LAYERED COMPOSITE ANALYSIS CAPABILITY
FOR NASTRAN

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SUMMARY

Laminated composite material construction is gaining popularity within industry as an attractive alternative to metallic designs where high strength at reduced weights is of prime consideration. This has necessitated the development of an effective analysis capability for the static, dynamic and buckling analyses of structural components constructed of layered composites. Theoretical and user aspects of layered composite analysis and its incorporation into C.S.A.R. Corporation's proprietary version of the NASTRAN® program, CSA/NASTRAN®, are discussed. The availability of stress based and strain based failure criteria is described which aids the user in reviewing the voluminous output normally produced in such analyses. Simple strategies to obtain minimum weight designs of composite structures are discussed. Several example problems are presented to demonstrate the accuracy and user convenient features of the capability.

INTRODUCTION

As structural designers turn more often to high strength light weight composite materials to solve critical design problems, the internal loads and stress analysis tasks become more complex. The finite element models generated to describe composite laminates using existing NASTRAN capabilities either require a considerable number of membrane elements "stacked" on top of one another to represent the plies or require some form of lumping/delumping procedure when using a single element to represent the plies. Both methods of modeling are used to overcome the substantial amount of work involved in determining the material properties to be referenced by an element. Neither method is without its drawbacks. The "stacked" membrane model requires a considerable number of elements and neglects bending effects while the single element representation requires pre-processing functions to generate an appropriate set of element and material properties and also requires post-processing to obtain the individual ply stresses and strains. The

*CSA/NASTRAN is an advanced proprietary version of the NASTRAN® general purpose structural analysis program. NASTRAN is a registered trademark of NASA. CSA/NASTRAN is developed, maintained and marketed by the C.S.A.R. Corporation, Northridge, California.
method of composite material construction analysis discussed in this work and incorporated into CSA/NASTRAN employs the single element technique. The user describes the laminate by means of new PCOMP, PCOMP1, PCOMP2 and MAT8 bulk data cards.

The finite elements used to model the composite structure must be capable of representing coupling between the membrane and bending actions to handle the general case of unsymmetrical ply layups and/or element plane offset from the plane of the grid points. Since none of the existing NASTRAN combination membrane/bending plate elements consider coupling, some work on the finite elements available was also required to implement this new layered composite analysis capability. After some review of the current element formulations and implementations, a decision was made to incorporate new general purpose combined membrane/bending plate elements. The two new elements added to the CSA/NASTRAN library are the CQUAD4 and CTRIA3. The CQUAD4 is a 4-node bilinear isoparametric general quadrilateral element. It is capable of membrane/bending coupling, variable thickness over the element surface and considers the effects of transverse shear flexibility. The CTRIA3 is the 3-node triangular shaped companion to the CQUAD4 element.

User convenient features to scan the voluminous output normally produced in such analyses are provided. The evaluation of a "failure index" for each element based on the commonly used failure theories (maximum stress, maximum strain, Hill, Hoffman and Tsai-Wu) allows the user to review at a glance whether any laminate is stressed (or strained) beyond allowable limits. Some simple techniques to obtain minimum weight designs of layered composite structures are also discussed.

THEORETICAL DISCUSSION

Before discussing the theoretical details of the implementation of the layered composite analysis capability, the theory of the CQUAD4 and CTRIA3 elements is discussed briefly.

The CQUAD4 Element

The CQUAD4 element is a four-node bilinear isoparametric element capable of representing membrane, bending (with transverse shear effects) and membrane-bending coupling behavior. Geometric and kinematic data for the element are shown in figure 1.

Shape of the Element

Standard isoparametric theory is used to represent the shape of the element. A set of element parametric co-ordinates (ς,γ) have been selected which vary linearly between zero and one with the extreme values occurring on the sides of the quadrilateral. Lines of constant ς and lines of constant γ are indicated on figure 1.
Element Co-ordinate System

The x-axis is along the line connecting the first two grid points; the y-axis is perpendicular to the x-axis and lies in the "plane" of the element. If all four grid points do not lie in a plane, a mean plane is defined as discussed below. Finally, the z-axis is normal to the plane of the element and forms a right-handed coordinate system with the x- and y-axes.

