CAE Implementor Forum

STEP AP209 ed2
Linear Static Structural FEA Handbook

Volume 2: FEA Steps, Loads and Boundary Conditions for LOTAR EAS Pilot Study #2

LOTAR

LONG TERM ARCHIVING AND RETRIEVAL

Release 1.1
March 25, 2019

Contacts:

CAE-IF

Jochen Boy	Jean-Marc Crepel	Phil Rosché
PROSTEP AG	AFNeT	ACCR, LLC.
Dolivostraße 11	30, Rue de Miromesnil	125 King Charles Circle
64293 Darmstadt / Germany	75008 Paris / France	Summerville, SC 29485 USA
jochen.boy@prostep.com	jean-marc.crepel@afnet.fr	phil.rosche@accr-llc.com

LOTAR EAS

Chris Johnson	Joseph G. Draper	Albert Lévy
Technical	Co-leader	Co-leader
LOTAR EAS WG - Americas	LOTAR EAS WG – Americas	LOTAR EAS WG - Europe
Lockheed Martin	The Boeing Company	CIMPA on behalf of Airbus
john.c.johnson@lmco.com	joseph.g.draper@boeing.com	albert.levy.external@airbus.com

Table of Contents

List of Figures

Trademark Acknowledgments

NASTRAN is a registered trademark of NASA.

VERSION LOG

Version Description	By	Revision	Date
Original Draft	JCJ	0.0	3/12/2018
Updated Draft, added References and Links	JCJ	0.2	4/15/2018
Split Output request and Results into Volume3 (now only Sections 1-6 in Vol.2)	JCJ	0.3	7/16/2018
Incorporated edits recommended by AL	AL/JCJ	0.4	8/27/2018
Incorporated edits recommended by RD	RD/JCJ	0.5	9/24/2018
Remove markups and incorporate final comments per winter 2018 workshop	JCJ	1.0	10/20/2018
Updated source STEP files and text to conform to handbook identifier guidelines	JCJ	1.1	3/25/2019

JCJ - John C Johnson
AL - Albert Levy
RD - Rod Dreisbach

1 Introduction

This document is a second volume of the AP209 ed2 Linear Static Structural FEA Handbook documenting the finite element load cases and boundary conditions used as source data for the LOTAR International Engineering Analysis and Simulation (EAS) pilot study number two (pilot#2). This study focused on extending implementations of the International Standards Organization (ISO) 10303-209 ed2 (AP209 ed2) Standard, one Part of the 10303 family of Standards commonly known as STEP (Standard for The Exchange of Product data). The document requires at least a cursory understanding of the Finite Element Method, finite element models and analysis (FEM & FEA) and the information technologies involved in applying the AP209 ed2 application protocol. This document can also help the reader focus on those parts of STEP needed to encode FEA information and the documentation resources available to producers, consumers and implementers of this information. Familiarity with the details of Volume 1 of this handbook, covering model definition, is highly recommended; Volume 1 is publicly available at https://www.cax-if.org/documents_cae/HandbookVolume1_V2.2_CAE-IF.pdf. A condensed version of the introductory sections is repeated here with minor changes from Volume 1.

2 Pilot Study Overview

The pilot studies were created to encourage software providers to participate in initial efforts to develop commercial tools capable of converting traditional FEA information, expressed in solver ASCII format, to the AP209 ed2 format. A second goal of the pilot studies was to produce a reference set of AP209 ed2 STEP files that have been validated with the AP209 ed2 EXPRESS schema and have been checked for semantics with respect to the Recommended Practices for AP 209 ed2 10303-209:2014 and the document, Geometric Founding and Associativity in ISO 10303-209, Rev. B, 2/15/2001. A longer term goal is to enable FEA pre and post processors to both read and write AP209ed2 compliant data sets.

The pilot studies provide a small test suite of FEA models and solutions to be translated from a native solver format, in this case NASTRAN, to the STEP AP209 ed2 ASCII file representation (Part 21). These models are prismatic beam models with various linear element types, boundary conditions, load cases, and output requests. The overall geometry for each model is the same and is simple (see Figure 1). This simplicity was intentional to focus the effort on the interpretation of the FEM definitions, constructs and results, not the geometric abstractions related to meshing techniques.

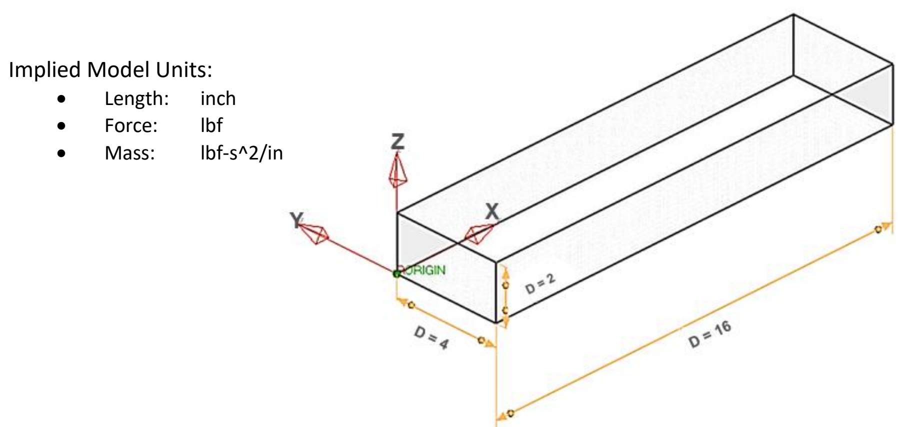


Figure 1 Pilot Model Geometry

Discretization of the geometry to the finite element model domain was accomplished through the abstractions and resulting finite element models shown in Figure 2. The finite element models were exported in NASTRAN bulk data format for use in this pilot study. These models were solved using MSC/NASTRAN V2013.1.0 to generate the requested results.

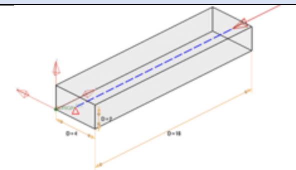
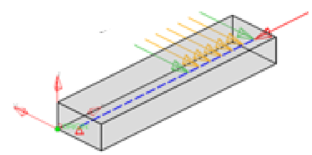
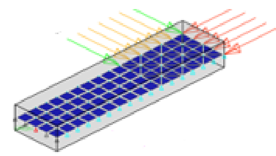
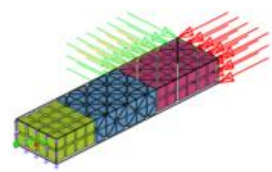
Abstraction - Geometry	NASTRAN Element Type	Pilot Model
1 Dimensional - Line	Linear CROD [Axial Stiffness – 1 DOF]	
1 Dimensional - Line	Linear CBAR [Bending/Axial/Shear – 5 DOF]	
2 Dimensional - Surface	Linear CQUAD4/CTRIA3 [Bending/Membrane/Shear – 5 DOF]	
3 Dimensional - Solid	Linear CHEXA/CPENTA/CTETRA [Bending/Membrane/Shear – 3 DOF]	

Figure 2 Pilot Model Abstractions

Volume 1 of this handbook discussed each pilot model in order and presented the same topics in each sub-section. Where topics were identical (such as using a common isotropic material for all models), a reference to the first occurrence of the topic was presented. This allowed the discussion to focus on the new information unique to each model.

Volume 2 of the handbook differs in how the material is presented to the reader. First, the overall structure of solution controls is discussed, followed by the details of the loads and boundary conditions. Examples from the pilot models are presented to illustrate how the concepts apply to the different model abstractions. Lastly, complete listings of the solver input, excerpts of the solver outputs, and the STEP output are included in the Appendices.

3 AP209 Overview

This section introduces several of the information technologies used in working with the STEP standard, and in particular those standards used via AP209 ed2. The reader can use this introduction to locate and explore in detail the topics highlighted herein. This information is a distillation of material found in similar sections of Volume 1 of this handbook. It is repeated here to ensure these topics are well understood.

AP209, formally known as ISO-10303-209 ed2, Application Protocol: Multidisciplinary Analysis and Design, provides the data structures for the exchange of part and configuration identification with configuration control data, with or without associated 3D part model information. AP209 was developed under the auspices of the International Organization for Standardization (ISO), Technical Committee 184, Sub-Committee 4, and is one of a series of parts comprising the full STandard for the Exchange of Product model data (STEP) standard known as ISO 10303.

3.1 STEP Module and Resource Library

Application Protocols such as AP209 ed2 are published in HTML format. All STEP Application Protocols are built from common modules in the SMRL (STEP Module and Resource Library) thus assuring integration and interoperability. The HTML format provides a convenient web browser format to locate definitions for all the entities, types and rules needed for these pilot studies, along with the associated EXPRESS schemas. These documents are copyrighted and published by ISO, so therefore the reader is referred to the ISO web site for access information.

The SMRL contains all the 10303 STEP standards other than the Application Protocols themselves, and consists of the following 10303 Parts:

- Integrated resources series of parts: ISO 10303 Parts 41 to 112;
- Application modules series of parts: ISO 10303 Parts 401 to 499 and 1001 to 1999;
- Application interpreted constructs series of parts: ISO 10303 Parts 501 to 599;
- Logical model of expressions: ISO 13584 Part 20;
- Business object models series of parts: ISO 10303 Parts 3001 to 3099.

Volume 1 of this handbook provides a more complete introduction to the SMRL and is not repeated here.

4 AP209 ed2 Data Model Organization

Due to the large scope of the Standard, the AP209 ed2 schema is large and complex. Many views of the data model are presented in the application protocol (AP209 ed2) and recommended practices (RP) documents. In addition to the figures in the RP, Figure 3 shown below illustrates refinements of the RP information to show how the data model can be considered as smaller conceptual topics and how those topics are related to the pilot models.

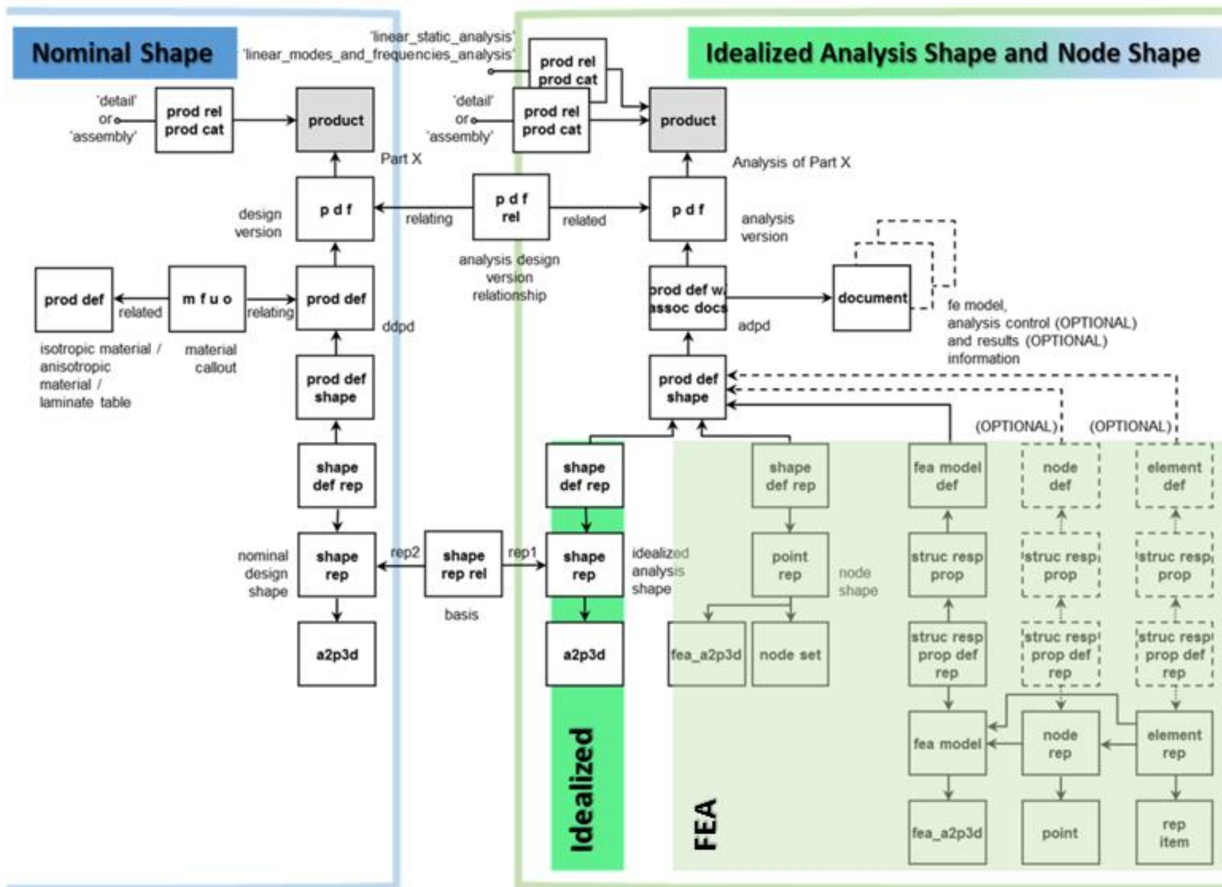


Figure 3 AP209 ed2 Relationship Between Design and Analysis

This view clearly illustrates how the design geometry (nominal shape) is related to the abstracted analysis geometry (idealized analysis shape), the finite element model (node shape) and analysis control and results (optional).

The pilot models in this Handbook use a native solver format (NASTRAN) as the FEM information source and therefore no nominal design or idealized analysis geometry is captured. However, the tools being developed under this pilot study will eventually be required to include the AP209 ed2 constructs that are used to capture the full FEA model definition and solution results. Full FEA model definition includes associativity to nominal design geometry or the idealized analysis geometry used for mesh generation and for mesh and geometry based loads and boundary condition specifications.

Traditionally, FEA solver models do not specify a system of units but are required to be internally consistent. Recent practices have begun to define explicitly a consistent set of units as part of the solver input for FEA model definition. The STEP standard can capture this information when constructing model contexts and associated unit entities. The pilot models do not explicitly specify a system of units, however, there is an implied use of the English inch-pound force-second system due to the existence of recognized material property values. While it may be possible to deduce a likely system of units for a given input file, it is recommended that direct user input define explicitly which system of units applies. How to specify this information for the conversion process is an active area of development and discussion.

4.1 Analysis Product Metadata

The right side of Figure 3 represents the AP209 ed2 analysis product. The figure hides many entities that deal with metadata about the product for the sake of clarity. Figure 4 includes more of these entities and categorizes the metadata of the analysis product; this figure was created from an early STEP file generated for the pilot study using the 1st pilot study model.

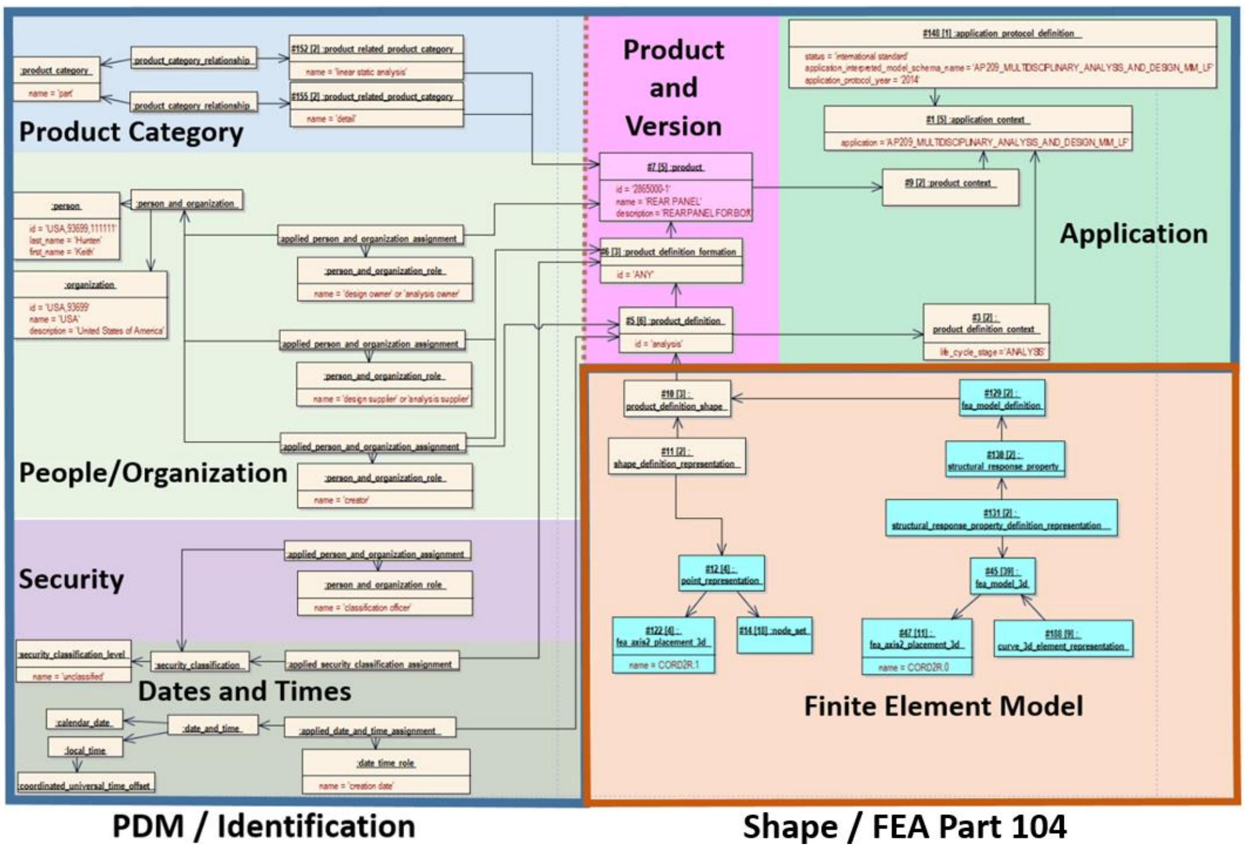


Figure 4 AP209 ed2 Analysis Product Categories

The details of the analysis product model metadata are discussed in Volume 1 of this handbook; the reader is encouraged to review those topics.

This document expands on the lower right corner of Figure 4; it captures the definitions of the finite element pilot models and the resultant control structures not shown in the figure. The contents of this part of the data model are documented in detail in the ISO 10303-104 Integrated application resource: Finite element analysis document (Part 104). Part 104, the associated schema definitions and the Recommended Practice for AP209 ed2 are the primary sources of information needed to map the native solver information (NASTRAN) found in the pilot project input and output files, to the AP209 ed2 data models and produce the familiar Part 21 STEP file representation.

5 Analysis Control Structures

The remaining sections in this document discuss the source of FEA results information and the mapping process to AP209 ed2 constructs. These topics are scoped to the following:

- NASTRAN Analysis Control Overview
- Analysis Control Structures – Structures used to describe the operations performed on the FEM
- Steps and States – Describe the specification or requesting of model variables for a single execution of the solution process

5.1 NASTRAN Analysis Control Input Overview

The ATS pilot models are simplistic but useful to demonstrate the processes involved in defining the solution controls and interpretation of results. A quick overview of the NASTRAN solution control input information is presented prior to delving into the AP209 ed2 data model mapping and implementation. A complete NASTRAN analysis file is divided into five main input data sections:

- NASTRAN (NASTRAN Command) – Allows specification of NASTRAN execution options
- FMS (File Management Section) – Controls attachment and initialization of database management sets and files
- EXEC (Executive Control Section) – Selects solution sequences, alters and diagnostics
- CASE (Case Control Section) – Specifies load cases, loads, boundary conditions and requests for output formats and output variables
- BULK (Bulk Data Section) – Defines the FEA model along with input data required for the selected solution sequence and subcases

The pilot models use the linear static analysis solution sequence (SOLUTION 101) specified in the Executive Control Section. No further details of the linear static solution sequence are presented in this document, but the details of the Case Control and related Bulk Data Sections and their mapping to AP209 ed2 are discussed. The reader can always explore more detailed explanations of the source information by reviewing the NASTRAN Quick Reference Guide (available online). The documentation is organized by the sections outlined above. The particular version used in this handbook is MSC/NASTRAN Version 2013.1 but any software provider that offers a version of the NASTRAN solver will have similar documentation available.

The pilot models used for this handbook are very similar to the original volume 1 models with the exception of addition output requests or output options specified in the NASTRAN Case Control Section subcases.

