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Space engineering

Structural finite element models

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Foreword

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Introduction

The concept of model is of primary importance in all the fields of the science. In engineering disciplines - and specifically in structure mechanics - a model is a representation, able to describe and predict the behaviour of a structure in terms of quantifiable variables. A first step to build a model is to choose the variables which are relevant to the studied phenomenon (e.g. displacements, stress, or frequencies) and the types of relationships among them (e.g. the theories provided by elasticity, plasticity, stability, statics, or dynamics): this representation is called the physical model. The second step is to build a mathematical representation (e.g. using differential equations, integral equations, or probability methods): this representation is called the mathematical model. A third step is to build a numerical model, which is a formulation of the mathematical model by means of numerical algorithms, based on several approaches (e.g. the finite element method, the boundary method, or the finite difference method). A finite element model of a structure is such a type of numerical model of structure behaviours.

This Standard is restricted only to the requirements for finite element models of space structures, to be fulfilled to ensure modelling quality, i.e. the correct use of this specific technology – the finite element method - and the acceptance of the results.

1
Scope

ECSS-E-ST-32-03 (Space engineering – Structural finite element models) defines the requirements for finite element models used in structural analysis.

This Standard specifies the requirements to be met by the finite element models, the checks to be performed and the criteria to be fulfilled, in order to demonstrate model quality.

The Standard applies to structural finite element models of space products including: launch vehicles, transfer vehicles, re-entry vehicles, spacecraft, landing probes and rovers, sounding rockets, payloads and instruments, and structural parts of all subsystems.

This standard may be tailored for the specific characteristics and constrains of a space project in conformance with ECSS-S-ST-00.

2
Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this ECSS Standard. For dated references, subsequent amendments to, or revision of any of these publications, do not apply. However, parties to agreements based on this ECSS Standard are encouraged to investigate the possibility of applying the more recent editions of the normative documents indicated below. For undated references, the latest edition of the publication referred to applies.

ECSS-S-ST-00-01	ECSS system – Glossary of terms
ECSS-E-ST-32	Space engineering – Structural general requirements

3
Terms, definitions and abbreviated terms

3.1 Terms from other standards

For the purpose of this Standard, the terms and definitions from ECSS-S-ST-00-01 and ECSS-E-ST-32 apply.

3.2 Terms specific to the present standards

3.2.1 constrained DOF

DOF which has a known value, given as input

3.2.2 degrees of freedom

scalar components of the solution vector in the FE method

NOTE Examples of DOF are displacement and rotation components, and other physical quantities as beam warping variable, or modal coordinates.

3.2.3 dependent DOF

DOF which is computed from the values of other DOF, by means of a multi-constraint equation, provided as additional modelling input

NOTE Examples of multi-constraint equations are the rigid body relationship of two or more DOFs.

3.2.4 dynamic reduction (also referred as dynamic condensation)

method to reduce the FE model size by means of a transformation of the full set of FE DOFs in a set of modal coordinates, and a subset of retained displacement and rotation components

NOTE There are several methods of dynamic reduction (e.g. Craig-Bampton, MacNeal).

3.2.5 free DOF

unconstrained independent DOF

3.2.6 modal DOFs (also referred as modal coordinates)

DOFs related to a basis of dynamic eigenmodes

3.2.7 output transformation matrix

matrix which pre-multiplies the reduced model DOF vector or its time derivatives to obtain the value of remaining non-retained DOFs and output variables (e.g. element force and stress)

3.2.8 quantifiable structure variable

structure property which can be measured and is chosen to quantify a structure behaviour

NOTE Examples of quantifiable structure variables are: displacements, stresses, natural frequencies, material properties, element properties, loads, temperatures.

3.2.9 rigid body motion matrix

matrix which has as columns the vectors of rigid body displacements

3.2.10 size of FE model

number of all the DOFs of the FE model

3.2.11 static reduction (also referred as static condensation)

method to reduce the number of the DOFs in a model by means of a reduction transformation matrix or constraint modes matrix.

NOTE Guyan reduction is a widely employed method of static reduction.