Mean-Plane

If the four grid points of the CQUAD4 element do not lie in a plane, a mean-plane containing the projections of the four points is defined such that the four points are alternately H units above and H units below the mean-plane as shown in figure 2 and reference 1.

Membrane Behavior

An enhanced formulation of the four noded isoparametric quadrilateral membrane element available in the NASTRAN® program, the CQDMEM1 element, is used to represent the membrane behavior of the CQUAD4 element. The enhancement consists of using reduced integration to the in-plane shear representation (single point integration, at the center of the element, instead of 2x2 integration). All other details of the element formulation are the same as that discussed in reference 2.

If the element is non-planar, mean-plane transformations that produce only forces and not moments at grid points are used to expand the 8x8 stiffness matrix to 12x12 to allow for three displacements per grid point.

Bending Behavior

A simple, inexpensive to formulate and accurate bending behavior is a necessary prerequisite for plate elements that are to be used in a layered composite analysis. The four-node bilinear isoparametric element discussed by Hughes and Tezduyar (ref. 3) possesses these qualities and is therefore used to represent the bending behavior of the CQUAD4 element. Detailed derivation of the element stiffness, load vector calculations and the stress resultants are provided in reference 3; salient points from the derivations are discussed below.

The concept is to have the transverse displacement interpolated via nine-node Lagrange shape functions and the rotations via four-node bilinear shape functions. The transverse shear strains are calculated in a special way independent of the mid side and center node displacement degrees of freedom; hence four-node bilinear shape functions may be used for transverse displacement also. In other words, the use of special calculations for transverse shear strains allows the use of bilinear shape functions for transverse displacement, rotations and transverse shear strains together with the benefit to the element of quadratic accuracy with respect to Kirchoff modes.
The implementation of the element follows standard isoparametric theory. Interested readers may consult references 3 and 4 for additional details.

If the element is non-planar, mean plane transformations are derived to ensure that the element is in equilibrium when the stiffness matrix is transformed from grid points on the mean-plane to the actual grid point locations.

Membrane/Bending Coupling Effects

The membrane and bending actions are decoupled for plate theory. However, practical situations may necessitate use of CQUAD4 elements to model bending of plates about an axis offset from the geometrical neutral axis. Membrane-bending coupling effects have to be included to analyze such models; these effects also occur in unsymmetric laminates. The CQUAD4 element is therefore designed to include membrane-bending coupling behavior.

The CTRIA3 Element

The CTRIA3 element is a three-node linear element capable of representing membrane, bending (with transverse shear effects) and membrane-bending coupling behavior. The element and the element co-ordinate system are shown in figure 3. The membrane behavior is modeled using the TRMEM element formulation (reference 2), the bending and membrane-bending coupling behavior are modeled using a procedure analogous to that used for the CQUAD4. Being a linear element, the CTRIA3 element is not as accurate as the bilinear CQUAD4 element. It must, therefore, be mentioned in this context that the CQUAD4 element is to be used for all plate modeling requirements; the CTRIA3 element is to be used only where geometrical considerations preclude the use of the CQUAD4 element.

The PSHELL Bulk Data Card

The properties for both the CQUAD4 and the CTRIA3 elements are specified using the new PSHELL element property bulk data card. The PSHELL card data input format provides for specification of element thickness, moment of inertia parameter, transverse shear thickness parameter, stress recovery coefficients and material property references. Provisions are made for specifying up to four different material property identification numbers to separately represent membrane, bending, transverse shear and coupled membrane/bending behaviors.