The Executive and Case Control template for the ATS1 pilot model is illustrated in Figure 5. The other models have additional subcases but each is structured as shown with similar output requests. Requests that are not supported for a particular element type are ignored. The target for each output request is the 'ALL' string which indicates a request to output the quantity for all applicable nodes or elements.

```
$ Linear Static Analysis
SOL 101
TIME 600
CEND
$
SEALL = ALL
SUPER = ALL
TITLE = Nastran job EAS test case ATS1m5
ECHO = NONE
MAXLINES = 999999999
GPFORCE(PRINT,PUNCH) = ALL
$
SUBCASE 1
   SUBTITLE=subcase1
   SPC = 100
   LOAD = 200
   DISPLACEMENT(PRINT,PUNCH,SORT1,REAL)=ALL
   SPCFORCES(PRINT,PUNCH,SORT1,REAL)=ALL
   STRESS(PRINT,PUNCH,SORT1,REAL,VONMISES,BILIN)=ALL
   STRAIN(PRINT,PUNCH)=ALL
   FORCE(PRINT,PUNCH)=ALL
$
<...Additional Subcases 2 through n...>
```

Figure 5 NASTRAN CASE Control

NASTRAN uses a hierarchical technique to interpret certain output request options. Output options specified for the first subcase STRESS output request are applied to subsequent subcases and to similar output quantities such as STRAIN. Also, output specified above the first subcase definition is applied to all subcases if not overridden. A brief discussion of each of the listed cards is shown in Table 1. Items in gray italics are solver specific control entries and are not currently processed or mapped to any STEP entity.

CARD	**Option or Value**	**Description**
SOL	101	Select the linear static solution sequence
TIME	*600*	*Set maximum CPU and I/O time*
CEND		*Indicates the end of the EXEC section*
SEALL	*ALL*	*Superelement ID used in executing the solution sequence*
SUPER	*ALL*	*Assigns subcases to superelement or sets of superelements*
TITLE		Text label for overall solution
ECHO	*NONE*	*No printout of the input bulk data is selected*
MAXLINES	*9999999999*	*Maximum number of output lines*
GPFORCE	PRINT,PUNCH	Generate printed and punch file output for grid point force balance data
SUBCASE	1	Identifies start of subcase definitions
SUBTITLE	Subcase1	Text label for this subcase
SPC	100	Selects the ID of a set or combination of single point constraint boundary conditions for this subcase

LOAD	200	Selects the ID of a set or combination of applied loads for this subcase
DISPLACEMENT	PRINT,PUNCH	Generate printed and punch file output for node displacements for this subcase
	SORT1, REAL	Organize node output as a deformed shape of the real component of displacement for this subcase
SPCFORCE	PRINT,PUNCH	Generate printed and punch file output for forces of single point constraint (reaction forces for equilibrium)
	SORT1, REAL	Real values sorted by subcase
STRESS	PRINT,PUNCH	Generate printed and punch file output for element stresses
	SORT1, REAL	Real values sorted by subcase
	VONMISES,BILIN	Compute Von Mises stresses at element center and bilinear interpolation to the element corners
STRAIN	PRINT,PUNCH	Generate printed and punch file output for element strains
FORCE	PRINT,PUNCH	Generate printed and punch file output for element forces

Table 1 NASTRAN Solution Control Card Data

The PRINT output option generates an ASCII output that is human readable and is formatted for printing on a line printer. The file extension for this file is .f06 and also contains model statistics, summaries and diagnostics information. PUNCH output is also ASCII but is a data-record formatted file that can easily be read by humans or computers. The 'Item Codes' tables located in the NASTRAN Quick Reference Guide define the data record formats for this file. Additional binary output files (.op2, .xdb or .h5) can be requested that contain NASTRAN data blocks used in the solution sequence. Reading a binary file is the preferred method to obtain result data for all but trivial sized FEA models. For the pilot studies, several formats are provided.

The sections that follow present how each quantity and option is implemented in the AP209 ed2 data model for the categories of elements (curve, surface or volume) used in the pilot studies.

5.2 AP209 ed2 Analysis Control Structures

The AP209 ed2 control structures represent the operations that are specified and performed on the **fea_model_3d** entity. Also, they relate the analysis results to the appropriate input controls. The basic control and result structure is presented in the AP209 ed2 Recommended Practices document and is repeated here as Figure 6.

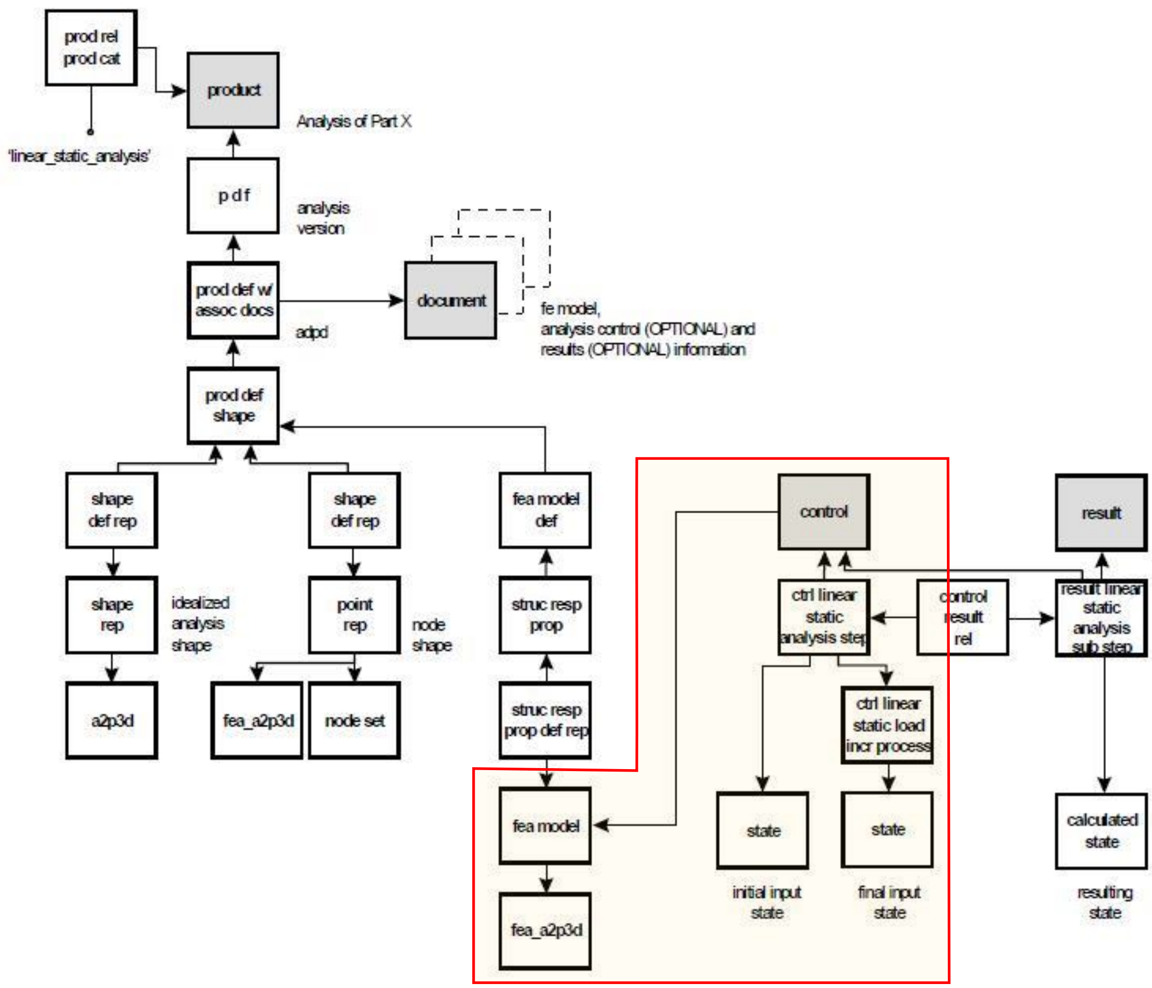


Figure 6 Linear Static Analysis - Control Structures

This document focuses on the shaded area which shows the top level relationship of the control to the **fea_model** (superclass of **fea_model_3d**). The **fea_model** is the top level entity for the definition of the FEA model mesh, physical properties and material properties while the control structures define load cases, boundary conditions, loads and links to results. Refer to Volume 1 for a discussion of the **fea_model** and also the entities outside the shaded area.

Below the control entities in Figure 6 are entities that are specializations of the EXPRESS **analysis_step** class. These subclasses represent the FEA load case or subcase concept. A new set of the **control_linear_static_analysis_step** entities will be instantiated for each subcase. If no results are being mapped to AP209 ed2, then only the **control_linear_static_analysis_step** and related entities will be present. If only the model definition (mesh) without loads and boundary conditions are being processed, then no control entity will be required.

Figure 7 is the class inheritance diagram for the **analysis_step** subclasses followed by the flattened EXPRESS schema definitions in Figure 8. Through the inheritance mechanism, it shows how the full set of attributes for each subclass are built up to support the control entity structure defined in Figure 6. Note that each subclass references 'to' the top level control which forms a 'many-to-one' relationship between the analysis steps and the top level control.

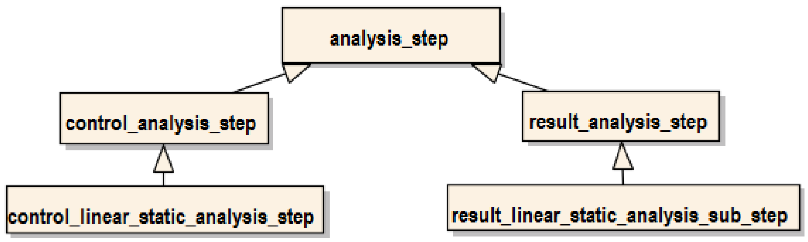


Figure 7 Analysis_step Class Inheritance Diagram

The **control_result_relationship** class definition is also included in Figure 8. Instances of this class allow results steps to be associated to the appropriate control steps. Note that this is a 'one-to-one' relationship necessitating a separate instance for each combination of **control_analysis_step** and **result_analysis_step**.

A basic understanding of the EXPRESS schema language for class and type definitions was discussed in Volume 1 of this handbook and is not repeated. Again, the reader is encouraged to review the AP209 ed2 standard and the Recommended Practices document which discusses these entities in detail. Red text are the formal names and the blue text highlights relevant attributes for review.

```
 ENTITY control_linear_static_analysis_step;
    ENTITY analysis_step;
        analysis_control                    : control;
    ENTITY control_analysis_step;
        step_id                             : IDENTIFIER;
        sequence                            : INTEGER;
        initial_state                       : state;
        description                         : TEXT;
    ENTITY control_linear_static_analysis_step;
        process                             : control_linear_static_load_increment_process;
END_ENTITY;

ENTITY control_linear_static_load_increment_process;
    ENTITY control_process;
        process_id                          : IDENTIFIER;
        description                         : TEXT;
    ENTITY control_linear_static_load_increment_process;
        final_input_state                   : state;
END_ENTITY;

ENTITY control_result_relationship;
        control                               : control_analysis_step;
        result                                : result_analysis_step;
END_ENTITY;

ENTITY specified_state;
    ENTITY state;
        state_id                              : IDENTIFIER;
        description                           : TEXT;
    ENTITY specified_state;
END_ENTITY;
```

Figure 8 EXPRESS Schema for Control Step and Load Increment Process

These schema definitions also contain attributes that refer to several other entity classes. The **control_step** references a **control_linear_static_load_increment_process**, which in turn, refers to a single **state** entity through the **final_input_state** attribute. These **state** entities function as top level collectors of all the information defining each subcase or step. A brief definition of the collector **state** entities used in Figure 6 is presented in Figure 9 along with an illustration of these states for a cantilevered beam.

Initial input state	The initial values of the solution variables and related field variables (can be values from a prior step)
Final input state	The boundary conditions and applied loads that are to be balanced by reaction forces and internal forces of the model to achieve static equilibrium
Output request state	Requests specific output quantities. A single template instance of each result state with unspecified values. Relates directly to an analysis step
Resulting state	The calculated values of the solution variables and related field variables after equilibrium has been achieved at the end of the solution process

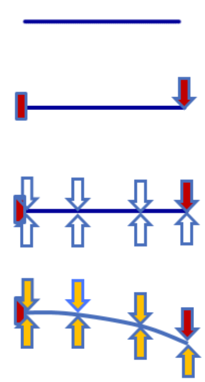


Figure 9 Interpretation of State Collectors for a Control_Step

These collector **state**(s) are referenced 'from' an analysis step or process entity through a simple entity reference; therefore, there can only be a single instance for each analysis step. In general, **state** entities and its subclasses can be related to each other through use of **state_relationship** entities that have attributes representing the **relating** and the **related** state entities. Through use of these entities, complex hierarchical data structures can be constructed to represent the collections of FEA information associated to a load step or subcase. The **relating** state is the parent or aggregator while the **related** state is the child or item being aggregated.

Figure 10 is taken from the Recommended Practice document for AP209 ed2 to illustrate use of the **state_relationships** in relating the top level collector **state** and the lower level **specified_states** in a simple tree structure under the process entities. **Specified_states** are a sub-class of the **state** class but have no additional attributes and can be referenced by the **state_relationships**. This type of sub-classing is used to distinguish instances of the specialized sub-class from other entity classes that also inherit from the **state** super-class. Instances of **specified_state** can be used for the top level aggregator.

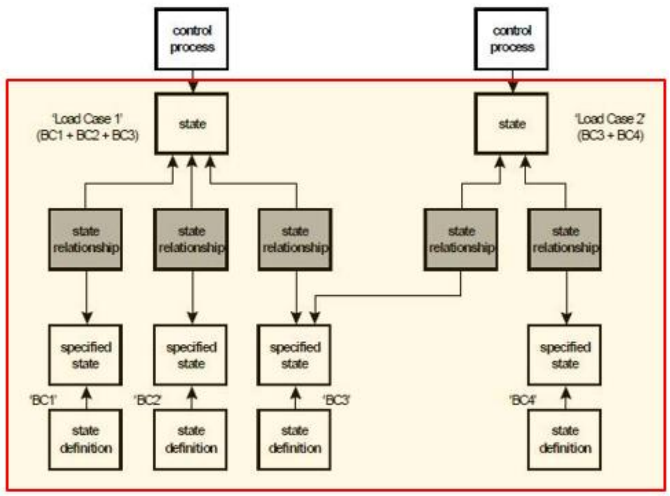


Figure 10 Simple Tree Structure of States

One concept that often causes confusion is the use of the terms 'initial' and 'final' in the context of the control inputs. Do not confuse 'initial' with the applied loads or specified boundary conditions. 'Initial' refers to initial values of solution variables known from a prior step while 'final' refers to the set of inputs that are the specified part of the final set of solution variables at equilibrium. Details of these control structures are presented in the next section.

5.3 NASTRAN Case Control Specified as Analysis Steps

The AP209 ed2 control structures are used to capture the information specified in the NASTRAN Case Control Section. Specifically, the subcase definitions in a NASTRAN solver deck are mapped directly to **control_linear_static_analysis_step** and the related process and state entities. These top level control, process and state entities together provide attributes to capture the semantics of the subcase information. Each of the diagrams presented in this handbook follows this aggregate view of the subcase (step+process+state).

There is limited guidance in the recommended practice on how to capture identifiers for this information; participants in the pilot study chose different mappings which led to problems interpreting each other's STEP output as well as problems identifying and visualizing the loads and boundary conditions for each subcase. Specifically, for each **control** entity, the

control_linear_static_analysis_step.step_id must be populated with a unique subcase identifier. In NASTRAN, this refers to the unique integer subcase id. Additionally, the optional NASTRAN title, subtitle, and label for each subcase should map to the description attributes for the step, process and top level state instance. Figure 11 illustrates guidance for identifying the subcase id and highlights the aggregate view of an FEA subcase. The sequence attribute provides an index for sorting the steps into the solver order and should be used for the **step_id** when no other value is provided. The sequence attribute also has a uniqueness requirement.

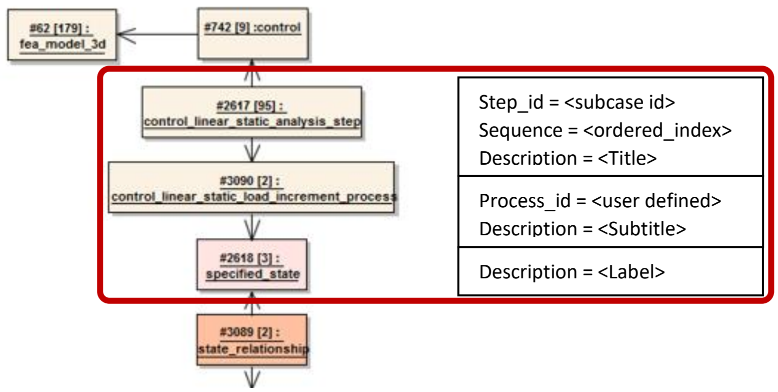


Figure 11 Aggregate View of an FEA Subcase

The pseudo listing shown in Figure 12 illustrates where these attributes might appear in a typical NASTRAN Case Control Section and notional values for each.

```
$ first subcase =>  <analysis_step.sequence>           1
SUBCASE <analysis_step.step_id>                        100
   TITLE= <analysis_step.description>                  'EAS Analysis 001 Model'
   SUBTITLE=<control_process.description>              'Subcase 100 -34T_Limit'
   LABEL=<specified_state.description>                 'Pull Up'

$ second subcase =>  <analysis_step.sequence>          2
SUBCASE <analysis_step.step_id>                        237
   TITLE= <analysis_step.description>                  'EAS Analysis 001 Model'
   SUBTITLE=<control_process.description>              'Subcase 237 +07R_Limit'
   LABEL=<specified_state.description>                 'Roll Left'

$ etc…
```

Figure 12 NASTRAN Source Data Mapping for STEP Analysis_Step

The **control_process.process_id** and the top level **specified_state.state_id** should be populated with user defined identifiers that can include the **analysis_step.step_id** for readability. These guidelines are reflected in the pilot study STEP files that were used for developing this handbook. No additional guidance is provided for the state relationship instances.

6 Pilot Model States

The concept of steps and states was introduced in Section 5. This section greatly expands on these concepts and give examples taken from the pilot study models.

The **control_linear_static_load_increment_process** and the single **state** entity that it refers to (**final_input_state**) collects all the information specified for boundary conditions and applied loads. The use of **state** entities, **state_definition**(s) and **state_relationship**(s) provides the flexibility needed to represent the boundary conditions, applied loads and combinations that are specified in the pilot study models. Using tree structures also enables reuse of lower level entities that are used in more than one load step. Even though the pilot study models are simplistic, the subcase, loads and boundary conditions specifications use typical constructs that can be found in a majority of linear static analysis models. Boundary conditions are discussed first followed by applied loads.

6.1 Specified States Related to Boundary Conditions

The ATS model boundary conditions are specified as fixed displacements at a node or nodes. These constrain the rigid body motion of the model that would normally result from application of external forces and moments if the model were in a free state. The specification of displacements is restated as specifying values for degrees of freedom (DOF) in the solution.

A full discussion of matrix algebra and partitioning as related to the Finite Element Method is beyond the scope of this handbook but a brief discussion of the foundation is presented to provide context to the discussion of displacement boundary conditions and constrained degrees of freedom. In the matrix form of the familiar Hook's Law equation {F} = -[K] * {X}, the X vector represents the displacements of the nodes of the finite element model, K represents the stiffness matrix, and F is the vector of applied forces. Static equilibrium is achieved when this equation is satisfied and all forces sum to zero at all points in all directions. A non-trivial unique solution requires a boundary condition that constrains the rigid body motion of the model. Typically, this is accomplished by specifying zero displacement at enough DOFs to prevent (at a minimum) the rigid body motion of the model and allow only elastic deformation (additional DOFs can be specified if desired). The resulting vector of displacements at the nodal DOFs are referred to as the deformed shape of the model for a particular subcase. The calculated forces at these constrained DOFs are referred to as reaction forces since they react/balance the applied loads. The number of free DOFs at each point can be reduced for other model types and solutions, but for the 3 dimensional models discussion here, assume all 6 degrees of freedom are present at each node.

6.1.1 NASTRAN Specification of Constraints

A boundary condition that enforces a value for one or more of these DOFs in NASTRAN is specified on the SPC, SPC1 or SPCD bulk data card entries. The base card name is an acronym for 'single point constraint' and the name has been retained in the AP209 ed2 schema class that represents this concept. The alternate NASTRAN forms, SPC1 and SPD, enable more efficient specification of sets of constraints at multiple nodes in the solver. The SPC1 form is used in the ATS pilot models and is represented using the same AP209 ed2 constructs as a basic SPC. There are several variations of the SPC1 card used in the ATS pilot models and the NASTRAN card image and examples are shown in Figure 13. Refer to the NASTRAN Quick Reference Guide for further details.