3.2.12 structural model

representation of a specific structure behaviour - described by a chosen sets of quantifiable structure variables - by means of relationships which predict the values of variables subset (named output variables) as depending from the remaining variables (named input variables)

3.3 Abbreviated terms

For the purpose of this Standard, the abbreviated terms from ECSS-S-ST-00-01 and the following apply:

Abbreviation	**Meaning**
DOF	degree of freedom
FE	finite element
OTM	output transformation matrix

3.4 Symbols

The following symbols are defined and used within this Standard:

Symbol	Meaning
$\mathbf{E}_R$	rigid body motion strain energy matrix
$\mathbf{F}_R$	rigid body motion residual nodal force vector
$\mathbf{K}$	stiffness matrix
$\mathbf{M}$	mass matrix
$\mathbf{\Phi}_R$	rigid body motion matrix

4
General requirements

4.1 Overview

The Finite Element (FE) models are categorized as follows:

- 'Non-reduced' models: defined only by nodes and finite elements (with their properties), and using as DOFs the node displacements and rotations.
- 'Statically reduced' models: defined by nodes and matrices obtained from static reduction, and using as DOFs the node displacements and rotations.
- 'Dynamically reduced' models: defined by nodes and matrices obtained from dynamic reduction, and using as DOFs both modal coordinates and node displacements and rotations.

NOTE 1 'Reduced' models are also referred to as 'condensed' models.

NOTE 2 Combinations of non-reduced and reduced models can be used.

4.2 Coordinate systems and unit system

a. All local coordinate systems of the mathematical model shall refer, directly or indirectly, to a unique local coordinate system that is defined with respect to the basic coordinate system.

NOTE 1 The basic coordinate system is a Cartesian rectangular system having the origin in x=0; y=0; z=0.

NOTE 2 The requirement allows easy merging of different FE models.

b. The following units should be used for FE models:

1. meter, for length
2. kilogram, for mass
3. second, for time
4. newton, for force.

4.3 Modelling requirements

a. Modelling guidelines shall be established and agreed with the customer.

NOTE Guidelines are established at least on the following modeling aspects:

- Types of elements to be used or avoided
- Aspect ratio thresholds for the elements
- Warping threshold for shell elements
- Types of springs to be avoided (e.g. non-zero length)
- Types of permitted rigid elements
- Modelling of the offset of elements
- Modelling of bolted and riveted connections
- Specific aspects of dynamic models
- Specific aspects of the thermal stress models (e.g. ability to represent temperature discontinuities due for instance to thermal washer)
- Specific aspects of non-linear analysis models
- Specific aspects for axi-symmetric models, cyclic symmetry models and Fourier series development
- Suggested, required and to-be-avoided analysis related parameters
- Mesh density
- Mesh refinement
- Interface definition
- Numbering rules
- Coordinate system definition
- Definition of equivalent properties
- Fluid effects (e.g. sloshing, added mass)

4.4 Requirements for reduced models

a. The static behaviour of the structure shall be described by the reduced stiffness and mass matrices, and reduced force vector relative to the retained degrees of freedom.

b. The dynamic behaviour of the structure shall be described by the reduced stiffness, mass and damping matrices, and reduced force vector relative to the retained degrees of freedom.

c. The reduced model shall be supplied with related instructions for model integration.

d. The modal DOFs shall be ordered in the matrices according to the mode numbering sequence.

e. The numbering range of the modal DOFs shall be outside of numbering ranges of other DOFs (e.g. node displacements).

f. Output Transformation Matrices (OTMs) shall be provided and separated according to the type of output.

g. OTMs shall be supplied with related user instructions and output item lists.

h. A specific format of reduced matrices and OTMs shall be agreed with the customer.

i. OTMs shall be verified by consistency with non reduced model (see clause 5.8)

j. OTMs provided for the recovery of displacements and displacement-related data (e.g. element stresses, element forces, constraint forces) shall correct for modal truncation (e.g. mode acceleration method, residual vector method or alternative modal enrichment techniques).

k. The damping for the elastic modes shall be viscous modal damping.

5
Model checks

5.1 General

a. At least the following checks shall be performed:

1. Model geometry checks for non reduced models.
2. Elements topology checks for non reduced models.
3. Rigid body motion checks for reduced and non reduced models.
4. Static analysis checks for reduced and non reduced models
5. Stress free thermo-elastic deformation check for non reduced models.
6. Modal analysis checks for reduced and non reduced models.
7. Reduced model versus non reduced model consistency checks.