Force-Displacement Relationship

The relationship between forces and strains used for the CQUAD4 and CTRIA3 elements is
\[
\begin{bmatrix}
F \\
M \\
Q
\end{bmatrix}
= \begin{bmatrix}
tG_1 & t^2G_4 & 0 \\
t^2G_4 & IG_2 & 0 \\
0 & 0 & t_sG_3
\end{bmatrix}
\begin{bmatrix}
\varepsilon_m - \varepsilon^T \\
\chi - \chi^T \\
\gamma
\end{bmatrix}
\]

where 
\[
\begin{aligned}
\{F\} &= \begin{bmatrix} F_x \\ F_y \\ F_{xy} \end{bmatrix}, \\
\{M\} &= \begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix}, \\
\{Q\} &= \begin{bmatrix} Q_x \\ Q_y \end{bmatrix}, \\
\{\varepsilon_m\} &= \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix}, \\
\{\chi\} &= \begin{bmatrix} \chi_x \\ \chi_y \\ \chi_{xy} \end{bmatrix}, \\
\{\gamma\} &= \begin{bmatrix} \gamma_x \\ \gamma_y \end{bmatrix},
\end{aligned}
\]

- membrane forces per unit length
- bending moments per unit length
- transverse shear force per unit length
- membrane strains in mean plane
- curvatures
- transverse shear strains
and

\[ G_1 \text{ is the 3x3 elasticity matrix for membrane action} \]
\[ G_2 \text{ is the 3x3 elasticity matrix for bending action} \]
\[ G_3 \text{ is the 2x2 elasticity matrix for transverse shear action} \]
\[ t \text{ is the element thickness} \]
\[ I \text{ is the element moment of inertia} \]
\[ t_s \text{ is the effective thickness for transverse shear} \]

**LAYERED COMPOSITE ANALYSIS**

Composite laminates have a number of laminae stacked at various orientations (see figure 4 and reference 5). Ideally, a full 3-dimensional analysis using anisotropic material properties is to be performed. However, lamination theory is a good starting point to perform 2-dimensional analysis that gives satisfactory results at a much reduced cost.

**Assumptions Used in Lamination Theory**

The following assumptions are used in lamination theory:

(i) Lamina is in a state of plane stress.

(ii) Perfect bonding exists between layers so that no slippage of one lamina relative to another occurs.

(iii) There is no z-variation of the transverse displacement; in other words, thin plate theory can be used.

All of the above assumptions are found to be reasonable in practice (especially in cases where the thickness of the laminate is small in comparison with the length and width).

For unidirectional composites, two orthogonal planes of symmetry exist. One plane is parallel to the fibers and the other is transverse to the fibers. Knowing the material properties in this system, the 3x3 elasticity matrix \([G_M]\) can be evaluated for each lamina. Knowing the orientation of each lamina, the elasticity matrix \([G_M]\) can be transformed to \([G_E]\) in a common element system. Knowing the elasticity matrix \([G_E]\) for all laminae in the common element coordinate system, the membrane, bending membrane-bending and transverse shear elasticity matrices for the laminate are calculated as follows:

\[
[G_i] = \frac{1}{t} \int [G_E] \, dz
\]
The \( [G_3] \) matrix is calculated by assuming that the equations of equilibrium similar to the simple beam theory can be developed independently for the X- and Y-directions. It is to be noted that this is an approximation and that the inter-laminar stresses evaluated by lamination theory are only approximate. However, it is felt that this approximate analysis is better than an analysis neglecting the effects of transverse shear matrix \([G_3]\).

**USER INPUT**

Composite laminate analysis requires input of laminate data and the orthotropic material property information. This is accomplished by designing the following new bulk data cards shown in the Appendix:

- **MAT8**: two-dimensional orthotropic material data
- **PCOMP, PCOMP1, PCOMP2**: Property cards for composites

User specifies the property identification number of a PCOMP (or PCOMP1 or PCOMP2) property card instead of PSHOW property card for the CQUAD4 and CTRIA3 elements for use as a layered composite element. PCOMP, PCOMP1 and PCOMP2 cards refer to the material properties of each lamina using MAT1, MAT2 or MAT8 cards.