1	2	3	4	5	6	7	8	9	10
SPC1	SID	C	G1	G2	G3	G4	G5	G6	
	G7	G8	G9	-etc.-					

```
$ ATS2 - all degrees of freedom (dof=1-6) on node 1 are fixed, displacement = 0
SPC1     100      123456   1

$ ATS3 – the x translation (dof=1) is fixed for nodes 1,12,34 and 45
SPC1     101      1        1        12       34       45

$ ATS3 – the x and y rotations (dof=45) are fixed to ground for node ids in range 1 through 55
SPC1     110      45       1        THRU     55
```

Figure 13 Single Point Constraint Specification in NASTRAN

The SID field represents the set ID of the SPC1 card and is selected in the case control using an SPC=<set_id> entry. This set ID corresponds to the SPC Case Control Section record in Table 1 (not to be confused with the SPC Bulk Data card). Many SPC1 bulk data cards may be specified with the same or different SIDs. The 'C' field represents the degrees of freedom that are being constrained. NASTRAN input for this field is any unique combination of integers 1 through 6 with no embedded blanks or spaces representing each DOF to be constrained. There are special cases where this value can be blank or 0 but they do not apply to nodes used to define the model shape. The G(i) fields are node IDs where the DOFs specified are constrained. If non-zero enforced displacement boundary conditions were defined, an accompanying SPCD would be required to define the real value to be enforced. However, for simplicity, all the ATS pilot models use only SPC1 cards with no accompanying SPCD. This implies that specified DOFs are all constrained to zero displacement for each ATS pilot model.

Lastly, multiple sets can be added together to form a complete set of constraints referenced from the case control. Different subcases can reference individual SPC1 sets or the combined set defined on the SPCADD bulk data card. This card simply defines an additional set ID and a list of the individual set IDs to be combined.

The ATS3 pilot model, which is a shell element model, demonstrates this usage scenario by constraining the model on the end closest to the origin to prevent rigid body motion without over constraining the model. For the tension only subcase, Poisson's effect will cause a displacement in the Y-axis due to a force applied in the X-axis and therefore, the Y-axis translation should only be constrained at a single node at the fixed end while the displacement of the remaining nodes on the end are only constrained in the X-axis. The intent of how constraints are specified should be captured to the greatest extent possible.

Figure 14 shows the case control and combined SPC1 and SPCADD used for ATS3 subcase 1.

```
$ ATS3 Case control fragment for subcase 1
SUBCASE 1
   SUBTITLE=subcase1
   SPC = 11

…

$ ATS3 Corresponding bulk data entries referenced by SPC=11
SPCADD   11       100      101      110

SPC1     100      123      23
SPC1     101      1        1        12       34       45
SPC1     110      45       1        THRU     55
SPC1     110      45       57       58       59       60       61       62
         64       65       66       67       68       69       71       72
         73       74       75       76       78       79       80       81
         82       83       85       86       87       88       89       90
```

Figure 14 Boundary Conditions for ATS3 Subcase 1

A brief explanation of each entry follows. The set ID 100 specifies that node 23 is constrained in the xyz translational directions. Set ID 101 constraints the x translation for nodes 1, 12, 34 and 45. All these nodes are on the fixed edge of the shell model nearest the origin. The set ID 110 entries constrain the x and y rotational degrees of freedom at all the nodes specified. Finally, SPCADD 11 combines all of these constraints into one set that is referenced on the case control entry. Note that the z rotational DOF is not constrained anywhere. This was intentional because the NASTRAN shell element does not normally have any stiffness in rotational DOF about the element normal axis. These additional degrees of freedom are constrained by other mechanisms during the solution process and are currently not included in the STEP representation.

The boundary conditions for the other ATS models and subcases follow similar concepts but are tailored to the element types and applied loads. Lastly, each constrained DOF in a model will have a reaction force associated with the constrained DOF at the end of the solution process.

6.1.2 AP209 ed2 Specification of Constraints

The STEP equivalent of the NASTRAN single point constraint is the **single_point_constraint_element**. This entity is a sub-class of the general **constrain_element** class. The **single_point_constraint_element** is defined as a constraint on a node, group of nodes or a geometry element. The constraint element definitions are taken from the AP209 ed2 Recommended Practices document shown in Figure 15. The highlighted case represents a **single_point_constraint_element** applied to a node as is used in the ATS pilot models.

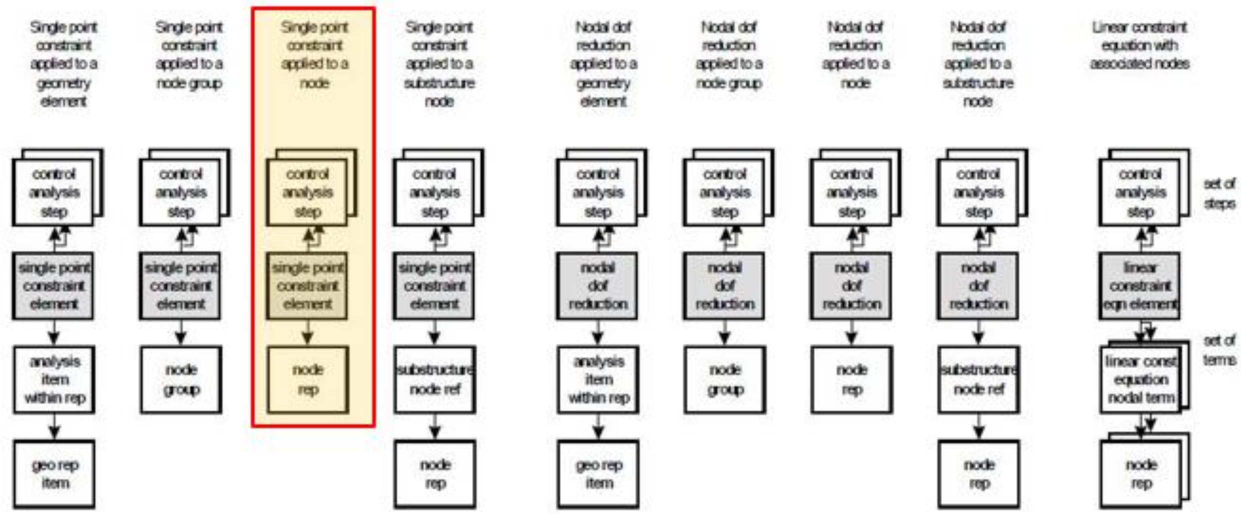


Figure 15 Constraint Definition Reference

A common question arises concerning why the node constraints in NASTRAN are mapped to a **constraint_element** class subtype in STEP? The reason is that the treatment of constraints in STEP has been split into two separate concepts that are consistent with how these constraints are cast in the finite element solution. A constraint equation is applied to a degree of freedom and is generally expressed as A(i) x DOF(i) = B(i), where 'A' is a coefficient and 'DOF' is the specified degree of freedom at a node and 'B' is the specified value for every instance 'i'. The left side of this equation is captured by the **freedoms_and_values** attribute (a set of **freedom_and_coefficient**(s)) and a **required_node** attribute (node_output_reference type) for each **single_point_constraint_element** entity. The **single_point_constraint_element** also contains a set of **control_analysis_steps** references to indicate which subcases this constraint element applies to. The right side of the equation is captured by the **single_point_constraint_element_values** entity that references the **single_point_constraint_element**. This entity contains a **degrees_of_freedom** attribute and an attribute '**b**' which is a list of values corresponding to B(i). Part 104, Section 6.4.11 presents similar information.

The key takeaway from this discussion is that the **single_point_constraint_element** is related directly to the **control_linear_static_analysis_step**(s) while the **single_point_constraint_element_values** are part of the final input state definition. This allows the same constraint element to be specified once, but have enforced constraint values that are different for each subcase. While this capability is not exercised directly in the pilot study models (all constraints are zero valued), this scenario is supported in many commercial FEA solvers and the AP209 ed2 data model supports it.

The EXPRESS schema for these entities is shown in Figure 16.

```
ENTITY single_point_constraint_element;
    ENTITY constraint_element;
        element_id                              : IDENTIFIER;
        steps                                   : SET [1:?] OF control_analysis_step;
    ENTITY single_point_constraint_element;
        required_node                           : NODE_OUTPUT_REFERENCE;
        coordinate_system                       : fea_axis2_placement_3d;
        freedoms_and_values                     : SET [1:?] OF freedom_and_coefficient;
        description                             : TEXT;
END_ENTITY;

ENTITY freedom_and_coefficient;
        freedom                                 : DEGREE_OF_FREEDOM;
        a                                       : MEASURE_OR_UNSPECIFIED_VALUE;
END_ENTITY;

ENTITY single_point_constraint_element_values;
    ENTITY state_definition;
        defined_state                      : state;
    ENTITY single_point_constraint_element_values;
        element                            : single_point_constraint_element;
        degrees_of_freedom                 : freedoms_list;
        b                                  : LIST [1:?] OF MEASURE_OR_UNSPECIFIED_VALUE;
END_ENTITY;

TYPE DEGREE_OF_FREEDOM = SELECT
   (ENUMERATED_DEGREE_OF_FREEDOM,
    APPLICATION_DEFINED_DEGREE_OF_FREEDOM);
END_TYPE;

TYPE MEASURE_OR_UNSPECIFIED_VALUE = SELECT
   (CONTEXT_DEPENDENT_MEASURE,
    UNSPECIFIED_VALUE);
END_TYPE;

TYPE NODE_OUTPUT_REFERENCE = SELECT
   (node_representation,
    node_group,
    substructure_node_reference,
    analysis_item_within_representation);
END_TYPE;
```

Figure 16 EXPRESS Schema Related to Single_Point_Constraint_Element

6.1.3 AP209 ed2 Instantiation of Constraints

The preceding discussion focused on the EXPRESS classes and relationships that are used to specify the AP209 ed2 data model for analysis controls, and for boundary conditions in particular. No direction is explicitly given on how to structure the state definitions to represent common usage patterns provided by FEA solvers such as NASTRAN. This section discusses one such mapping but is not necessarily the only possible mapping. Other solvers may require different mapping.

All the boundary condition constructs specified in the ATS pilot models can be built using a 3 layered state definition hierarchy. Figure 17 shows an example diagram of this 3 layer organization. The red text labels indicate the NASTRAN card concept that the **specified_state** instance on each layer represents. State relationships are indicated as ovals with the letter 'R'. This diagram illustrates two subcases (step ID 1 and 2) that reference two unique constraint set IDs (3 and 4) that have unique enforced values for a single constraint element, at a single node, used in both subcases.

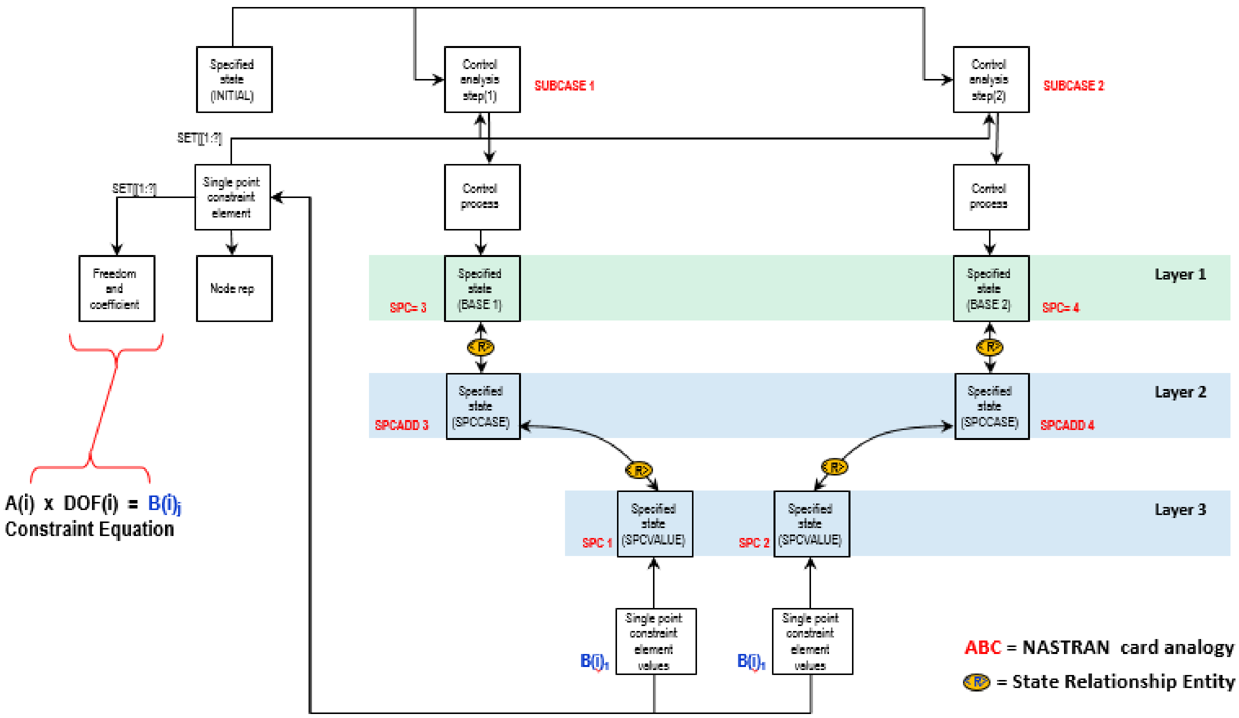


Figure 17 Example of 3 Layer Organization for Constraint Boundary Conditions

Layer 1 maps to the constraint set selected in the case control. The Layer 2 maps to the constraint combinations specified on 2 different SPCADD cards. These specified states are considered to be 'aggregation' states. In cases where there are no multiple constraints being aggregated (as shown), the layer 2 **specified_state** is optional. However, even in the absence of the SPCADD card, a layer 2 **specified_state** can be instantiated as a pass-thru entity for consistency. Lastly, layer 3 maps to the actual constraint set bulk data cards. These are considered to be 'value' states that are referenced from the **single_point_constraint_element_values** instances that specify the enforced value for this subcase and for the specified degrees of freedom. The 'value' **specified_state** of these **state_definition**(s) should match the constraint set identifier used in the bulk data.

In all cases, the selected constraint set ID must match the ID of the first constraint **specified_state** in layer 2 or layer 3.

Figure 18 is a variation of Figure 17 where two constraint elements at two nodes are related to both subcases. The case control for each subcase selects the same constraint set, which is an SPCADD card combining the same two constraint sets on layer 3. The **single_point_constraint_element_values** instances specify a value for each constraint equation at each node. Note that the layer 2 **specified_state** instances could be collapsed into a single instance and two of the relationship instances eliminated. While optimization and minimization of entities is a goal, there can be valid reasons not tied to the standard to use explicit instances where one would suffice. One such reason could be situations where a unique attribute value is set based on the usage by a higher level entity. For example, each layer 2 **specified_state** could contain the subcase ID as a part of its description attribute from the referencing **analysis_step**. This can aid readability of the STEP file but is not to be relied on by any pre or post processor.

This organization provides great flexibility but also puts more requirements on the recommended practices documentation to ensure interoperability of the resulting data models.

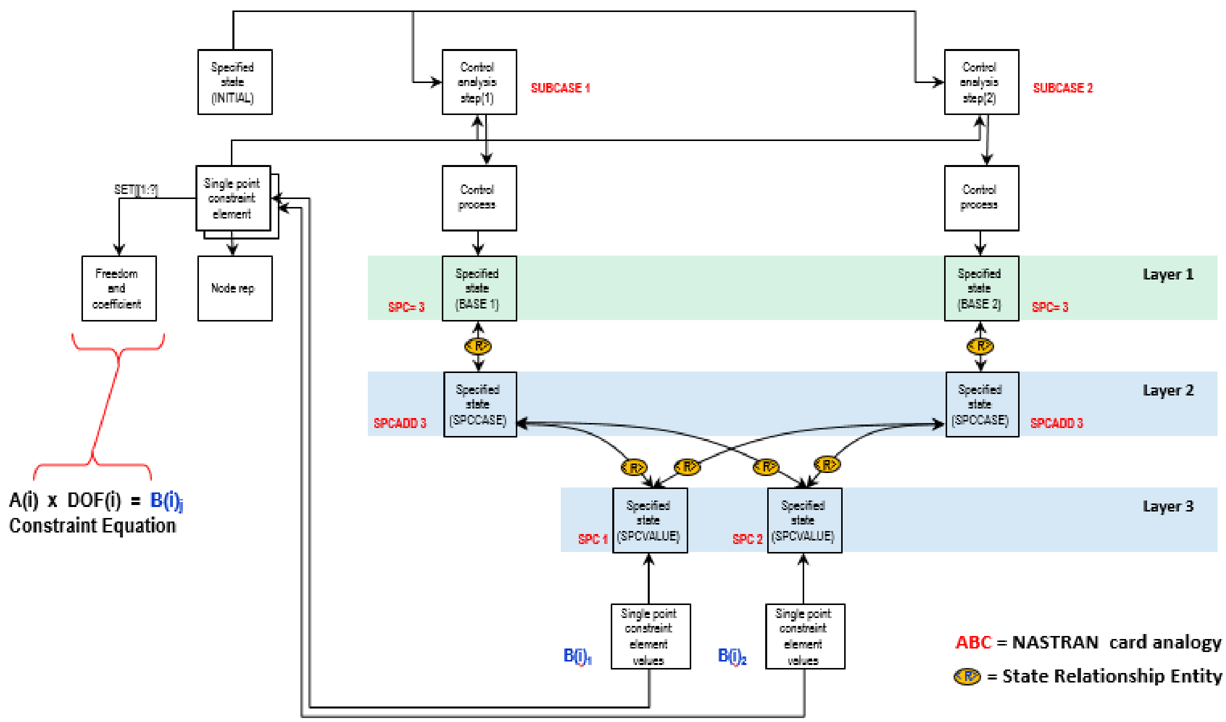


Figure 18 Variation of 3 Layer Organization of Constraint Boundary Conditions

A fragment of the ATS1 pilot study model input is shown in Figure 19. This corresponds to one load case with one **single_point_constraint_element** and one **single_point_constraint_element_values** entities. This matches a single column of the diagram in Figure 16. Only the translational degrees of freedom are constrained at node 1 in this case.

```
$ ATS1 Case control fragment for subcase 1
SUBCASE 1
   SUBTITLE=subcase1
   SPC = 100
…

$ ATS1 Corresponding bulk data entries referenced by SPC=100
SPC1     100     123     1
```

Figure 19 NASTRAN ATS1 Boundary Conditions

Figure 20 is the ATS1 pilot study model diagram for instantiation of these boundary conditions. This diagram uses the same notation as Volume 1 of this handbook. Not all related instances are shown.