5.2 Model geometry checks for non reduced models

a. Unconnected nodes shall be justified.

b. Coincident elements shall be justified.

c. The free edges of the model shall be the expected model boundaries.

5.3 Elements topology checks for non reduced models

a. The warping of shell elements shall be checked to have limited deviation with respect to a flat layout, as specified in the guidelines (see clause 4.3).

b. The interior angle of shell and solid elements shall be checked to be within the limits specified in the guidelines (see clause 4.3).

c. The shell element positive normal side shall be checked for consistency.

d. Aspect ratio of the elements shall be within acceptance limits specified in the guidelines (see clause 4.3).

e. Convergence of the mesh refinement for stress analysis should be checked and documented.

5.4 Rigid body motion checks for reduced and non reduced models

5.4.1 Overview

The rigid body motions of FE model are defined by the matrix Φ_R, where the rotations are defined with respect to a selected reference point.

5.4.2 Rigid body motion mass matrix

a. The rigid body motion mass matrix M_R shall give the expected mass *m*, moments of inertia (I_{xx}, I_{xy}, I_{xz}, I_{yy}, I_{yz}, I_{zz}) and the expected values of the centre of gravity coordinates (x_{cog} y_{cog}, z_{cog}).

NOTE The test to be performed is to calculate M_R as defined below:

$$M_R = \Phi_R^T M \Phi_R$$

This matrix M_R provides the desired values:

$$M_R = \begin{bmatrix} m & 0 & 0 & 0 & -mz_{cog} & my_{cog} \\ 0 & m & 0 & mz_{cog} & 0 & -mx_{cog} \\ 0 & 0 & m & -my_{cog} & mx_{cog} & 0 \\ 0 & mz_{cog} & -my_{cog} & I_{xx} & I_{xy} & I_{xz} \\ -mz_{cog} & 0 & mx_{cog} & I_{yx} & I_{yy} & I_{yz} \\ my_{cog} & -mx_{cog} & 0 & I_{zx} & I_{zy} & I_{zz} \end{bmatrix}$$

b. Discrepancies between expected values and numerically computed terms of the rigid body motion matrix shall be justified.

5.4.3 Rigid body motion strain energy and residual forces check

a. Value of strain energy and residual forces due to rigid body motions shall be computed and reported for the following sets of DOFs:

1. for all the DOFs,
2. for all independent DOFs,
3. for all free DOFs.

NOTE This check is performed in order to ensure that nor strain energy neither nodal residual forces arise due to rigid body motions of the model (e.g. to identify hidden constraints).

b. For each set level of DOFs and for each of the six unit rigid body motions (three unit translations and three unit rotations) the rigid body motion strain energy E_R shall be computed by using the formula

$$E_R = \frac{1}{2}\Phi_R^T K \Phi_R$$

c. The maximum acceptable non-zero terms of the (6x6) matrix K_R shall be agreed.

NOTE 1 All the terms of E_R are theoretically equal to zero.

NOTE 2 For 1 meter or 1 radian rigid motion, typical acceptable values of E_R terms are not exceeding 1.E-03 joule.

d. For each set of DOFs, mentioned in 5.4.3.a, and for each of the six unit rigid body motions (three unit translations and three unit rotations) residual nodal forces F_R shall be computed by using the formula:

$$F_R = K\Phi_R$$

e. The maximum acceptable non-zero terms of the matrix F_R shall be agreed.

NOTE 1 All the terms of FR are theoretically equal to zero.

NOTE 2 For 1 meter or 1 radian rigid motion, typical acceptable values are:

- Residual force components not exceeding 0,1 newton
- Residual moment components not exceeding 1,5*newton*meter

5.5 Static analysis checks for reduced and non reduced models

a. Unit load check shall be performed as follows:

1. apply a static unit load (e.g. unit acceleration along X,Y,Z directions separately, unit force, unit pressure);
2. compare the external load resultant to the reaction force resultant at constrained nodes;
3. justify unexpected output.

b. When the model is constrained at all but one DOF of a given node and unit displacement (or rotation) is imposed to the unconstrained DOF, all the nodes shall have as output the unit imposed value.