**OUTPUT FROM LAYERED COMPOSITE ANALYSIS**

The stresses and strains output for each lamina for all the elements yield voluminous output. Some of these output items are shown in figure 5(a) and 5(b) (stresses and strains in each lamina). The concept of failure index for each laminate is introduced to review the output easily. Five commonly used failure theories are provided for this purpose. These are (i) maximum stress theory, (ii) maximum strain theory, (iii) Hill's theory, (iv) Hoffman's theory, and (v) Tsai-Wu theory. Based on the user specified failure theory, the state of stress (or strain) in each lamina is used to evaluate a failure index for the
lamina. The highest failure index value among all laminae of the laminate and
the interlaminar stress to allowable bonding stress ratio is defined as the
failure index of the laminate. By examining the failure index table, the results
of the analysis can be easily reviewed to see whether any lamina has failed
according to the specified criterion. A sample output of the failure index
table is shown in figure 5(c).

NASTRAN MODIFICATIONS

The design of the layered composite analysis capability that has been in-
corporated into CSM/NASTRAN was driven by two important requirements. The first
was that the capability has maximum versatility and convenience in describing
the composite laminate with a minimum of user action necessary. The second was that
modifications to existing NASTRAN functional capabilities be kept to a minimum.
To achieve the first requirement, seven new bulk data card types shown in the
Appendix, and a new functional module were designed and added to the program.
The second requirement was satisfied without considerable effort when the decision
was made to implement new finite element technology, rather than try and adapt
the existing membrane/bending plate elements to the layered composite environment.
This decision also reduced the risk of inadvertently disturbing some aspect of
the existing finite element implementations. Thus, the modifications made to the
NASTRAN program for the layered composite analysis capability can be divided into
two parts: (1) those required for the addition of the new general purpose QUAD4
and TRIA3 finite elements, and (2) those required for the specification and data
recovery of the composite laminate itself.

The incorporation of the new 4-node quadrilateral shaped plate and 3-node
triangular shaped plate finite elements into NASTRAN has been achieved with the
addition of only three new bulk data cards. These new cards are the finite
element connection cards, CQUAD4 and CTRIA3, and the element property card, PSHELL,
which is referenced by both elements. This new general purpose capability required
the following modifications to existing areas of the NASTRAN program for Statics
and Normal Modes solution sequences:

* Preface IFSIP and IFXSBD routines to process the CQUAD4, CTRIA3 and
  PSHELL bulk data cards

* GPTABD block data routine to add the internal descriptions of the new
  finite elements to the NASTRAN element library and establish various
  element-dependent pointer data

* TAI table processing module routines to process the material property
  orientation single definition options available on the CQUAD4 and CTRIA3
  element connection cards

* EMG module EMGPRO routine to call the new element matrix generation
  subroutines
SSGl module TEMPL routine to call the new element thermal load vector generation subroutines

SDR2 module routines to call the new element stress data recovery subroutines

OFP module routines to provide additional output file page headings for the CQUAD4 and CTRIA3 element forces and stresses

Modifications to the DSMGL module and RANDOM modules are presently underway to extend this capability to differential stiffness/buckling and the dynamics solution sequences.