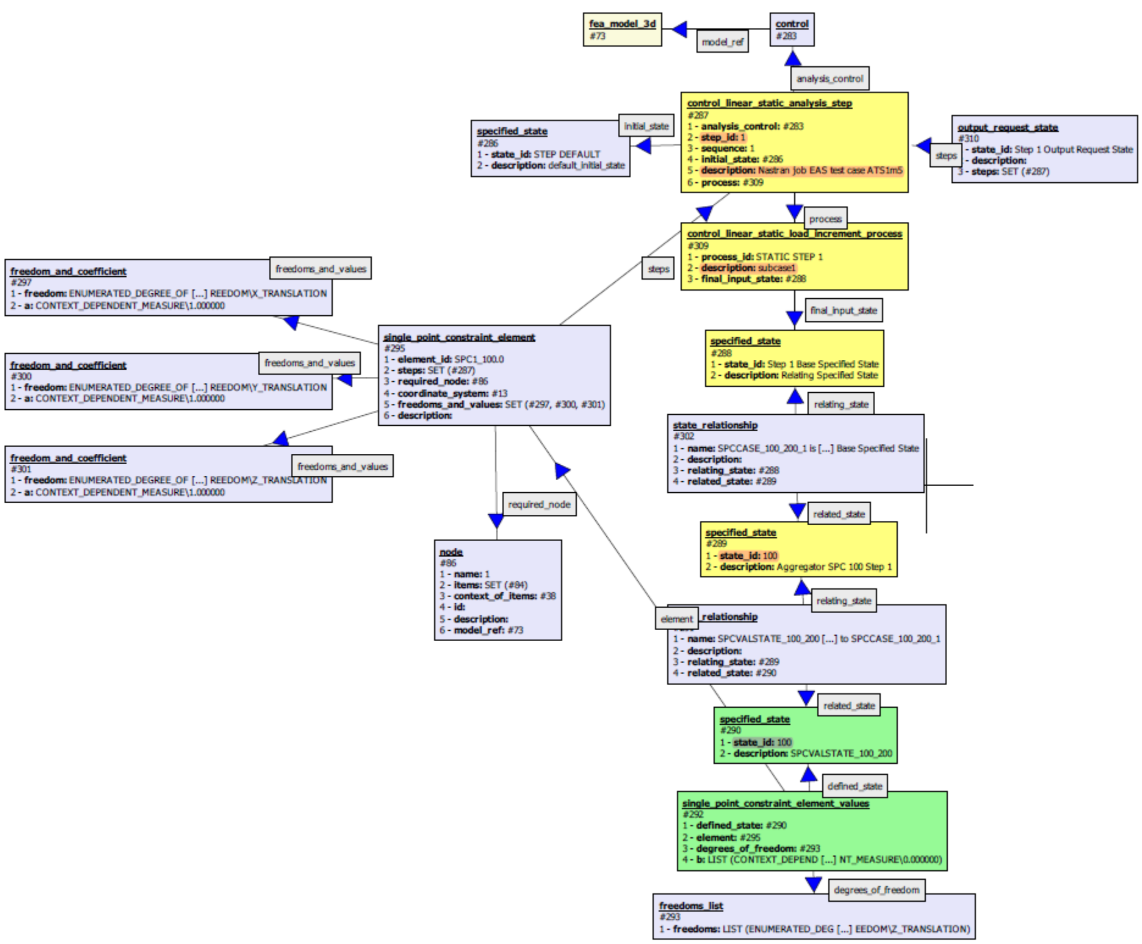


Figure 20 ATS1 Boundary Condition Instance Diagram

The corresponding STEP file fragment for these entities is shown in Figure 21. The order of the entities follows the diagram from top to bottom and some reformatting has been done for readability. Note the **context_dependent_measure** values equal to 0 and the coefficients for the DOFs equal to 1.

```
#73= FEA_MODEL_3D('Identification',(#13),#28,
      'NASTRAN BDF Converter v0.0.0',('NASTRAN'),'AnalysisModelType');

#283= CONTROL(#73,'Control.0','FemConvert','Nastran job EAS test case ATS1m5',
      ('101','TIME 600','CEND','0','1','ENDDATA'),('NASTRAN'));

#287= CONTROL_LINEAR_STATIC_ANALYSIS_STEP(#283,'1',1,#286,
      'Nastran job EAS test case ATS1m5',#309);
#286= SPECIFIED_STATE('STEP DEFAULT','default_initial_state');
#309= CONTROL_LINEAR_STATIC_LOAD_INCREMENT_PROCESS('STATIC STEP 1','subcase1',#288);

#288= SPECIFIED_STATE('Step 1 Base Specified State','');
#302= STATE_RELATIONSHIP(
      'SPCCASE_100_200_1 is related to Step 1 Base Specified State','',#288,#289);

#289= SPECIFIED_STATE('100','Aggregator SPC 100 Step 1');
#291= STATE_RELATIONSHIP(
      'SPCVALSTATE_100_200 is related to SPCCASE_100_200_1','',#289,#290);

#290= SPECIFIED_STATE('100','SPCVALSTATE_100_200');
#292= SINGLE_POINT_CONSTRAINT_ELEMENT_VALUES(#290,#295,#293,(
      CONTEXT_DEPENDENT_MEASURE(0.),
      CONTEXT_DEPENDENT_MEASURE(0.),
      CONTEXT_DEPENDENT_MEASURE(0.)));
#293= FREEDOMS_LIST((
      ENUMERATED_DEGREE_OF_FREEDOM(.X_TRANSLATION.),
      ENUMERATED_DEGREE_OF_FREEDOM(.Y_TRANSLATION.),
      ENUMERATED_DEGREE_OF_FREEDOM(.Z_TRANSLATION.)));

#295= SINGLE_POINT_CONSTRAINT_ELEMENT('SPC1_100.0',(#287),#86,#13,(#297,#300,#301),'');
#297= FREEDOM_AND_COEFFICIENT(
      ENUMERATED_DEGREE_OF_FREEDOM(.X_TRANSLATION.),CONTEXT_DEPENDENT_MEASURE(1.));
#300= FREEDOM_AND_COEFFICIENT(
      ENUMERATED_DEGREE_OF_FREEDOM(.Y_TRANSLATION.),CONTEXT_DEPENDENT_MEASURE(1.));
#301= FREEDOM_AND_COEFFICIENT(
      ENUMERATED_DEGREE_OF_FREEDOM(.Z_TRANSLATION.),CONTEXT_DEPENDENT_MEASURE(1.));

#86= NODE('1',(#84),#38,#73);
```

Figure 21 STEP Part 21 File Fragment of ATS1 Boundary Conditions

Similar figures can be constructed for all the ATS pilot study models. However, for surface and volume element models with several load cases and combinations of boundary conditions, these diagrams become very large and complex and are not included here.

6.2 Specified States Related to Applied Loads

The applied loads are treated in a similar manner to constraints with the exception that the associated **state_definition**(s) reference existing model entities such as nodes or element aspects (face, edge, corner, etc..). The tree structure of **states**, **state_relationship**(s) and **state_definition**(s) is defined to capture the specification of loads for each subcase.

6.2.1 NASTRAN Specification of Applied Loads

The loads used in the pilot study model are NASTRAN nodal forces, moments, and pressures. There are many other loading types in NASTRAN but the loads used in the pilot study are typical and demonstrate how these entities are mapped to AP209 ed2 entities. The FORCE and PLOAD2 cards are used for application of point loads on nodes and pressure loads on the faces of surface elements. Figure 22 shows the card format used for these two bulk data entries and several examples for the ATS pilot models.

1	2	3	4	5	6	7	8	9	10
FORCE	SID	G	CID	F	N1	N2	N3		

1	2	3	4	5	6	7	8	9	10
PLOAD2	SID	P	EID1	EID2	EID3	EID4	EID5	EID6	

```
$ ATS1 – 1000 lb force applied to node 17 in –X direction of the basic coordinate system
FORCE    200     17      0       1000.   -1.      0.      0.

$ ATS3 – pressure lb/sq inch applied to the face of elements 8 and 9 normal to the element
PLOAD2   500    -125.0          8
PLOAD2   500    -125.0          9
```

Figure 22 Applied Loads Specification in NASTRAN

Both inputs have a SID field that represents the applied load set ID. This set ID corresponds to the LOAD <u>Case Control Section</u> record in Table 1 (not to be confused with the LOAD Bulk Data card). Many load cards can be specified that share the same SID or specified with independent SID(s). The FORCE card field 'G' defines the node ID that the force is applied. The 'CID' is the ID of the coordinate system that the direction vector information ('N1', 'N2', and 'N3') should be interpreted in. Lastly, the field 'F' defines the magnitude of the total force applied at the node in the vector direction specified. The pure vector definition of the applied force is simply F*N1, F*N2, F*N3 in coordinate system 'CID'. The example listed above is an applied force of 1000.0 lb in the –X direction of the basic coordinate system (CID=0 or blank).

The PLOAD2 card defines a pressure applied normal to the plane of the element. A positive value of 'P' results in a net force that acts in the same direction as the positive normal to the element plane, in other words, the +Z axis of the local element coordinate system. This pressure is multiplied by the area of the element to compute the total load applied to the element. Multiple element ID(s) can be specified on each card to apply the pressure to larger regions of the model or multiple PLOAD2 cards with the same SID can be specified.

Load specifications can be combined into a single composite set ID that is referenced by the case control LOAD=SID entry. This is accomplished using the LOAD Bulk Data card and is illustrated in Figure 23.

1	2	3	4	5	6	7	8	9	10
LOAD	SID	S	S1	L1	S2	L2	S3	L3	
	S4	L4	-etc.-						

```
$ ATS3 – combination of load sets 200, 300 and 400 with unit scale factors
LOAD     23       1.       1.       200      1.       300      1.       400

$ ATS3 – all core load definitions for axial and lateral load combination
FORCE    200      62       0        125.     -1.      0.       0.
FORCE    200      69       0        250.     -1.      0.       0.
FORCE    200      76       0        250.     -1.      0.       0.
FORCE    200      83       0        250.     -1.      0.       0.
FORCE    200      90       0        125.     -1.      0.       0.
FORCE    300      55       0        10.      0.      -1.       0.
FORCE    300      90       0        10.      0.      -1.       0.
FORCE    400      85       0        20.      0.      -1.       0.
FORCE    400      86       0        20.      0.      -1.       0.
FORCE    400      87       0        20.      0.      -1.       0.
FORCE    400      88       0        20.      0.      -1.       0.
FORCE    400      89       0        20.      0.      -1.       0.
```

Figure 23 Linear Load Combination Used in Subcase 3 of ATS3

In addition to combining loads, this card provides scale factors for each individual load set and an overall scale factor for the linearly superimposed load sets. The field ‘S(i)’ is the individual scale factors applied to the individual ‘L(i)’ sets being linearly superimposed. The field ‘S’ is the overall scale factor. Older versions of MSC/NASTRAN did not allow combined LOAD cards to reference other combined LOAD cards; however, this restriction was removed in later releases. Therefore, a LOAD card can now form a deep nested structure. The pilot study models do not use any deep nested load combinations; however, the 3 layer organization is still valid as the second layer would handle all combinations of loads.

There are many other load specification cards defined for the various versions of NASTRAN. The loads discussed herein cover the pilot study models used for development of this handbook. As such, implementations should clearly state which cards and which options are supported.

6.2.2 AP209 ed2 Specification of Applied Loads

The AP209 ed2 standard defines specialized entities to represent the many different ways that loads can be applied to an FE model. The recommended practices document summarized these in Section 2.11.3.3.3 States and State Definitions. The figures from the recommended practices document are repeated here in Figure 24 and Figure 27, with highlights indicating the **state_definition**(s) used in the pilot study models. The details of each of these specialized **state_definition**(s) can be investigated in the Part 104 document or by reviewing the EXPRESS schema.

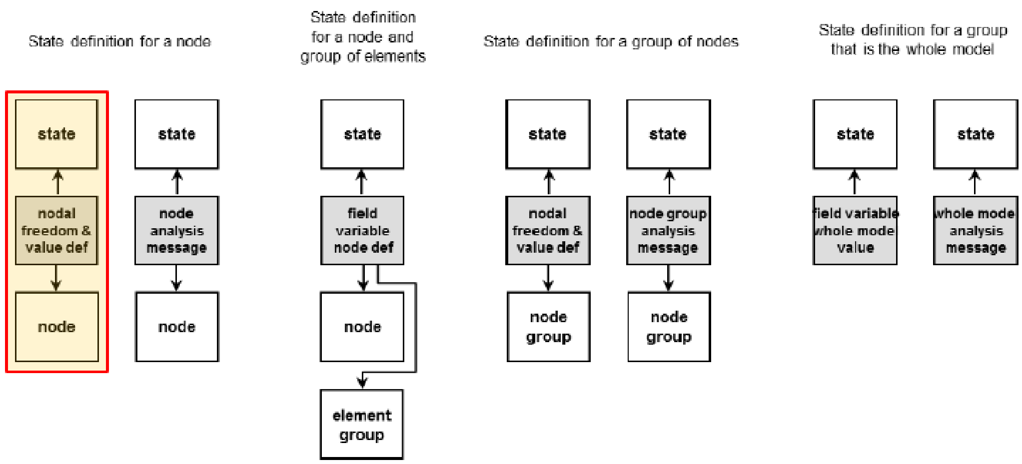


Figure 24 Recommended Practices Figure for State_Definitions Related to Nodes (Nodal Force)

The **nodal_freedom_and_value_definition** shown in Figure 24 is further specialized to **nodal_freedom_action_definition**. The inheritance diagram is shown in Figure 25 and the flattened EXPRESS listing is shown in Figure 26. Following the inheritance is straight forward as the base class provides the link to the state entity, the **nodal_freedom_and_value_definition** adds the attributes for node references, coordinate systems, degrees of freedom and the list of values. Lastly, the **nodal_freedom_action_definition** adds the action attribute which is an enumerated list defining how to interpret these data values.

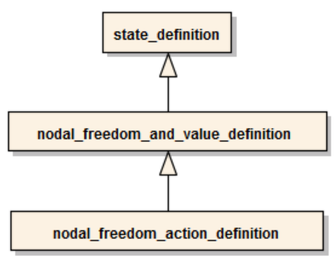


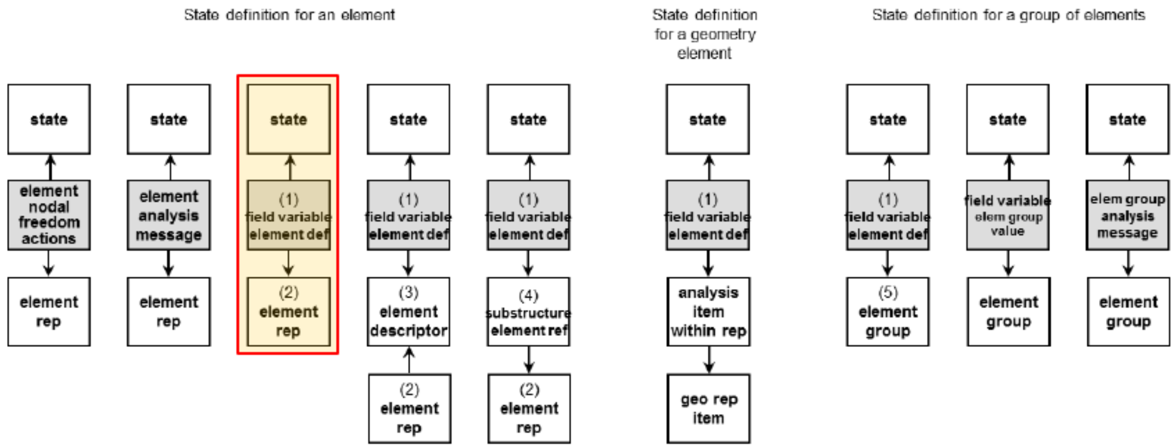
Figure 25 Inheritance Diagram for Applied Loads at Nodes Mapped from NASTRAN FORCE Card

```
ENTITY nodal_freedom_action_definition;
    ENTITY state_definition;
        defined_state                    : state;
    ENTITY nodal_freedom_and_value_definition;
        node                             : NODE_OUTPUT_REFERENCE;
        coordinate_system                : fea_axis2_placement_3d;
        degrees_of_freedom               : freedoms_list;
        values                           : LIST [1:?] OF MEASURE_OR_UNSPECIFIED_VALUE;
    ENTITY nodal_freedom_action_definition;
        action                           : ACTION_TYPE;
END_ENTITY;

TYPE ACTION_TYPE = ENUMERATION OF
   (APPLIED_LOADS,
    RESIDUAL_LOADS);
END_TYPE;
```

Figure 26 Flattened EXPRESS Schema for Nodal Loads

The state definitions for an element shown in Figure 27 should be interpreted as defined by the integer tags enclosed in parentheses. The highlighted state definition has a (1) tag on the **field_variable_element_definition** and a (2) tag on the **element_representation**. Using the table below the figure completes the proper state definition. Therefore, an element pressure load is represented as a **surface_3d_element_field_value_definition** and references a **surface_3d_element_representation**. This is consistent with the ATS3 pilot study model pressure loads. However, this is still not the final class instantiated.



(1)	(2)	(3)	(4)	(5)
volume_3d_element_field_value_defn	volume_3d_element_rep	volume_3d_element_descriptor	volume_3d_substructure_element_ref	volume_3d_element_grp
volume_2d_element_field_value_defn	planar_volume_2d_element_rep	planar_volume_2d_element_descriptor	volume_2d_substructure_element_ref	volume_2d_element_grp
volume_2d_element_field_value_defn	axisymmetric_volume_2d_element_rep	volume_2d_element_descriptor	volume_2d_substructure_element_ref	volume_2d_element_grp
surface_3d_element_field_value_defn	surface_3d_element_rep	surface_3d_element_descriptor	surface_3d_substructure_element_ref	surface_3d_element_grp
surface_2d_element_field_value_defn	planar_surface_2d_element_rep	planar_surface_2d_element_descriptor	surface_2d_substructure_element_ref	surface_2d_element_grp
surface_2d_element_field_value_defn	axisymmetric_surface_2d_element_rep	axisymmetric_surface_2d_element_descr	surface_2d_substructure_element_ref	surface_2d_element_grp
curve_3d_element_field_value_defn	curve_3d_element_rep	curve_3d_element_descriptor	curve_3d_substructure_element_ref	curve_3d_element_grp
curve_2d_element_field_value_defn	planar_curve_2d_element_rep	planar_curve_2d_element_descriptor	curve_2d_substructure_element_ref	curve_2d_element_grp
curve_2d_element_field_value_defn	axisymmetric_curve_2d_element_rep	axisymmetric_curve_2d_element_descr	curve_2d_substructure_element_ref	curve_2d_element_grp

Figure 27 Recommended Practices Figure for State_Definitions Related to Elements (Face Pressure)

The **field_variable_element_definition** shown in Figure 27 is further specialized to represent a constant applied pressure on a face of a 3d element. The instantiated class is a **surface_3d_element_boundary_constant_specified_surface_variable_value**.

The inheritance diagram is shown in Figure 28. This hiearchy diagram shows only the construction of the final class instantiated. The full class hiearchy below the **field_variable_definition** is quite large and complex as it also includes all the result classes. The Recommended Practices document does not provide guidance other than the figures already discussed. The Part 104 document should be used to explore what all the various classes are intended to represent. The **surface_3d_element_boundary_constant_specified_surface_variable_value** class is documented in Part 104, Section 6.7.43.

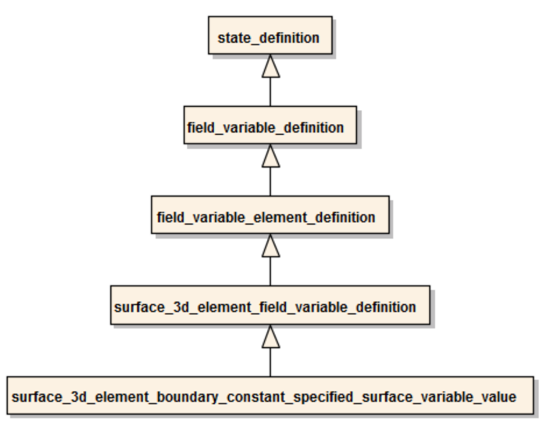


Figure 28 Inheritance Diagram for Applied Loads at Elements Mapped from NASTRAN PLOAD2 Card

The flattened EXPRESS listing is shown in Figure 29. This shows what each inheritance level adds to the final class definition. Using the flattened listing simplifies the presentation of a final class definition and is easier to understand. Determining which final class is appropriate for a NASTRAN entity is a difficult task when implementing a NASTRAN to AP209 ed2 converter. The LOTAR Engineering Analysis Work Group (EAS WG) can assist with these tasks (see References and Links for contact information).

```
ENTITY surface_3d_element_boundary_constant_specified_surface_variable_value;
    ENTITY state_definition;
        defined_state                        : state;
    ENTITY field_variable_definition;
    ENTITY field_variable_element_definition;
    ENTITY surface_3d_element_field_variable_definition;
        element                              : SURFACE_3D_ELEMENT_OUTPUT_REFERENCE;
    ENTITY surface_3d_element_boundary_constant_specified_surface_variable_value;
        simple_value                         : FIELD_VALUE;
        variable                             : BOUNDARY_VARIABLE;
        element_face                         : SURFACE_3D_FACE;
        coordinate_system                    : OPTIONAL SURFACE_3D_ELEMENT_COORDINATE_SYSTEM;
END_ENTITY;

TYPE SURFACE_3D_ELEMENT_OUTPUT_REFERENCE = SELECT
   (surface_3d_element_representation,
    surface_3d_element_descriptor,
    surface_3d_element_group,
    surface_3d_substructure_element_reference,
    analysis_item_within_representation);
END_TYPE;

TYPE BOUNDARY_VARIABLE = SELECT
   (BOUNDARY_SURFACE_SCALAR_VARIABLE,
    BOUNDARY_SURFACE_VECTOR_3D_VARIABLE,
    APPLICATION_DEFINED_SCALAR_VARIABLE,
    APPLICATION_DEFINED_VECTOR_3D_VARIABLE);
END_TYPE;

TYPE BOUNDARY_SURFACE_SCALAR_VARIABLE = ENUMERATION OF
   (PRESSURE);
END_TYPE;

TYPE SURFACE_3D_FACE = INTEGER;  END_TYPE;
```

Figure 29 Flattened EXPRESS Schema for Element Pressure

The variable is selected to be a **boundary_surface_scalar_variable** which has a single enumeration equal to **.PRESSURE.** . In AP209 ed2, a positive pressure acts normal to the surface and into the volume of the element. This definition is consistent with NASTRAN volume elements, but differs from the NASTRAN surface element defintion which uses the element normal to determine the positive direction as illustrated in Figure 30.

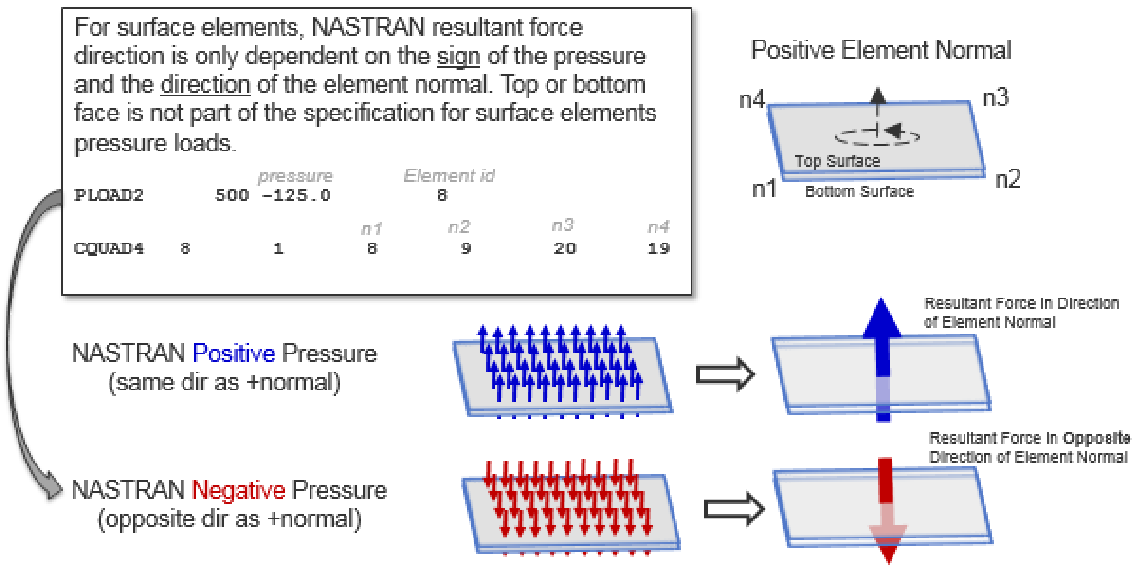


Figure 30 NASTRAN Surface Element Pressure Sign Convention

AP209 ed2 uses an **element_face** attribute for surface elements which enables the definition of positive pressure to be consistent for both surface and volume elements. It also allows a model to capture the true physics of a problem where you may have positive pressure on both sides of a surface element that could result in a net force of zero. Figure 31 illustrates the AP209 ed2 convention.

