 Pa

9.2 Analysis Results and Documentation

An analysis report shall summarize the structural verification process and the calculations which support the design in each phase. It shall also describe the issues discovered and the necessary corrective actions. The structural analysis shall be documented to such detail and include all references so that an independent structural verification process is possible from the analysis report and supplied data only.

Once the design is finalized the reports shall demonstrate the achievement of the full structural integrity.

The official language of the report shall be English.

9.2.1 Units

All physical quantities presented in a structural analysis report shall be expressed using the International System of Units, and temperature shall be expressed in Celsius.

9.2.2 Report Structure

The report template shall contain as minimum the following information.

Scope
Definition of the scope of the document, and the objectives of the analysis described. Presentation of the software tools adopted.

Reference Design
Identification of the design configuration which is object of the analysis report

Main assumptions
Assumptions taken in the modelling, the modelling of the boundary conditions, materials, loading cases and postprocessing. Description of the analysis method.

Modelling
There shall be a detail description of the model used in the analysis. This includes geometry, coordinate system, configuration, section properties, boundary conditions, application of loads, type of elements, and resulting mass versus the nominal mass. The model should be represented with sketches and plots.

Loading cases
The loading cases used in the analysis and their application into the model shall be documented.

Structural Analysis Results
Presentation of the results obtained. This includes general results (ex. natural modes) as well as data related to results to be compared with allowable values associated to performance or failure criteria (deformations. stress, safety factors, buckling …). A comparison table shall summarize the calculated values against the allowable values.

Conclusions:
Summary of the most important results versus requirements and discussion of possible non-conformities. Any open work in terms of incomplete or missing analyses shall be reported.

Annex
The result of FE model analysis quality check shall be documented.

9.3 Von Karman Model

The model describing the wind dynamic characteristics is the Von Karman Power Spectral Density model:

$$S(f) = (I \text{ x } V_m)^2 \text{ x } \frac{4 \text{ x } L/V_m}{[1 + 70.8 \text{ x } (f \ x \ \ L/V_m)^2]^{5/6}}$$

where

f: frequency [Hz];

***I*:** turbulence intensity (assumed at 25%)

***v_m*:** mean wind speed [m / s]

L: integral length scale [m] = 50m

---------------- *End of document* --------------------