The incorporation of the composite laminate specification capability has been achieved with the addition of only four new bulk data cards. These new cards are the MAT8 card which describes the material properties of ply layers, and the PCOMP, PCOMP1 and PCOMP2 cards which describe the laminate ply layup with varying degrees of generality and convenience. One new functional module was also required which performs composite element ply stress data recovery operations. A preface processor converts the supplied PCOMP and MAT8 data into equivalent PSHELL and MAT2 data, updates element connection data references to property data and adds the PSHELL data to the element property table (EFT) and the MAT2 data to the material property table (MPT). The preface then also sets a DMAP parameter to control data recovery operations based upon whether composite element properties are referenced. The layered composite analysis capability required the following modifications to the NASTRAN code:

Preface IFSIP and IFXIBD routines to process the PCOMP, PCOMP1, PCOMP2 and MAT8 bulk data cards

A new preface processor, IFP6, which generates equivalent PSHELL and MAT2 bulk data from the PCOMP and MAT8 data supplied; IFP6 also updates the GEOM2 data block to reflect the element references to the newly generated property data and adds the data to the EPT and MPT

XMPLDO routine to establish module properties for the new composite element stress data recovery processor, SDRCOMP

PREMAT/MAT material property processing routine to handle the MAT8 data

SDRCOMP, a new functional module added to generate individual ply stresses and strains for the layered composite elements and to generate a failure index table of ply data based upon several available failure theories

OFP module to process the new composite element Failure Index Table, ply stress data block and ply strain data block

The action required on the part of the user to access this new layered composite analysis capability is considered to be very minimal. The user must insert the
appropriate PCOMP and MAT8 data which describe the composite laminate into the
bulk data deck. Then if the user wishes to have ply data recovery operations
performed, a STRAIN= case control request must be present and the SDRCOMP and
OFP modules must be altered into the rigid format.

Once the initial capability verification testing process was satisfactorily
completed, modifications were made to the NASTRAN rigid format data base to
provide the necessary CHKPNT/RESTART functions associated with the addition of
the new bulk data cards. Quality assurance testing procedures were then completed
satisfactorily demonstrating the incorporation of the layered composite analysis
capability as a general purpose feature of CSA/NASTRAN.

CAPABILITY VERIFICATION TESTING

When any new capability is added to NASTRAN, a series of tests is performed
to ensure that the capability has been incorporated properly. These tests are
designed to ensure that the new capability performs according to design speci-
fications and that existing functions: capability has not been adversely
affected by the new features. The capability verification tests performed to
ensure satisfactory implementation of the layered composite analysis feature
were divided into two categories. The first series of tests were designed to
validate the proper installation of the new CQUAD4 and CTRIA3 finite elements.
They demonstrated the accuracy of the elements under various geometry, material
property and loading configurations. Several of the test cases were taken from
those proposed in reference 6. The remainder of the tests were designed to
demonstrate implementation correctness and not necessarily theoretical accuracy.
The test problems considered to be most important are now briefly described:

- Patch test - measures the ability of the element to represent constant
strain states of deformation. The model geometry and results are shown
in figure 6.

- Twisted beam - measures the effect of warping on the element. The model
geometry and results are shown in figure 7.

- Equilibrium tests - each column/row of the elemental stiffness matrix was
summed about some point (say, node one) of the element to ensure that the
matrix represented a set of forces that were in equilibrium. This test
was performed on several configurations which included non-rectangular
shapes and element warping. In all instances, the resulting summations
were computational zeroes. An additional set of tests were also run which
extracted the free-free mode shapes of the plate using unit masses at each
degree of freedom. This test resulted in extraction of six distinct rigid
body modes which further guarantees equilibrium of the stiffness matrix.

Several other elemental tests were performed to ensure that the elements performed
according to specifications. These tests are the same as those described in
reference 6 and the twisted ribbon problem described in reference 3. The results
from these tests are summarized in table 1.
In addition to the tests performed to validate the addition of new finite elements, a series of tests were also performed to validate the installation of the layered composite analysis capability into CSA/NASTRAN. Once again, many sample problems were run to demonstrate that the capability performed up to design specifications. These tests included exercising all of the various options available on the PCOMP, PCOMP1, and PCOMP2 bulk data cards. Two example problems were run to demonstrate the theoretical correctness of the implementation. These problems were taken from reference 7. The geometry for the first problem, a static analysis of a simply supported square plate subjected to sinusoidally varying pressure load, is presented in figure 8. The geometry for the second problem, a modal analysis of a simply supported cylinder, is presented in figure 9. The modal analysis was accomplished using the cyclic symmetry analysis capability within NASTRAN. The results of these example problems are presented in table 2.