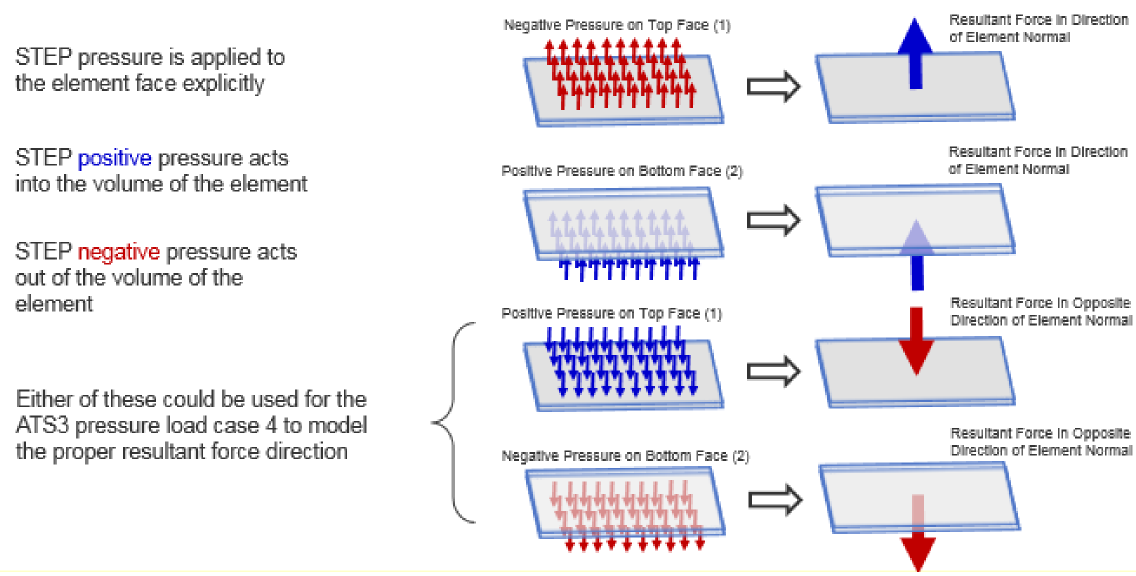


Figure 31 AP209 ed2 Convention for Positive Pressure

6.2.3 AP209 ed2 Superposition of Applied Loads

The next topic to be addressed is the linear superposition of the defined states for forces and pressure loads. The use of scale factors on individual load sets and the overall combination is easily mapped to AP209 ed2 constructs. The **linearly_superimposed_state** entity class provides this capability.

A **linearly_superimposed_state** is referenced from all the individual **state_component**(s) that are being superimposed. The 'INVERSE' qualifier indicates that the value of the components attribute is determined by the set of **state_component**(s) that reference this state. There is no explicit component attribute populated with this set of **state_component**(s) in the ASCII Part 21 file.

The **state_component** provides a real value **factor** attribute for scaling the **state_definition**(s) that are related through **state_relationship** instances. To fully define the NASTRAN load combination card, two **linearly_superimposed_state**(s) would be required. One collecting the scaled individual loads and another for the overall scaled load set. Figure 32 shows the flattened EXPRESS definitions.

```
ENTITY linearly_superimposed_state;
    ENTITY state;
        state_id                                : IDENTIFIER;
        description                             : TEXT;
    ENTITY linearly_superimposed_state;
      INVERSE
        components                              : SET [1:?] OF state_component FOR state;
END_ENTITY

ENTITY state_component;
    ENTITY state;
        state_id                                : IDENTIFIER;
        description                             : TEXT;
    ENTITY state_component;
        state                                   : linearly_superimposed_state;
        factor                                  : CONTEXT_DEPENDENT_MEASURE;
END_ENTITY;
```

Figure 32 Flattened EXPRESS Schema for Linearly Superimposed Load Cases with Scale Factors

Similar to the boundary condition discussion in Section 6.1.3, all load combinations modeled with superimposed state definitions and associated scaling factors would appear in layer 2 of the 3 layer state tree. If only unit scale factors are needed, then loads could be aggregated using simple **state_relationship** instances instead of **linearly_superimposed_state**(s). However, it is recommended to be explicit when combining load state definition entries by using the **linearly_superimposed_state**(s) and unit scale factors. This provides an unambiguous definition that minimizes assumptions.

Several examples and diagrams are provided in the following section to illustrate the concept of load superposition and how it is expressed in AP209 ed2.

6.2.4 AP209 ed2 Instantiation of Applied Loads

The instantiation of applied loads in AP209 ed2 using the constructs presented in the prior section uses a similar presentation as for constraints. First, general figures are presented followed by examples from the ATS pilot models illustrating the concept.

All the applied loads in the ATS pilot study models can be instantiated using the same 3 layer approach discussed for constraints. Figure 33 is an example where a single load is reused for 2 subcases.

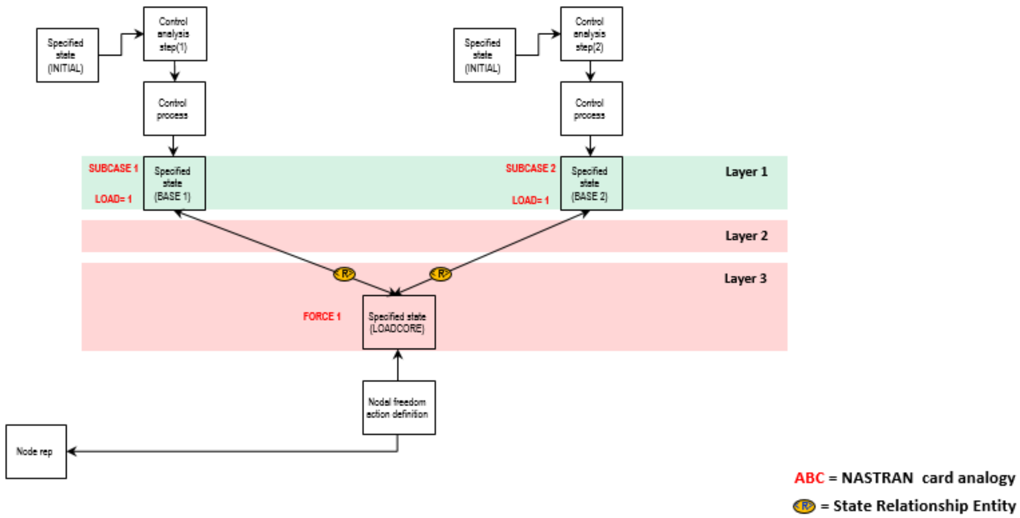


Figure 33 Example of Shared Single Applied Load

The 'base' **specified_state**(s) in layer 1 are shared with the constraint definitions since only one reference from the control process is allowed. It represents the load set selected in the case control. Since no combinations are used, there are no layer 2 entities. The **state_relation** directly relates the **state_definition** for applied forces at nodes to the 'base' **specified_state**. For discussion, these **state_definition**(s) refer to the 'loadcore' **specified_state** in layer 3.

Figure 34 illustrates a more complex example. There are three subcases, the first two subcases share the same **linearly_superimposed_state** which is a scaled combination of three 'loadcore' **state_definition**(s).

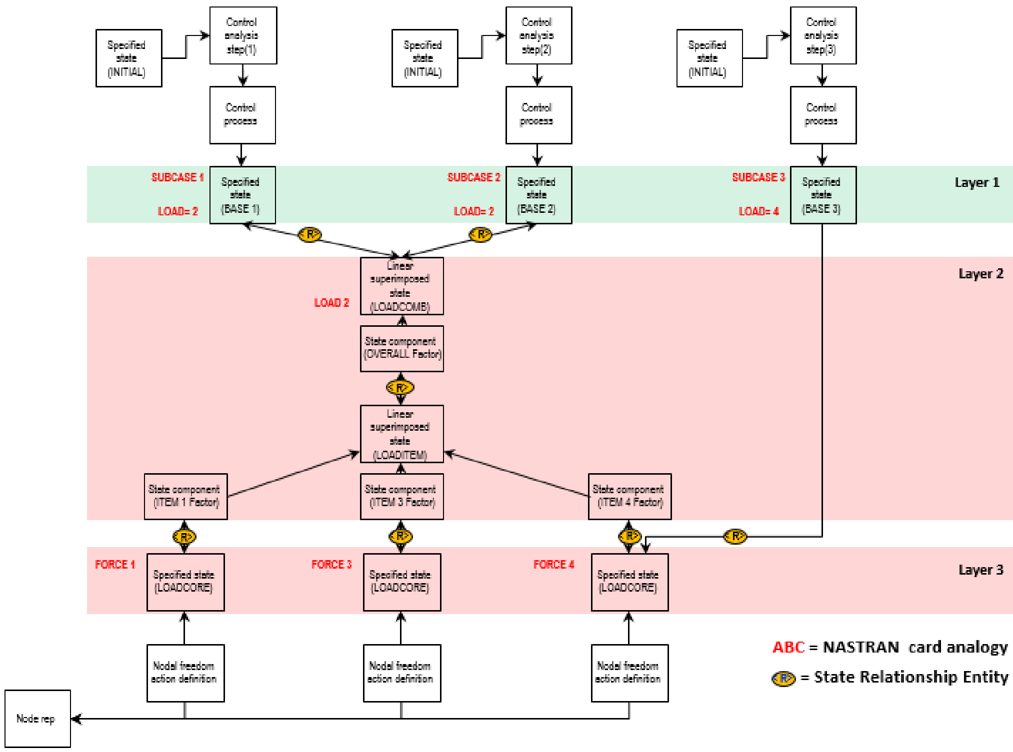


Figure 34 Example of Combined Applied Loads

Subcase 3 is a direct selection of one of the un-scaled state_components. The additional terminology such as 'base', 'loadcore' and the others found in these figures such as 'loadcomb' and 'loaditem' are simply textual aids for discussion. They were used in the labeling of these instances in the ASCII Part 21 files to help with debugging but are currently not specified in the standard or the recommended practices.

The recommended practice defines where material, node and element IDs should be located in the data model; however, currently no guidance is provided for the boundary condition or load set IDs. To reproduce a solver input listing from the STEP population, a convention for load and boundary condition set IDs must be adopted by the implementors.

A convention for subcase and constraint set identification has been described in sections 5.3 and 6.1.3. A similar convention should be used for load set identifications. In the hierarchy of **specified_state**(s), the top-most **specified_state** related to the 'base' state should use the **state_id** that matches the selected load set ID for that step. Similarly, the lowest **specified_state** in the hierarchy (layer 3) should use the load set identification found on the source load definitions (FORCE or PLOAD2 entries in the NASTRAN source). Note that a **specified_state** can assume both roles if the selected set is the load defintion set as illustrated in subcase 3 from Figure 34 or subcase 4 of Figure 36.

Finally, load cases for ATS3 are presented in Figure 35 and Figure 36. These figures show only a relevent subset of the entities used to model the applied loads for the ATS3 pilot study model in AP209 ed2.

The guidelines provided in this handbook present a working solution for loads and boundary conditions as defined for the pilot test models. Guidelines for other solvers and other NASTRAN case control will be addressed as additional test cases are introduced and the translator implementations mature.

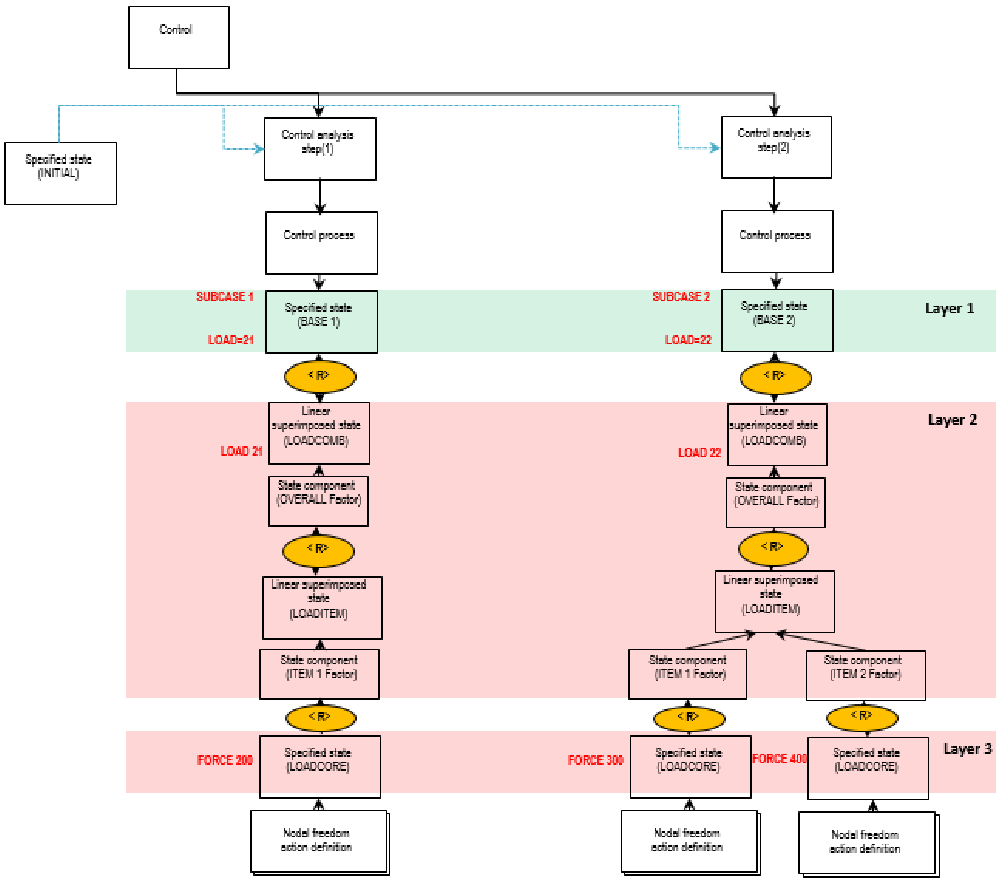


Figure 35 ATS3 Applied Loads Subcase 1 and 2

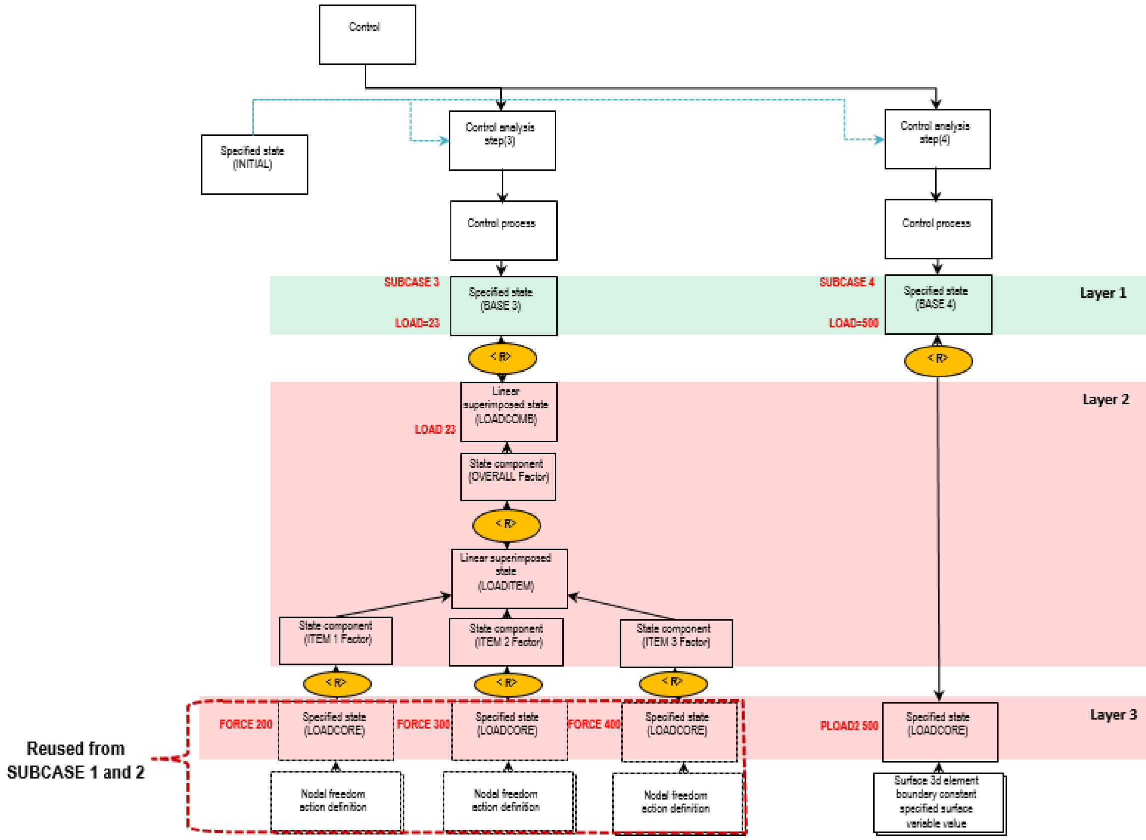


Figure 36 ATS3 Applied Loads Subcase 3 and 4

As model size increases, the ability to make actual instance diagrams is quickly exceeded. Figure 37 demonstrates that even the simple ATS2 bar model with three load cases and simple boundary conditions results in a complex diagram. However, it does illustrate the needed concepts.

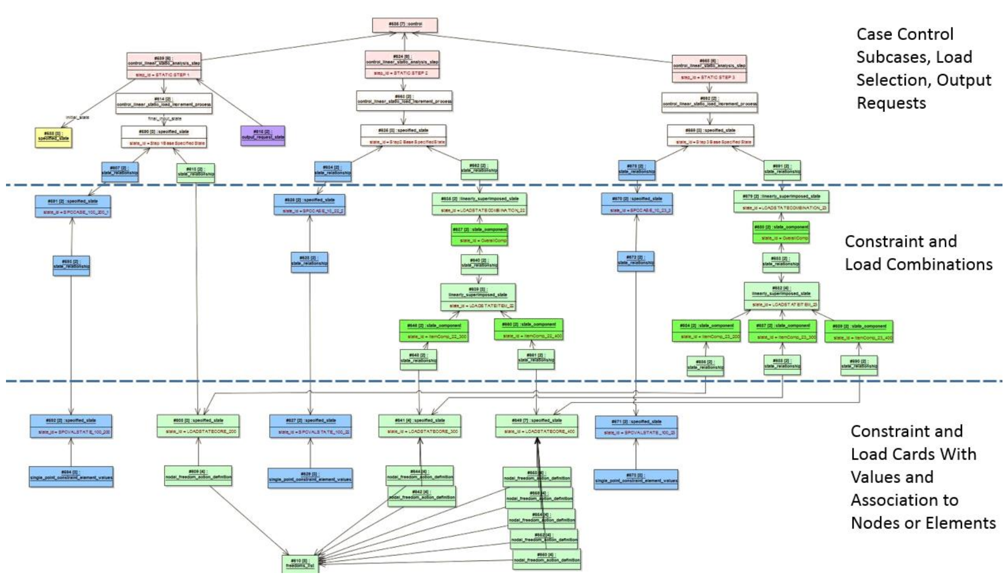


Figure 37 STEP Input Control Structures for ATS2 CBAR Model

The instance diagram for subcase 3 of the ATS3 pilot study model is presented in Figure 38. This diagram corresponds to the NASTRAN information presented in Figure 23 and part of Figure 36.