c. Load resultant shall be verified to be equal to constraint load resultant.

d. DOFs with zero stiffness shall be listed and justified.

e. A test shall be performed to demonstrate that the model has no internal mechanisms, or mechanisms shall be justified.

f. Check of residual loads vector work shall be performed as follows:

1. Compute the residual force vector δF by subtracting the applied load vector F from the product of the stiffness matrix K times the computed displacement vector u: $\delta F = K\,u - F$
2. Compute the residual work δW: $\delta W = uT\,\delta F$
3. Compute the applied load work *W*: $W = \frac{1}{2}u^T F = \frac{1}{2}u^T K u$
4. Compute the ratio ε: $\varepsilon = \delta W/W$

g. The ratio ε shall be smaller than the maximum value agreed with the customer.

NOTE The ratio ε is theoretically equal to zero. A typical maximum acceptable value is 1.E-08.

5.6 Stress free thermo-elastic deformation check for non reduced models

a. A thermo-elastic deformation test shall be performed to demonstrate that, when the model is assumed build of homogenous and isotropic material and is submitted to an unconstrained isothermal expansion, the stresses and rotations do not exceed values agreed with the customer.

NOTE 1 This check verifies model adequacy to perform thermal stress analysis and can be used to find artificial stiffness introduced in the model (e.g. by rigid elements and bar offsets).

NOTE 2 Typically an isothermal expansion test is performed with statically determined boundary conditions. All the thermal coefficients of expansion as well as Young’s and Poisson’s moduli are changed to a single value of a dummy isotropic material (e.g. aluminium alloy). A uniform temperature increase (Δ T) is applied to the model. If the model is “clean”, there should be no rotations, reaction loads, element forces, or stresses.
The maximum acceptable values of isothermal stress and rotation are pre-defined (e.g. typical maximum Von Mises stress less than 0,01 MPa and maximum rotation less than 10^{-7} rad, for an aluminium alloy used as dummy material and a Δ T equal to 100 K).

5.7 Modal analysis checks

a. The modal analysis of the free model shall show the expected number of "rigid body" with frequencies equal or less than δ Hz, to be agreed with the customer.

NOTE 1 Six rigid body motions are expected for a three dimensional model without internal mechanisms.

NOTE 2 A typical value is δ Hz = 0,005 Hz.

b. The ratio between the highest computed frequency of the rigid body modes and the lowest elastic mode frequency shall be less that a value χ agreed with the customer.

NOTE Typical acceptance ratio is $\chi = 10^{-4}$.

5.8 Reduced model versus non reduced model consistency checks

a. The reduced model shall be compared to the non reduced model and the discrepancies justified.

NOTE These checks demonstrate the consistent behaviour of the reduced model with respect to non reduced model. They typically consist of comparing the output generated by the reduced model with the one generated by the non reduced model, under the same prescribed load and interface conditions. In practice the following parameters are compared: rigid body mass and inertia properties, modal properties (including effective modal masses), and structural response of selected parameters under static and dynamic loads. In this way evidence is provided that the structural matrices (mass, stiffness and damping) and the output transformation matrices are correct. Maximum discrepancy values should be pre-defined.

6
Test – Analysis correlation

6.1 Overview

The purpose of the test-analysis correlation is usually to substantiate the adequacy of the FE model to represent the structural behaviour measured during test on actual hardware.

6.2 Provisions

a. Test-analysis correlation criteria shall be defined.

> NOTE For modal survey assessments, the correlation criteria are generally in line with the ones suggested and reported in ECSS-E-ST-32-11"Space engineering - Modal survey assessment".

b. If the mathematical model predictions are outside the applicable correlation criteria, the mathematical model shall be modified and the analysis rerun until it meets the criteria.

> NOTE 1 This process is known as “model updating”.
>
> NOTE 2 The FE model is commonly said to be “valid” when it meets the correlation criteria.

c. Changes introduced in the FE model due to “model updating” process shall be documented and justified.

d. If the correlation criteria are not met, the consequences on the structural verification process shall be assessed.

Bibliography

ECSS-S-ST-00	ECSS system – Description, implementation and general requirements
ECSS-E-ST-32-11	Space engineering – Modal survey assessment