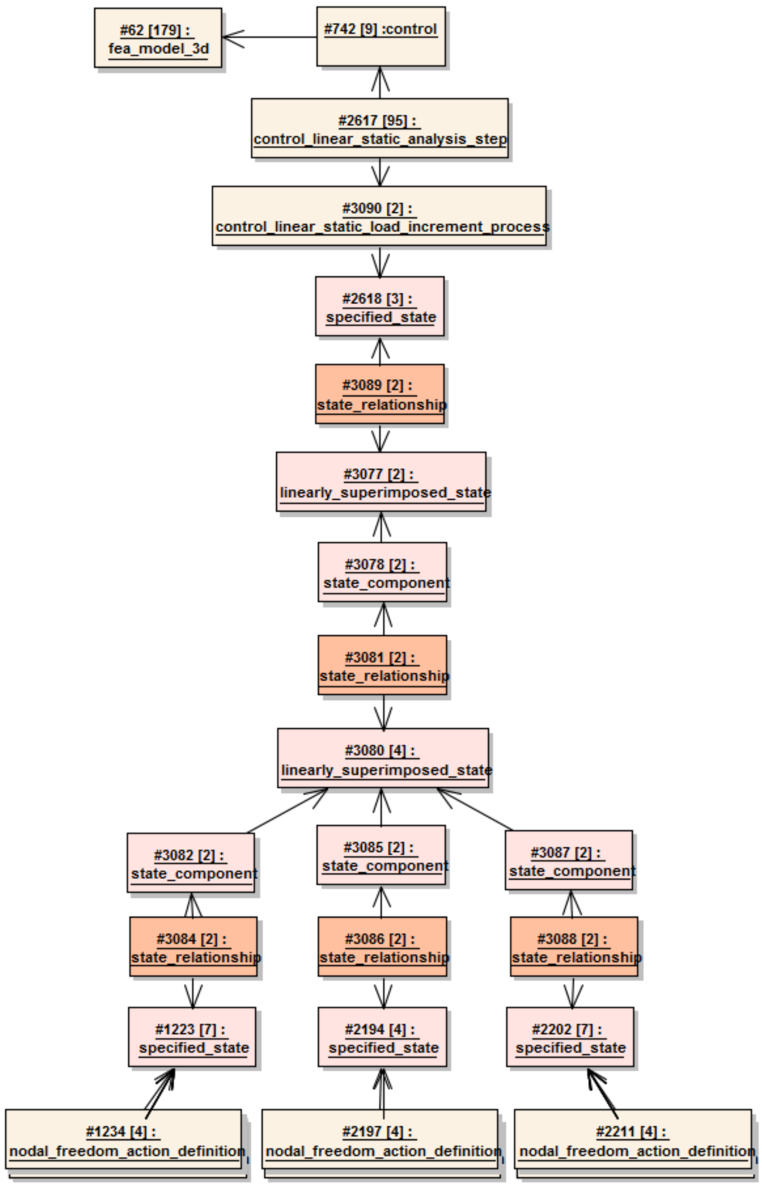


Figure 38 Instance Diagram for ATS3 Subcase 3

Lastly, the corresponding STEP file fragment is presented in Figure 39. One complete traversal from the **fea_model_3d** down to the **nodal_freedom_action_definition**(s) of Figure 38 is shown. Only the **nodal_freedom_action_definition**(s) from the lower left side of the figure are listed. The reader is referred to the Appendix B for the complete Part 21 listing.

```
#62= FEA_MODEL_3D('Identification',(#13),#28,
     'NASTRAN BDF Converter 0.0.0',('NASTRAN'),'AnalysisModelType');

#742= CONTROL(#62,'Control.0','FemConvert','Nastran job EAS test case ATS3m5',
      ('101','TIME 600','CEND','0','1','2','3','4','ENDDATA'),('NASTRAN'));
#2617= CONTROL_LINEAR_STATIC_ANALYSIS_STEP(#742,'STATIC STEP 3',3,#745,'',#3090);
#3090= CONTROL_LINEAR_STATIC_LOAD_INCREMENT_PROCESS('STATIC STEP 3','',#2618);

#2618= SPECIFIED_STATE('Step 3 Base Specified State','Relating Specified State');
#3089= STATE_RELATIONSHIP(
       'LOADSTATECOMBINATION_23 is related to Step 3 Base Specified State','',#2618,#3077);

#3077= LINEARLY_SUPERIMPOSED_STATE('23','Overall Factor Combined State');
#3078= STATE_COMPONENT('OverallComp','',#3077,1.);
#3081= STATE_RELATIONSHIP('LOADSTATEITEM_23 is related to OverallComp','',#3078,#3080);

#3080= LINEARLY_SUPERIMPOSED_STATE('LOADSTATEITEM_23','ItemComp Collector State');
#3082= STATE_COMPONENT('ItemComp_23_200','',#3080,1.);
#3085= STATE_COMPONENT('ItemComp_23_300','',#3080,1.);
#3087= STATE_COMPONENT('ItemComp_23_400','',#3080,1.);
#3084= STATE_RELATIONSHIP('LOADSTATECORE_200 is related to ItemComp_23_200','',#3082,#1223);
#3086= STATE_RELATIONSHIP('LOADSTATECORE_300 is related to ItemComp_23_300','',#3085,#2194);
#3088= STATE_RELATIONSHIP('LOADSTATECORE_400 is related to ItemComp_23_400','',#3087,#2202);

#1223= SPECIFIED_STATE('200','Core Loads Specified State');
#1224= NODAL_FREEDOM_ACTION_DEFINITION(#1223,#320,#13,#1225,(
CONTEXT_DEPENDENT_MEASURE(-125.),CONTEXT_DEPENDENT_MEASURE(0.),CONTEXT_DEPENDENT_MEASURE(0.)),
.APPLIED_LOADS.);
#1228= NODAL_FREEDOM_ACTION_DEFINITION(#1223,#344,#13,#1225,(
CONTEXT_DEPENDENT_MEASURE(-250.),CONTEXT_DEPENDENT_MEASURE(0.),CONTEXT_DEPENDENT_MEASURE(0.)),
.APPLIED_LOADS.);
#1230= NODAL_FREEDOM_ACTION_DEFINITION(#1223,#368,#13,#1225,(
CONTEXT_DEPENDENT_MEASURE(-250.),CONTEXT_DEPENDENT_MEASURE(0.),CONTEXT_DEPENDENT_MEASURE(0.)),
.APPLIED_LOADS.);
#1232= NODAL_FREEDOM_ACTION_DEFINITION(#1223,#392,#13,#1225,(
CONTEXT_DEPENDENT_MEASURE(-250.),CONTEXT_DEPENDENT_MEASURE(0.),CONTEXT_DEPENDENT_MEASURE(0.)),
.APPLIED_LOADS.);
#1234= NODAL_FREEDOM_ACTION_DEFINITION(#1223,#416,#13,#1225,(
CONTEXT_DEPENDENT_MEASURE(-125.),CONTEXT_DEPENDENT_MEASURE(0.),CONTEXT_DEPENDENT_MEASURE(0.)),
.APPLIED_LOADS.);

       <…state_definitions for Core load set 300 and 400 are similar and omitted…>

#1225= FREEDOMS_LIST(
      (ENUMERATED_DEGREE_OF_FREEDOM(.X_TRANSLATION.),
       ENUMERATED_DEGREE_OF_FREEDOM(.Y_TRANSLATION.),
       ENUMERATED_DEGREE_OF_FREEDOM(.Z_TRANSLATION.)));

#320= NODE('62',(#318),#28,#62);
#344= NODE('69',(#342),#28,#62);
#368= NODE('76',(#366),#28,#62);
#392= NODE('83',(#390),#28,#62);
#416= NODE('90',(#414),#28,#62);
```

Figure 39 STEP File Fragment for Applied Load Entities in for ATS3 Subcase 3

7 References and Links

This section provides a list of useful links the reader can use to learn more about the STEP standard, the US and European organizations that administer, develop and support these standards, and the LOTAR Engineering and Simulation Workgroup which authored this handbook in the frame of the CAE-IF.

The reader is encouraged to visit all the links for an introduction and overview of the activities of these organizations. However, the LOTAR EAS WG link and the CAx-IF and CAE-IF links contain reference material that is directly applicable to the topics discussed in the handbook.

LOTAR International	http://www.lotar-international.org
LOTAR EAS WG	http://www.lotar-international.org/lotar-workgroups/engineering-analysis-simulation.html
NAFEMS	http://www.nafems.org
AFNeT	http://www.afnet.fr
PDES, Inc.	https://www.pdesinc.org
prostep ivip	http://www.prostep.org/en.html
AIA	http://www.aia-aerospace.org
ASD-STAN	http://www.asd-stan.org
ISO STEP AP209 ed2	http://www.ap209.org
CAx-IF	https://www.cax-if.org
CAE-IF	http://afnet.fr/dotank/sps/cae-if

Table 2 Useful Links for Further Reading on ISO 10303-209 (STEP AP209)

Table 3

8 Appendix A – NASTRAN Input File Full Listing

The NASTRAN input files for the four pilot models, as listed in the following four subsections, were used for this pilot study. They are not expected to be changed or updated unless a significant issue is identified that materially affects the generation of the STEP files. The first load case is defined consistently for all models with appropriate loads and boundary conditions to enable comparable solution data. However, the results will not be numerically identical due to differences in the model abstractions and element selection.

8.1 ATS1m5.bdf

```
$ Linear Static Analysis
SOL 101
TIME 600
CEND
$
SEALL = ALL
SUPER = ALL
TITLE = Nastran job EAS test case ATS1m5
ECHO = NONE
MAXLINES = 999999999
GPFORCE(PRINT,PUNCH) = ALL
$
SUBCASE 1
   SUBTITLE=subcase1 - axial load at tip
   SPC = 100
   LOAD = 200
   DISPLACEMENT(PRINT,PUNCH,SORT1,REAL)=ALL
   SPCFORCES(PRINT,PUNCH,SORT1,REAL)=ALL
   STRESS(PRINT,PUNCH,SORT1,REAL,VONMISES,BILIN)=ALL
   STRAIN(PRINT,PUNCH)=ALL
   FORCE(PRINT,PUNCH)=ALL
   ELSUM=ALL
$
BEGIN BULK
PARAM   POST    -1
PARAM   AUTOSPC YES
PARAM   NOCOMPS -1
PARAM   PRTMAXIM YES
PARAM   GRDPNT  0
$
PROD    1       1       8.      0.
$
CROD    1       1       1       2
CROD    2       1       2       3
CROD    3       1       3       4
CROD    4       1       4       5
CROD    5       1       5       6
CROD    6       1       6       7
CROD    7       1       7       8
CROD    8       1       8       9
CROD    9       1       9       10
CROD    10      1       10      11
CROD    11      1       11      12
CROD    12      1       12      13
CROD    13      1       13      14
CROD    14      1       14      15
CROD    15      1       15      16
CROD    16      1       16      17
$
MAT1    1       1.+7            .33     2.54-4  1.3-5   70.
$
GRID    1       1       0.      -2.     1.
GRID    2       1       1.      -2.     1.
GRID    3       1       2.      -2.     1.
GRID    4       1       3.      -2.     1.
GRID    5       1       4.      -2.     1.
GRID    6       1       5.      -2.     1.
GRID    7       1       6.      -2.     1.
GRID    8       1       7.      -2.     1.
GRID    9       1       8.      -2.     1.
GRID    10      1       9.      -2.     1.
```

```
GRID     11      1       10.     -2.      1.
GRID     12      1       11.     -2.      1.
GRID     13      1       12.     -2.      1.
GRID     14      1       13.     -2.      1.
GRID     15      1       14.     -2.      1.
GRID     16      1       15.     -2.      1.
GRID     17      1       16.     -2.      1.
$
SPC1     100     123     1
$
FORCE    200     17      0       1000.  -1.      0.      0.
$
CORD2R   1               0.      0.      0.      0.      0.      1.
         1.      0.      0.
$
ENDDATA
```

8.2 ATS2m5.bdf

```
$ Linear Static Analysis
SOL 101
TIME 600
CEND
$
SEALL = ALL
SUPER = ALL
TITLE = Nastran EAS test case ATS2m5
ECHO = NONE
MAXLINES = 999999999
GPFORCE(PRINT,PUNCH) = ALL
SUBCASE 1
   SUBTITLE=subcase1
   SPC = 100
   LOAD = 200
   DISPLACEMENT(PRINT,PUNCH,SORT1,REAL)=ALL
   SPCFORCES(PRINT,PUNCH,SORT1,REAL)=ALL
   STRESS(PRINT,PUNCH,SORT1,REAL,VONMISES,BILIN)=ALL
   STRAIN(PRINT,PUNCH)=ALL
   FORCE(PRINT,PUNCH)=ALL
   ELSUM=ALL
SUBCASE 2
   SUBTITLE=subcase2
   SPC = 10
   LOAD = 22
   DISPLACEMENT(PRINT,PUNCH,SORT1,REAL)=ALL
   SPCFORCES(PRINT,PUNCH,SORT1,REAL)=ALL
   STRESS(PRINT,PUNCH,SORT1,REAL,VONMISES,BILIN)=ALL
   STRAIN(PRINT,PUNCH)=ALL
   FORCE(PRINT,PUNCH)=ALL
SUBCASE 3
   SUBTITLE=subcase3
   SPC = 10
   LOAD = 23
   DISPLACEMENT(PRINT,PUNCH,SORT1,REAL)=ALL
   SPCFORCES(PRINT,PUNCH,SORT1,REAL)=ALL
   STRESS(PRINT,PUNCH,SORT1,REAL,VONMISES,BILIN)=ALL
   STRAIN(PRINT,PUNCH)=ALL
   FORCE(PRINT,PUNCH)=ALL
$
BEGIN BULK
PARAM   POST    -1
PARAM   AUTOSPC YES
PARAM   NOCOMPS -1
PARAM   PRTMAXIM YES
PARAM   GRDPNT  0
$
PBAR     1       1       8.       2.667   10.667  0.      0.
         1.      2.      1.      -2.      -1.     -2.     -1.     2.
                         0.
$
CBAR*    1               1               1               2
*        0.              7.54979-8       1.
CBAR*    2               1               2               3
*        0.              7.54979-8       1.
CBAR*    3               1               3               4
*        0.              7.54979-8       1.
CBAR*    4               1               4               5
*        0.              7.54979-8       1.
CBAR*    5               1               5               6
*        0.              7.54979-8       1.
CBAR*    6               1               6               7
*        0.              7.54979-8       1.
CBAR*    7               1               7               8
*        0.              7.54979-8       1.
CBAR*    8               1               8               9
*        0.              7.54979-8       1.
CBAR*    9               1               9               10
*        0.              7.54979-8       1.
CBAR*    10              1               10              11
*        0.              7.54979-8       1.
CBAR*    11              1               11              12
*        0.              7.54979-8       1.
CBAR*    12              1               12              13
*        0.              7.54979-8       1.
CBAR*    13              1               13              14
*        0.              7.54979-8       1.
CBAR*    14              1               14              15
```

```
*        0.              7.54979-8       1.
CBAR*    15              1               15              16
*        0.              7.54979-8       1.
CBAR*    16              1               16              17
*        0.              7.54979-8       1.
$
MAT1     1       1.+7            .33     2.54-4  1.3-5   70.
$
GRID     1       1       0.     -2.      1.
GRID     2       1       1.     -2.      1.
GRID     3       1       2.     -2.      1.
GRID     4       1       3.     -2.      1.
GRID     5       1       4.     -2.      1.
GRID     6       1       5.     -2.      1.
GRID     7       1       6.     -2.      1.
GRID     8       1       7.     -2.      1.
GRID     9       1       8.     -2.      1.
GRID     10      1       9.     -2.      1.
GRID     11      1       10.    -2.      1.
GRID     12      1       11.    -2.      1.
GRID     13      1       12.    -2.      1.
GRID     14      1       13.    -2.      1.
GRID     15      1       14.    -2.      1.
GRID     16      1       15.    -2.      1.
GRID     17      1       16.    -2.      1.
$
SPCADD   10      100
$
LOAD     22      1.      1.      300     1.      400
LOAD     23      1.      1.      200     1.      300     1.      400
$
SPC1     100     123456  1
$
FORCE    200     17      0       1000.  -1.      0.      0.
FORCE    300     11      0       10.     0.     -1.      0.
FORCE    300     17      0       10.     0.     -1.      0.
FORCE    400     12      0       20.     0.     -1.      0.
FORCE    400     13      0       20.     0.     -1.      0.
FORCE    400     14      0       20.     0.     -1.      0.
FORCE    400     15      0       20.     0.     -1.      0.
FORCE    400     16      0       20.     0.     -1.      0.
$
CORD2R   1               0.      0.      0.      0.      0.      1.
         1.      0.      0.
$
ENDDATA
```

8.3 ATS3m5.bdf

```
$ Linear Static Analysis
SOL 101
TIME 600
CEND
$
SEALL = ALL
SUPER = ALL
TITLE = Nastran job EAS test case ATS3m5
ECHO = NONE
MAXLINES = 999999999
GPFORCE(PRINT,PUNCH) = ALL
$
SUBCASE 1
   SUBTITLE=subcase1
   SPC = 11
   LOAD = 21
   DISPLACEMENT(PRINT,PUNCH,SORT1,REAL)=ALL
   SPCFORCES(PRINT,PUNCH,SORT1,REAL)=ALL
   STRESS(PRINT,PUNCH,SORT1,REAL,VONMISES,BILIN)=ALL
   STRAIN(PRINT,PUNCH,FIBER)=ALL
   FORCE(PRINT,PUNCH)=ALL
   ELSUM=ALL
SUBCASE 2
   SUBTITLE=subcase2
   SPC = 12
   LOAD = 22
   DISPLACEMENT(PRINT,PUNCH,SORT1,REAL)=ALL
   SPCFORCES(PRINT,PUNCH,SORT1,REAL)=ALL
   STRESS(PRINT,PUNCH,SORT1,REAL,VONMISES,BILIN)=ALL
   STRAIN(PRINT,PUNCH,FIBER)=ALL
   FORCE(PRINT,PUNCH)=ALL
SUBCASE 3
   SUBTITLE=subcase3
   SPC = 12
   LOAD = 23
   DISPLACEMENT(PRINT,PUNCH,SORT1,REAL)=ALL
   SPCFORCES(PRINT,PUNCH,SORT1,REAL)=ALL
   STRESS(PRINT,PUNCH,SORT1,REAL,VONMISES,BILIN)=ALL
   STRAIN(PRINT,PUNCH,FIBER)=ALL
   FORCE(PRINT,PUNCH)=ALL
SUBCASE 4
   SUBTITLE=subcase4
   SPC = 103
   LOAD = 500
   DISPLACEMENT(PRINT,PUNCH,SORT1,REAL)=ALL
   SPCFORCES(PRINT,PUNCH,SORT1,REAL)=ALL
   STRESS(PRINT,PUNCH,SORT1,REAL,VONMISES,BILIN)=ALL
   STRAIN(PRINT,PUNCH,FIBER)=ALL
   FORCE(PRINT,PUNCH)=ALL
$
BEGIN BULK
PARAM   POST    -1
PARAM   AUTOSPC YES
PARAM   NOCOMPS -1
PARAM   PRTMAXIM YES
PARAM   GRDPNT  0
$
PSHELL  1       1       2.      1               1
$
CQUAD4  1       1       1       2       13      12
CQUAD4  2       1       2       3       14      13
CQUAD4  3       1       3       4       15      14
CQUAD4  4       1       4       5       16      15
CQUAD4  5       1       5       6       17      16
CQUAD4  6       1       6       7       18      17
CQUAD4  7       1       7       8       19      18
CQUAD4  8       1       8       9       20      19
CQUAD4  9       1       9       10      21      20
CQUAD4  10      1       10      11      22      21
CQUAD4  11      1       12      13      24      23
CQUAD4  12      1       13      14      25      24
CQUAD4  13      1       14      15      26      25
CQUAD4  14      1       15      16      27      26
CQUAD4  15      1       16      17      28      27
CQUAD4  16      1       17      18      29      28
CQUAD4  17      1       18      19      30      29
CQUAD4  18      1       19      20      31      30
CQUAD4  19      1       20      21      32      31
```

```
CQUAD4  20      1       21      22      33      32
CQUAD4  21      1       23      24      35      34
CQUAD4  22      1       24      25      36      35
CQUAD4  23      1       25      26      37      36
CQUAD4  24      1       26      27      38      37
CQUAD4  25      1       27      28      39      38
CQUAD4  26      1       28      29      40      39
CQUAD4  27      1       29      30      41      40
CQUAD4  28      1       30      31      42      41
CQUAD4  29      1       31      32      43      42
CQUAD4  30      1       32      33      44      43
CQUAD4  31      1       34      35      46      45
CQUAD4  32      1       35      36      47      46
CQUAD4  33      1       36      37      48      47
CQUAD4  34      1       37      38      49      48
CQUAD4  35      1       38      39      50      49
CQUAD4  36      1       39      40      51      50
CQUAD4  37      1       40      41      52      51
CQUAD4  38      1       41      42      53      52
CQUAD4  39      1       42      43      54      53
CQUAD4  40      1       43      44      55      54
CTRIA3  41      1       64      22      11
CTRIA3  42      1       11      57      64
CTRIA3  43      1       57      58      64
CTRIA3  44      1       65      64      58
CTRIA3  45      1       66      65      58
CTRIA3  46      1       58      59      66
CTRIA3  47      1       59      60      66
CTRIA3  48      1       67      66      60
CTRIA3  49      1       68      67      60
CTRIA3  50      1       60      61      68
CTRIA3  51      1       61      62      68
CTRIA3  52      1       69      68      62
CTRIA3  53      1       22      64      33
CTRIA3  54      1       71      33      64
CTRIA3  55      1       72      71      64
CTRIA3  56      1       64      65      72
CTRIA3  57      1       65      66      72
CTRIA3  58      1       73      72      66
CTRIA3  59      1       74      73      66
CTRIA3  60      1       66      67      74
CTRIA3  61      1       67      68      74
CTRIA3  62      1       75      74      68
CTRIA3  63      1       76      75      68
CTRIA3  64      1       68      69      76
CTRIA3  65      1       78      44      33
CTRIA3  66      1       33      71      78
CTRIA3  67      1       71      72      78
CTRIA3  68      1       79      78      72
CTRIA3  69      1       80      79      72
CTRIA3  70      1       72      73      80
CTRIA3  71      1       73      74      80
CTRIA3  72      1       81      80      74
CTRIA3  73      1       82      81      74
CTRIA3  74      1       74      75      82
CTRIA3  75      1       75      76      82
CTRIA3  76      1       83      82      76
CTRIA3  77      1       44      78      55
CTRIA3  78      1       85      55      78
CTRIA3  79      1       86      85      78
CTRIA3  80      1       78      79      86
CTRIA3  81      1       79      80      86
CTRIA3  82      1       87      86      80
CTRIA3  83      1       88      87      80
CTRIA3  84      1       80      81      88
CTRIA3  85      1       81      82      88
CTRIA3  86      1       89      88      82
CTRIA3  87      1       90      89      82
CTRIA3  88      1       82      83      90
$
MAT1    1       1.+7            .33     2.54-4  1.3-5   70.
$
GRID*   1                              -6.24022-8      -4.
*       1.
GRID    2               1.      -4.     1.
GRID    3               2.      -4.     1.
GRID    4               3.      -4.     1.
GRID    5               4.      -4.     1.
GRID    6               5.      -4.     1.
GRID    7               6.      -4.     1.
GRID    8               7.      -4.     1.
GRID    9               8.      -4.     1.
```

```
GRID     10              9.     -4.     1.
GRID     11              10.    -4.     1.
GRID*    12                            -6.24022-8      -3.
*        1.
GRID     13              1.     -3.     1.
GRID     14              2.     -3.     1.
GRID     15              3.     -3.     1.
GRID     16              4.     -3.     1.
GRID     17              5.     -3.     1.
GRID     18              6.     -3.     1.
GRID     19              7.     -3.     1.
GRID     20              8.     -3.     1.
GRID     21              9.     -3.     1.
GRID     22              10.    -3.     1.
GRID*    23                            -6.24022-8      -2.
*        1.
GRID     24              1.     -2.     1.
GRID     25              2.     -2.     1.
GRID     26              3.     -2.     1.
GRID     27              4.     -2.     1.
GRID     28              5.     -2.     1.
GRID     29              6.     -2.     1.
GRID     30              7.     -2.     1.
GRID     31              8.     -2.     1.
GRID     32              9.     -2.     1.
GRID     33              10.    -2.     1.
GRID*    34                            -6.24022-8      -1.
*        1.
GRID     35              1.     -1.     1.
GRID     36              2.     -1.     1.
GRID     37              3.     -1.     1.
GRID     38              4.     -1.     1.
GRID     39              5.     -1.     1.
GRID     40              6.     -1.     1.
GRID     41              7.     -1.     1.
GRID     42              8.     -1.     1.
GRID     43              9.     -1.     1.
GRID     44              10.    -1.     1.
GRID*    45                            -6.24022-8      -5.27577-8
*        1.
GRID*    46                             1.             -5.27577-8
*        1.
GRID*    47                             2.             -5.27577-8
*        1.
GRID*    48                             3.             -5.27577-8
*        1.
GRID*    49                             4.             -5.27577-8
*        1.
GRID*    50                             5.             -5.27577-8
*        1.
GRID*    51                             6.             -5.27577-8
*        1.
GRID*    52                             7.             -5.27577-8
*        1.
GRID*    53                             8.             -5.27577-8
*        1.
GRID*    54                             9.             -5.27577-8
*        1.
GRID*    55                             10.            -5.27577-8
*        1.
GRID     57              11.    -4.     1.
GRID     58              12.    -4.     1.
GRID     59              13.    -4.     1.
GRID     60              14.    -4.     1.
GRID     61              15.    -4.     1.
GRID     62              16.    -4.     1.
GRID     64              11.    -3.     1.
GRID     65              12.    -3.     1.
GRID     66              13.    -3.     1.
GRID     67              14.    -3.     1.
GRID     68              15.    -3.     1.
GRID     69              16.    -3.     1.
GRID     71              11.    -2.     1.
GRID     72              12.    -2.     1.
GRID     73              13.    -2.     1.
GRID     74              14.    -2.     1.
GRID     75              15.    -2.     1.
GRID     76              16.    -2.     1.
GRID     78              11.    -1.     1.
GRID     79              12.    -1.     1.
GRID     80              13.    -1.     1.
GRID     81              14.    -1.     1.
```

```
GRID    82              15.     -1.     1.
GRID    83              16.     -1.     1.
GRID*   85                              11.             -5.27577-8
*       1.
GRID*   86                              12.             -5.27577-8
*       1.
GRID*   87                              13.             -5.27577-8
*       1.
GRID*   88                              14.             -5.27577-8
*       1.
GRID*   89                              15.             -5.27577-8
*       1.
GRID*   90                              16.             -5.27577-8
*       1.
$
SPCADD  11      100     101     110
SPCADD  12      100     102     110
$
LOAD    21      1.      1.      200
LOAD    22      1.      1.      300     1.      400
LOAD    23      1.      1.      200     1.      300     1.      400
$
SPC1    100     123     23
SPC1    101     1       1       12      34      45
SPC1    102     123     1       12      34      45
SPC1    103     123     23
SPC1    103     23      76
SPC1    103     3       1       12      34      45
SPC1    103     3       62      69      83      90
SPC1    110     45      1       THRU    55
SPC1    110     45      57      58      59      60      61      62
        64      65      66      67      68      69      71      72
        73      74      75      76      78      79      80      81
        82      83      85      86      87      88      89      90
$
FORCE   200     62      0       125.    -1.     0.      0.
FORCE   200     69      0       250.    -1.     0.      0.
FORCE   200     76      0       250.    -1.     0.      0.
FORCE   200     83      0       250.    -1.     0.      0.
FORCE   200     90      0       125.    -1.     0.      0.
FORCE   300     55      0       10.     0.     -1.      0.
FORCE   300     90      0       10.     0.     -1.      0.
FORCE   400     85      0       20.     0.     -1.      0.
FORCE   400     86      0       20.     0.     -1.      0.
FORCE   400     87      0       20.     0.     -1.      0.
FORCE   400     88      0       20.     0.     -1.      0.
FORCE   400     89      0       20.     0.     -1.      0.
$
PLOAD2      500-125.0          8
PLOAD2      500-125.0          9
PLOAD2      500-125.0         18
PLOAD2      500-125.0         19
PLOAD2      500-125.0         28
PLOAD2      500-125.0         29
PLOAD2      500-125.0         38
PLOAD2      500-125.0         39
$
ENDDATA
```

8.4 ATS4m5.bdf

```
$ Linear Static Analysis
SOL 101
TIME 600
CEND
$
SEALL = ALL
SUPER = ALL
TITLE = Nastran job EAS test case ATS4m5
ECHO = NONE
MAXLINES = 999999999
GPFORCE(PRINT,PUNCH) = ALL
$
SUBCASE 1
   SUBTITLE=subcase1
   SPC = 11
   LOAD = 21
   DISPLACEMENT(PRINT,PUNCH,SORT1,REAL)=ALL
   SPCFORCES(PRINT,PUNCH,SORT1,REAL)=ALL
   STRESS(PRINT,PUNCH,SORT1,REAL,VONMISES,BILIN)=ALL
   STRAIN(PRINT,PUNCH)=ALL
   FORCE(PRINT,PUNCH)=ALL
   ELSUM=ALL
SUBCASE 2
   SUBTITLE=subcase2
   SPC = 12
   LOAD = 22
   DISPLACEMENT(PRINT,PUNCH,SORT1,REAL)=ALL
   SPCFORCES(PRINT,PUNCH,SORT1,REAL)=ALL
   STRESS(PRINT,PUNCH,SORT1,REAL,VONMISES,BILIN)=ALL
   STRAIN(PRINT,PUNCH)=ALL
   FORCE(PRINT,PUNCH)=ALL
SUBCASE 3
   SUBTITLE=subcase3
   SPC = 12
   LOAD = 23
   DISPLACEMENT(PRINT,PUNCH,SORT1,REAL)=ALL
   SPCFORCES(PRINT,PUNCH,SORT1,REAL)=ALL
   STRESS(PRINT,PUNCH,SORT1,REAL,VONMISES,BILIN)=ALL
   STRAIN(PRINT,PUNCH)=ALL
   FORCE(PRINT,PUNCH)=ALL
$
BEGIN BULK
PARAM   POST    -1
PARAM   AUTOSPC YES
PARAM   PRTMAXIM YES
PARAM   GRDPNT  0
$
PSOLID  1       1       0
$
CHEXA   1       1       1       2       7       6       16      17
        22      21
CHEXA   2       1       2       3       8       7       17      18
        23      22
CHEXA   3       1       3       4       9       8       18      19
        24      23
CHEXA   4       1       4       5       10      9       19      20
        25      24
CHEXA   5       1       6       7       12      11      21      22
        27      26
CHEXA   6       1       7       8       13      12      22      23
        28      27
CHEXA   7       1       8       9       14      13      23      24
        29      28
CHEXA   8       1       9       10      15      14      24      25
        30      29
CHEXA   9       1       16      17      22      21      31      32
        37      36
CHEXA   10      1       17      18      23      22      32      33
        38      37
CHEXA   11      1       18      19      24      23      33      34
        39      38
CHEXA   12      1       19      20      25      24      34      35
        40      39
CHEXA   13      1       21      22      27      26      36      37
        42      41
CHEXA   14      1       22      23      28      27      37      38
        43      42
CHEXA   15      1       23      24      29      28      38      39
```

```
        44      43
CHEXA   16      1       24      25      30      29      39      40
        45      44
CHEXA   17      1       31      32      37      36      46      47
        52      51
CHEXA   18      1       32      33      38      37      47      48
        53      52
CHEXA   19      1       33      34      39      38      48      49
        54      53
CHEXA   20      1       34      35      40      39      49      50
        55      54
CHEXA   21      1       36      37      42      41      51      52
        57      56
CHEXA   22      1       37      38      43      42      52      53
        58      57
CHEXA   23      1       38      39      44      43      53      54
        59      58
CHEXA   24      1       39      40      45      44      54      55
        60      59
CHEXA   25      1       46      47      52      51      61      62
        67      66
CHEXA   26      1       47      48      53      52      62      63
        68      67
CHEXA   27      1       48      49      54      53      63      64
        69      68
CHEXA   28      1       49      50      55      54      64      65
        70      69
CHEXA   29      1       51      52      57      56      66      67
        72      71
CHEXA   30      1       52      53      58      57      67      68
        73      72
CHEXA   31      1       53      54      59      58      68      69
        74      73
CHEXA   32      1       54      55      60      59      69      70
        75      74
$
CTETRA  33      1       76      83      111     77
CTETRA  34      1       118     111     83      119
CTETRA  35      1       84      77      119     83
CTETRA  36      1       112     119     77      111
CTETRA  37      1       77      83      111     119
CTETRA  38      1       84      119     77      85
CTETRA  39      1       112     77      119     113
CTETRA  40      1       78      113     85      77
CTETRA  41      1       120     85      113     119
CTETRA  42      1       77      85      119     113
CTETRA  43      1       78      85      113     79
CTETRA  44      1       120     113     85      121
CTETRA  45      1       86      79      121     85
CTETRA  46      1       114     121     79      113
CTETRA  47      1       79      85      113     121
CTETRA  48      1       86      121     79      87
CTETRA  49      1       114     79      121     115
CTETRA  50      1       80      115     87      79
CTETRA  51      1       122     87      115     121
CTETRA  52      1       79      87      121     115
CTETRA  53      1       80      87      115     81
CTETRA  54      1       122     115     87      123
CTETRA  55      1       88      81      123     87
CTETRA  56      1       116     123     81      115
CTETRA  57      1       81      87      115     123
CTETRA  58      1       88      123     81      64
CTETRA  59      1       116     81      123     70
CTETRA  60      1       65      70      64      81
CTETRA  61      1       69      64      70      123
CTETRA  62      1       81      64      123     70
CTETRA  63      1       90      125     83      91
CTETRA  64      1       118     83      125     119
CTETRA  65      1       84      119     91      83
CTETRA  66      1       126     91      119     125
CTETRA  67      1       83      91      125     119
CTETRA  68      1       84      91      119     85
CTETRA  69      1       126     119     91      127
CTETRA  70      1       92      85      127     91
CTETRA  71      1       120     127     85      119
CTETRA  72      1       85      91      119     127
CTETRA  73      1       92      127     85      93
CTETRA  74      1       120     85      127     121
CTETRA  75      1       86      121     93      85
CTETRA  76      1       128     93      121     127
CTETRA  77      1       85      93      127     121
CTETRA  78      1       86      93      121     87
```

CTETRA	79	1	128	121	93	129
CTETRA	80	1	94	87	129	93
CTETRA	81	1	122	129	87	121
CTETRA	82	1	87	93	121	129
CTETRA	83	1	94	129	87	95
CTETRA	84	1	122	87	129	123
CTETRA	85	1	88	123	95	87
CTETRA	86	1	130	95	123	129
CTETRA	87	1	87	95	129	123
CTETRA	88	1	88	95	123	64
CTETRA	89	1	130	123	95	68
CTETRA	90	1	63	64	68	95
CTETRA	91	1	69	68	64	123
CTETRA	92	1	64	95	123	68
CTETRA	93	1	90	97	125	91
CTETRA	94	1	132	125	97	133
CTETRA	95	1	98	91	133	97
CTETRA	96	1	126	133	91	125
CTETRA	97	1	91	97	125	133
CTETRA	98	1	98	133	91	99
CTETRA	99	1	126	91	133	127
CTETRA	100	1	92	127	99	91
CTETRA	101	1	134	99	127	133
CTETRA	102	1	91	99	133	127
CTETRA	103	1	92	99	127	93
CTETRA	104	1	134	127	99	135
CTETRA	105	1	100	93	135	99
CTETRA	106	1	128	135	93	127
CTETRA	107	1	93	99	127	135
CTETRA	108	1	100	135	93	101
CTETRA	109	1	128	93	135	129
CTETRA	110	1	94	129	101	93
CTETRA	111	1	136	101	129	135
CTETRA	112	1	93	101	135	129
CTETRA	113	1	94	101	129	95
CTETRA	114	1	136	129	101	137
CTETRA	115	1	102	95	137	101
CTETRA	116	1	130	137	95	129
CTETRA	117	1	95	101	129	137
CTETRA	118	1	102	137	95	62
CTETRA	119	1	130	95	137	68
CTETRA	120	1	63	68	62	95
CTETRA	121	1	67	62	68	137
CTETRA	122	1	95	62	137	68
CTETRA	123	1	104	139	97	105
CTETRA	124	1	132	97	139	133
CTETRA	125	1	98	133	105	97
CTETRA	126	1	140	105	133	139
CTETRA	127	1	97	105	139	133
CTETRA	128	1	98	105	133	99
CTETRA	129	1	140	133	105	141
CTETRA	130	1	106	99	141	105
CTETRA	131	1	134	141	99	133
CTETRA	132	1	99	105	133	141
CTETRA	133	1	106	141	99	107
CTETRA	134	1	134	99	141	135
CTETRA	135	1	100	135	107	99
CTETRA	136	1	142	107	135	141
CTETRA	137	1	99	107	141	135
CTETRA	138	1	100	107	135	101
CTETRA	139	1	142	135	107	143
CTETRA	140	1	108	101	143	107
CTETRA	141	1	136	143	101	135
CTETRA	142	1	101	107	135	143
CTETRA	143	1	108	143	101	109
CTETRA	144	1	136	101	143	137
CTETRA	145	1	102	137	109	101
CTETRA	146	1	144	109	137	143
CTETRA	147	1	101	109	143	137
CTETRA	148	1	102	109	137	62
CTETRA	149	1	144	137	109	66
CTETRA	150	1	61	62	66	109
CTETRA	151	1	67	66	62	137
CTETRA	152	1	62	109	137	66
CTETRA	153	1	118	153	111	119
CTETRA	154	1	146	111	153	147
CTETRA	155	1	112	147	119	111
CTETRA	156	1	154	119	147	153
CTETRA	157	1	111	119	153	147
CTETRA	158	1	112	119	147	113
CTETRA	159	1	154	147	119	155
CTETRA	160	1	120	113	155	119

CTETRA	161	1	148	155	113	147
CTETRA	162	1	113	119	147	155
CTETRA	163	1	120	155	113	121
CTETRA	164	1	148	113	155	149
CTETRA	165	1	114	149	121	113
CTETRA	166	1	156	121	149	155
CTETRA	167	1	113	121	155	149
CTETRA	168	1	114	121	149	115
CTETRA	169	1	156	149	121	157
CTETRA	170	1	122	115	157	121
CTETRA	171	1	150	157	115	149
CTETRA	172	1	115	121	149	157
CTETRA	173	1	122	157	115	123
CTETRA	174	1	150	115	157	151
CTETRA	175	1	116	151	123	115
CTETRA	176	1	158	123	151	157
CTETRA	177	1	115	123	157	151
CTETRA	178	1	116	123	151	70
CTETRA	179	1	158	151	123	74
CTETRA	180	1	69	70	74	123
CTETRA	181	1	75	74	70	151
CTETRA	182	1	70	123	151	74
CTETRA	183	1	118	125	153	119
CTETRA	184	1	160	153	125	161
CTETRA	185	1	126	119	161	125
CTETRA	186	1	154	161	119	153
CTETRA	187	1	119	125	153	161
CTETRA	188	1	126	161	119	127
CTETRA	189	1	154	119	161	155
CTETRA	190	1	120	155	127	119
CTETRA	191	1	162	127	155	161
CTETRA	192	1	119	127	161	155
CTETRA	193	1	120	127	155	121
CTETRA	194	1	162	155	127	163
CTETRA	195	1	128	121	163	127
CTETRA	196	1	156	163	121	155
CTETRA	197	1	121	127	155	163
CTETRA	198	1	128	163	121	129
CTETRA	199	1	156	121	163	157
CTETRA	200	1	122	157	129	121
CTETRA	201	1	164	129	157	163
CTETRA	202	1	121	129	163	157
CTETRA	203	1	122	129	157	123
CTETRA	204	1	164	157	129	165
CTETRA	205	1	130	123	165	129
CTETRA	206	1	158	165	123	157
CTETRA	207	1	123	129	157	165
CTETRA	208	1	130	165	123	68
CTETRA	209	1	158	123	165	74
CTETRA	210	1	69	74	68	123
CTETRA	211	1	73	68	74	165
CTETRA	212	1	123	68	165	74
CTETRA	213	1	132	167	125	133
CTETRA	214	1	160	125	167	161
CTETRA	215	1	126	161	133	125
CTETRA	216	1	168	133	161	167
CTETRA	217	1	125	133	167	161
CTETRA	218	1	126	133	161	127
CTETRA	219	1	168	161	133	169
CTETRA	220	1	134	127	169	133
CTETRA	221	1	162	169	127	161
CTETRA	222	1	127	133	161	169
CTETRA	223	1	134	169	127	135
CTETRA	224	1	162	127	169	163
CTETRA	225	1	128	163	135	127
CTETRA	226	1	170	135	163	169
CTETRA	227	1	127	135	169	163
CTETRA	228	1	128	135	163	129
CTETRA	229	1	170	163	135	171
CTETRA	230	1	136	129	171	135
CTETRA	231	1	164	171	129	163
CTETRA	232	1	129	135	163	171
CTETRA	233	1	136	171	129	137
CTETRA	234	1	164	129	171	165
CTETRA	235	1	130	165	137	129
CTETRA	236	1	172	137	165	171
CTETRA	237	1	129	137	171	165
CTETRA	238	1	130	137	165	68
CTETRA	239	1	172	165	137	72
CTETRA	240	1	67	68	72	137
CTETRA	241	1	73	72	68	165
CTETRA	242	1	68	137	165	72

CTETRA	243	1	132	139	167	133		
CTETRA	244	1	174	167	139	175		
CTETRA	245	1	140	133	175	139		
CTETRA	246	1	168	175	133	167		
CTETRA	247	1	133	139	167	175		
CTETRA	248	1	140	175	133	141		
CTETRA	249	1	168	133	175	169		
CTETRA	250	1	134	169	141	133		
CTETRA	251	1	176	141	169	175		
CTETRA	252	1	133	141	175	169		
CTETRA	253	1	134	141	169	135		
CTETRA	254	1	176	169	141	177		
CTETRA	255	1	142	135	177	141		
CTETRA	256	1	170	177	135	169		
CTETRA	257	1	135	141	169	177		
CTETRA	258	1	142	177	135	143		
CTETRA	259	1	170	135	177	171		
CTETRA	260	1	136	171	143	135		
CTETRA	261	1	178	143	171	177		
CTETRA	262	1	135	143	177	171		
CTETRA	263	1	136	143	171	137		
CTETRA	264	1	178	171	143	179		
CTETRA	265	1	144	137	179	143		
CTETRA	266	1	172	179	137	171		
CTETRA	267	1	137	143	171	179		
CTETRA	268	1	144	179	137	66		
CTETRA	269	1	172	137	179	72		
CTETRA	270	1	67	72	66	137		
CTETRA	271	1	71	66	72	179		
CTETRA	272	1	137	66	179	72		
$								
CPENTA	273	1	189	188	181	224	223	216
CPENTA	274	1	181	182	189	216	217	224
CPENTA	275	1	182	183	189	217	218	224
CPENTA	276	1	190	189	183	225	224	218
CPENTA	277	1	191	190	183	226	225	218
CPENTA	278	1	183	184	191	218	219	226
CPENTA	279	1	184	185	191	219	220	226
CPENTA	280	1	192	191	185	227	226	220
CPENTA	281	1	193	192	185	228	227	220
CPENTA	282	1	185	186	193	220	221	228
CPENTA	283	1	186	76	193	221	111	228
CPENTA	284	1	83	193	76	118	228	111
CPENTA	285	1	188	189	195	223	224	230
CPENTA	286	1	196	195	189	231	230	224
CPENTA	287	1	197	196	189	232	231	224
CPENTA	288	1	189	190	197	224	225	232
CPENTA	289	1	190	191	197	225	226	232
CPENTA	290	1	198	197	191	233	232	226
CPENTA	291	1	199	198	191	234	233	226
CPENTA	292	1	191	192	199	226	227	234
CPENTA	293	1	192	193	199	227	228	234
CPENTA	294	1	200	199	193	235	234	228
CPENTA	295	1	90	200	193	125	235	228
CPENTA	296	1	193	83	90	228	118	125
CPENTA	297	1	203	202	195	238	237	230
CPENTA	298	1	195	196	203	230	231	238
CPENTA	299	1	196	197	203	231	232	238
CPENTA	300	1	204	203	197	239	238	232
CPENTA	301	1	205	204	197	240	239	232
CPENTA	302	1	197	198	205	232	233	240
CPENTA	303	1	198	199	205	233	234	240
CPENTA	304	1	206	205	199	241	240	234
CPENTA	305	1	207	206	199	242	241	234
CPENTA	306	1	199	200	207	234	235	242
CPENTA	307	1	200	90	207	235	125	242
CPENTA	308	1	97	207	90	132	242	125
CPENTA	309	1	202	203	209	237	238	244
CPENTA	310	1	210	209	203	245	244	238
CPENTA	311	1	211	210	203	246	245	238
CPENTA	312	1	203	204	211	238	239	246
CPENTA	313	1	204	205	211	239	240	246
CPENTA	314	1	212	211	205	247	246	240
CPENTA	315	1	213	212	205	248	247	240
CPENTA	316	1	205	206	213	240	241	248
CPENTA	317	1	206	207	213	241	242	248
CPENTA	318	1	214	213	207	249	248	242
CPENTA	319	1	104	214	207	139	249	242
CPENTA	320	1	207	97	104	242	132	139
CPENTA	321	1	224	223	216	259	258	251
CPENTA	322	1	216	217	224	251	252	259
CPENTA	323	1	217	218	224	252	253	259

```
CPENTA   324     1       225     224     218     260     259     253
CPENTA   325     1       226     225     218     261     260     253
CPENTA   326     1       218     219     226     253     254     261
CPENTA   327     1       219     220     226     254     255     261
CPENTA   328     1       227     226     220     262     261     255
CPENTA   329     1       228     227     220     263     262     255
CPENTA   330     1       220     221     228     255     256     263
CPENTA   331     1       221     111     228     256     146     263
CPENTA   332     1       118     228     111     153     263     146
CPENTA   333     1       223     224     230     258     259     265
CPENTA   334     1       231     230     224     266     265     259
CPENTA   335     1       232     231     224     267     266     259
CPENTA   336     1       224     225     232     259     260     267
CPENTA   337     1       225     226     232     260     261     267
CPENTA   338     1       233     232     226     268     267     261
CPENTA   339     1       234     233     226     269     268     261
CPENTA   340     1       226     227     234     261     262     269
CPENTA   341     1       227     228     234     262     263     269
CPENTA   342     1       235     234     228     270     269     263
CPENTA   343     1       125     235     228     160     270     263
CPENTA   344     1       228     118     125     263     153     160
CPENTA   345     1       238     237     230     273     272     265
CPENTA   346     1       230     231     238     265     266     273
CPENTA   347     1       231     232     238     266     267     273
CPENTA   348     1       239     238     232     274     273     267
CPENTA   349     1       240     239     232     275     274     267
CPENTA   350     1       232     233     240     267     268     275
CPENTA   351     1       233     234     240     268     269     275
CPENTA   352     1       241     240     234     276     275     269
CPENTA   353     1       242     241     234     277     276     269
CPENTA   354     1       234     235     242     269     270     277
CPENTA   355     1       235     125     242     270     160     277
CPENTA   356     1       132     242     125     167     277     160
CPENTA   357     1       237     238     244     272     273     279
CPENTA   358     1       245     244     238     280     279     273
CPENTA   359     1       246     245     238     281     280     273
CPENTA   360     1       238     239     246     273     274     281
CPENTA   361     1       239     240     246     274     275     281
CPENTA   362     1       247     246     240     282     281     275
CPENTA   363     1       248     247     240     283     282     275
CPENTA   364     1       240     241     248     275     276     283
CPENTA   365     1       241     242     248     276     277     283
CPENTA   366     1       249     248     242     284     283     277
CPENTA   367     1       139     249     242     174     284     277
CPENTA   368     1       242     132     139     277     167     174
$
MAT1     1       1.+7            .33     2.54-4  1.3-5   70.
$
GRID*    1                               0.              -4.
*       -3.43152-8
GRID*    2                               0.              -3.
*       -3.43152-8
GRID*    3                               0.              -2.
*       -3.43152-8
GRID*    4                               0.              -1.
*       -3.43152-8
GRID*    5                               0.              -6.01376-9
*       -3.43152-8
GRID     6               0.      -4.     1.
GRID     7               0.      -3.     1.
GRID     8               0.      -2.     1.
GRID     9               0.      -1.     1.
GRID*    10                              0.              -6.01376-9
*        1.
GRID     11              0.      -4.     2.
GRID     12              0.      -3.     2.
GRID     13              0.      -2.     2.
GRID     14              0.      -1.     2.
GRID*    15                              0.              -6.01376-9
*        2.
GRID*    16                              1.              -4.
*       -2.53545-8
GRID*    17                              1.              -3.
*       -2.09009-8
GRID*    18                              1.              -2.
*       -3.74229-8
GRID*    19                              1.              -1.
*       -5.3945-8
GRID*    20                              1.              -2.86429-9
*       -4.94913-8
GRID     21              1.      -4.     1.
GRID     22              1.      -3.     1.
```

```
GRID     23              1.      -2.     1.
GRID     24              1.      -1.     1.
GRID*    25                              1.              -3.28417-9
*        1.
GRID     26              1.      -4.     2.
GRID     27              1.      -3.     2.
GRID     28              1.      -2.     2.
GRID     29              1.      -1.     2.
GRID*    30                              1.              -3.70404-9
*        2.
GRID*    31                              2.              -4.
*       -1.63938-8
GRID*    32                              2.              -3.
*       -7.48651-9
GRID*    33                              2.              -2.
*       -4.05306-8
GRID*    34                              2.              -1.
*       -7.35747-8
GRID*    35                              2.               2.85177-10
*       -6.46674-8
GRID     36              2.      -4.     1.
GRID     37              2.      -3.     1.
GRID     38              2.      -2.     1.
GRID     39              2.      -1.     1.
GRID*    40                              2.              -5.54573-10
*        1.
GRID     41              2.      -4.     2.
GRID     42              2.      -3.     2.
GRID     43              2.      -2.     2.
GRID     44              2.      -1.     2.
GRID*    45                              2.              -1.39432-9
*        2.
GRID*    46                              3.              -4.
*       -7.43315-9
GRID*    47                              3.              -3.
*        5.92784-9
GRID*    48                              3.              -2.
*       -4.36383-8
GRID*    49                              3.              -1.
*       -9.32045-8
GRID*    50                              3.               3.43465-9
*       -7.98435-8
GRID     51              3.      -4.     1.
GRID     52              3.      -3.     1.
GRID     53              3.      -2.     1.
GRID     54              3.      -1.     1.
GRID*    55                              3.               2.17502-9
*        1.
GRID     56              3.      -4.     2.
GRID     57              3.      -3.     2.
GRID     58              3.      -2.     2.
GRID     59              3.      -1.     2.
GRID*    60                              3.               9.154-10
*        2.
GRID*    61                              4.              -4.
*        1.52753-9
GRID*    62                              4.              -3.
*        1.93422-8
GRID*    63                              4.              -2.
*       -4.6746-8
GRID*    64                              4.              -1.
*       -1.12834-7
GRID*    65                              4.               6.58412-9
*       -9.50196-8
GRID     66              4.      -4.     1.
GRID     67              4.      -3.     1.
GRID     68              4.      -2.     1.
GRID     69              4.      -1.     1.
GRID*    70                              4.               4.90462-9
*        1.
GRID     71              4.      -4.     2.
GRID     72              4.      -3.     2.
GRID     73              4.      -2.     2.
GRID     74              4.      -1.     2.
GRID*    75                              4.               3.22512-9
*        2.
GRID*    76                              10.             -5.27577-8
*        0.
GRID*    77                              9.              -5.27577-8
*        0.
GRID*    78                              8.              -5.27577-8
*        0.
```

```
GRID*   79                              7.              -5.27577-8
*       0.
GRID*   80                              6.              -5.27577-8
*       0.
GRID*   81                              5.              -5.27577-8
*       0.
GRID    83              10.     -1.     0.
GRID    84              9.      -1.     0.
GRID    85              8.      -1.     0.
GRID    86              7.      -1.     0.
GRID    87              6.      -1.     0.
GRID    88              5.      -1.     0.
GRID    90              10.     -2.     0.
GRID    91              9.      -2.     0.
GRID    92              8.      -2.     0.
GRID    93              7.      -2.     0.
GRID    94              6.      -2.     0.
GRID    95              5.      -2.     0.
GRID    97              10.     -3.     0.
GRID    98              9.      -3.     0.
GRID    99              8.      -3.     0.
GRID    100             7.      -3.     0.
GRID    101             6.      -3.     0.
GRID    102             5.      -3.     0.
GRID    104             10.     -4.     0.
GRID    105             9.      -4.     0.
GRID    106             8.      -4.     0.
GRID    107             7.      -4.     0.
GRID    108             6.      -4.     0.
GRID    109             5.      -4.     0.
GRID*   111                             10.             -5.27577-8
*       1.
GRID*   112                             9.              -5.27577-8
*       1.
GRID*   113                             8.              -5.27577-8
*       1.
GRID*   114                             7.              -5.27577-8
*       1.
GRID*   115                             6.              -5.27577-8
*       1.
GRID*   116                             5.              -5.27577-8
*       1.
GRID    118             10.     -1.     1.
GRID    119             9.      -1.     1.
GRID    120             8.      -1.     1.
GRID    121             7.      -1.     1.
GRID    122             6.      -1.     1.
GRID    123             5.      -1.     1.
GRID    125             10.     -2.     1.
GRID    126             9.      -2.     1.
GRID    127             8.      -2.     1.
GRID    128             7.      -2.     1.
GRID    129             6.      -2.     1.
GRID    130             5.      -2.     1.
GRID    132             10.     -3.     1.
GRID    133             9.      -3.     1.
GRID    134             8.      -3.     1.
GRID    135             7.      -3.     1.
GRID    136             6.      -3.     1.
GRID    137             5.      -3.     1.
GRID    139             10.     -4.     1.
GRID    140             9.      -4.     1.
GRID    141             8.      -4.     1.
GRID    142             7.      -4.     1.
GRID    143             6.      -4.     1.
GRID    144             5.      -4.     1.
GRID*   146                             10.             -5.27577-8
*       2.
GRID*   147                             9.              -5.27577-8
*       2.
GRID*   148                             8.              -5.27577-8
*       2.
GRID*   149                             7.              -5.27577-8
*       2.
GRID*   150                             6.              -5.27577-8
*       2.
GRID*   151                             5.              -5.27577-8
*       2.
GRID    153             10.     -1.     2.
GRID    154             9.      -1.     2.
GRID    155             8.      -1.     2.
GRID    156             7.      -1.     2.
```

```
GRID    157           6.    -1.     2.
GRID    158           5.    -1.     2.
GRID    160           10.   -2.     2.
GRID    161           9.    -2.     2.
GRID    162           8.    -2.     2.
GRID    163           7.    -2.     2.
GRID    164           6.    -2.     2.
GRID    165           5.    -2.     2.
GRID    167           10.   -3.     2.
GRID    168           9.    -3.     2.
GRID    169           8.    -3.     2.
GRID    170           7.    -3.     2.
GRID    171           6.    -3.     2.
GRID    172           5.    -3.     2.
GRID    174           10.   -4.     2.
GRID    175           9.    -4.     2.
GRID    176           8.    -4.     2.
GRID    177           7.    -4.     2.
GRID    178           6.    -4.     2.
GRID    179           5.    -4.     2.
GRID*   181                         16.          -5.27577-8
*       0.
GRID*   182                         15.          -5.27577-8
*       0.
GRID*   183                         14.          -5.27577-8
*       0.
GRID*   184                         13.          -5.27577-8
*       0.
GRID*   185                         12.          -5.27577-8
*       0.
GRID*   186                         11.          -5.27577-8
*       0.
GRID    188           16.   -1.     0.
GRID    189           15.   -1.     0.
GRID    190           14.   -1.     0.
GRID    191           13.   -1.     0.
GRID    192           12.   -1.     0.
GRID    193           11.   -1.     0.
GRID    195           16.   -2.     0.
GRID    196           15.   -2.     0.
GRID    197           14.   -2.     0.
GRID    198           13.   -2.     0.
GRID    199           12.   -2.     0.
GRID    200           11.   -2.     0.
GRID    202           16.   -3.     0.
GRID    203           15.   -3.     0.
GRID    204           14.   -3.     0.
GRID    205           13.   -3.     0.
GRID    206           12.   -3.     0.
GRID    207           11.   -3.     0.
GRID    209           16.   -4.     0.
GRID    210           15.   -4.     0.
GRID    211           14.   -4.     0.
GRID    212           13.   -4.     0.
GRID    213           12.   -4.     0.
GRID    214           11.   -4.     0.
GRID*   216                         16.          -5.27577-8
*       1.
GRID*   217                         15.          -5.27577-8
*       1.
GRID*   218                         14.          -5.27577-8
*       1.
GRID*   219                         13.          -5.27577-8
*       1.
GRID*   220                         12.          -5.27577-8
*       1.
GRID*   221                         11.          -5.27577-8
*       1.
GRID    223           16.   -1.     1.
GRID    224           15.   -1.     1.
GRID    225           14.   -1.     1.
GRID    226           13.   -1.     1.
GRID    227           12.   -1.     1.
GRID    228           11.   -1.     1.
GRID    230           16.   -2.     1.
GRID    231           15.   -2.     1.
GRID    232           14.   -2.     1.
GRID    233           13.   -2.     1.
GRID    234           12.   -2.     1.
GRID    235           11.   -2.     1.
GRID    237           16.   -3.     1.
GRID    238           15.   -3.     1.
```

```
GRID    239             14.     -3.      1.
GRID    240             13.     -3.      1.
GRID    241             12.     -3.      1.
GRID    242             11.     -3.      1.
GRID    244             16.     -4.      1.
GRID    245             15.     -4.      1.
GRID    246             14.     -4.      1.
GRID    247             13.     -4.      1.
GRID    248             12.     -4.      1.
GRID    249             11.     -4.      1.
GRID*   251                              16.             -5.27577-8
*       2.
GRID*   252                              15.             -5.27577-8
*       2.
GRID*   253                              14.             -5.27577-8
*       2.
GRID*   254                              13.             -5.27577-8
*       2.
GRID*   255                              12.             -5.27577-8
*       2.
GRID*   256                              11.             -5.27577-8
*       2.
GRID    258             16.     -1.      2.
GRID    259             15.     -1.      2.
GRID    260             14.     -1.      2.
GRID    261             13.     -1.      2.
GRID    262             12.     -1.      2.
GRID    263             11.     -1.      2.
GRID    265             16.     -2.      2.
GRID    266             15.     -2.      2.
GRID    267             14.     -2.      2.
GRID    268             13.     -2.      2.
GRID    269             12.     -2.      2.
GRID    270             11.     -2.      2.
GRID    272             16.     -3.      2.
GRID    273             15.     -3.      2.
GRID    274             14.     -3.      2.
GRID    275             13.     -3.      2.
GRID    276             12.     -3.      2.
GRID    277             11.     -3.      2.
GRID    279             16.     -4.      2.
GRID    280             15.     -4.      2.
GRID    281             14.     -4.      2.
GRID    282             13.     -4.      2.
GRID    283             12.     -4.      2.
GRID    284             11.     -4.      2.
$
SPCADD  11       100     101
SPCADD  12       100     102
$
LOAD    21       1.      1.       200
LOAD    22       1.      1.       300     1.       400
LOAD    23       1.      1.       200     1.       300     1.       400
$
SPC1    100      123     8
SPC1    100      3       6
SPC1    101      1       1        THRU    7
SPC1    101      1       9        THRU    15
SPC1    102      123     1        THRU    7
SPC1    102      123     9        THRU    15
$
FORCE   200      181     0        31.25   -1.      0.      0.
FORCE   200      209     0        31.25   -1.      0.      0.
FORCE   200      251     0        31.25   -1.      0.      0.
FORCE   200      279     0        31.25   -1.      0.      0.
FORCE   200      188     0        62.50   -1.      0.      0.
FORCE   200      195     0        62.50   -1.      0.      0.
FORCE   200      202     0        62.50   -1.      0.      0.
FORCE   200      216     0        62.50   -1.      0.      0.
FORCE   200      244     0        62.50   -1.      0.      0.
FORCE   200      258     0        62.50   -1.      0.      0.
FORCE   200      265     0        62.50   -1.      0.      0.
FORCE   200      272     0        62.50   -1.      0.      0.
FORCE   200      223     0        125.0   -1.      0.      0.
FORCE   200      230     0        125.0   -1.      0.      0.
FORCE   200      237     0        125.0   -1.      0.      0.
FORCE       300      76       01.0     0.0     -2.5    0.0
FORCE       300     146       01.0     0.0     -2.5    0.0
FORCE       300     181       01.0     0.0     -2.5    0.0
FORCE       300     251       01.0     0.0     -2.5    0.0
FORCE       300     111       01.0     0.0     -5.0    0.0
FORCE       300     186       01.0     0.0     -5.0    0.0
```

```
FORCE        300     183       01.0     0.0     -5.0    0.0
FORCE        300     184       01.0     0.0     -5.0    0.0
FORCE        300     185       01.0     0.0     -5.0    0.0
FORCE        300     182       01.0     0.0     -5.0    0.0
FORCE        300     216       01.0     0.0     -5.0    0.0
FORCE        300     252       01.0     0.0     -5.0    0.0
FORCE        300     253       01.0     0.0     -5.0    0.0
FORCE        300     254       01.0     0.0     -5.0    0.0
FORCE        300     255       01.0     0.0     -5.0    0.0
FORCE        300     256       01.0     0.0     -5.0    0.0
FORCE        400     217       01.0     0.0     -10.0   0.0
FORCE        400     218       01.0     0.0     -10.0   0.0
FORCE        400     219       01.0     0.0     -10.0   0.0
FORCE        400     220       01.0     0.0     -10.0   0.0
FORCE        400     221       01.0     0.0     -10.0   0.0
$
ENDDATA
```

9 Appendix B – STEP Part21 Output File Full Listing

The following are links to the full STEP Part21 file contents for the 4 pilot models. This section will be updated as the STEP converters mature and required corrections are incorporated into this document. As such, the actual instance identifiers in these files may not match the ones used in the figures and tables within the body of this document.

9.1 ATS1m4.stp

```
<Link available at the CAE-IF>
```

9.2 ATS2m4.stp

```
<Link available at the CAE-IF>
```

9.3 ATS3m4.stp

```
<Link available at the CAE-IF>
```

9.4 ATS4m4.stp

```
<Link available at the CAE-IF>
```

END OF DOCUMENT