EXAMPLE APPLICATION

To illustrate the application of the layered composite capability in CSA/NASTRAN for design of practical composite structures, the example of an optimum design aluminum rectangular plate (ref. 8, 9 and 10) is analyzed using 8-ply laminated composite made of graphite/epoxy (commercially identified by Type T 300/5208). The geometry, loading and finite element modeling is shown in figure 10(a) and 10(b). The material properties and allowable stresses used in the example are those specified in reference 5. Starting from the optimally designed aluminum plate thickness for the various element groupings, the thickness for the composite model is obtained in 2 or 3 iterations using the enhanced fully stressed design algorithm implemented in CSA/NASTRAN. The thickness for the layered composite plate and the aluminum plate are shown in figure 10(c). The mass for the composite model is 0.40275 kg (0.8879 lbs) versus the mass of 1.034 kg (2.28 lbs) reported in reference 8 and 1.0796 kg (2.38 lbs) reported in reference 9 and 0.9487 kg (2.0915 lbs) reported in reference 10. It is to be noted that it is possible to obtain other optimum designs for the layered composite model. The design shown in figure 10(c) is a feasible design (design that satisfies all specified constraints). The objective here was to find the weight savings possible between layered composite construction and aluminum on a practical example problem subjected to stress and displacement constraints. The capabilities provided in CSA/NASTRAN allows the engineers the option of reviewing such "optimum" designs to select the most economical designs for their needs.

WORK IN PROGRESS

Several additions and extensions to the layered composite analysis capability are currently underway. For versatility, two additional plate elements are being formulated and added to the CSA/NASTRAN finite element library. These elements are the 8-node isoparametric general quadrilateral element CQUAD8 and its 6-node triangular companion, the CTRIA6. Both elements will be able to reference com-
posite material properties. An option to model the composite elements for membrane behavior only (without any reference to ending, transverse shear or membrane-bending coupling) to facilitate modeling the upper and lower covers of a wingbox, for example, is now available. This option will be extended to include property optimization methods to consider the thickness or orientation of each individual ply as a design variable. The OPTPRI and OPTPR2 modules are being enhanced to incorporate evaluation of design sensitivity coefficients so that structural optimization using mathematical programming techniques can be performed in addition to fully stress design resizing.

CONCLUSION

The theoretical formulations of layered composite analysis capability for addition to the NASTRAN program are presented in this paper. The need to have simple, accurate plate elements for layered composite elements is discussed. The addition of two such elements, the CQUAD4 and TRIA3 elements, and the layered composite capability into the CSA/NASTRAN program, an enhanced proprietary version of the April 1984 release of NASTRAN, developed and maintained by C.S.A.R. Corporation, is described. Verification problems and example application problems to illustrate the useful features available to engineers to analyze and obtain optimum designs of layered composite structures are also presented.
REFERENCES


7. MSC/NASTRAN Application Manual. Section 2.12; Joseph, J., Editor; The MacNeal-Schwendler Corporation, Los Angeles, CA.


Table 1. Summary of Test Results for CSA/NASTRAN QUAD4 Plate Element.

<table>
<thead>
<tr>
<th>No.</th>
<th>Test</th>
<th>Element Loading</th>
<th>Element Shape*</th>
<th>Displacement</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Patch Test</td>
<td>X</td>
<td>Irregular</td>
<td>Figure 6</td>
<td>A</td>
</tr>
<tr>
<td>2.</td>
<td>Patch Test</td>
<td>X</td>
<td>Irregular</td>
<td>Figure 6</td>
<td>A</td>
</tr>
<tr>
<td>3a.</td>
<td>Straight Beam - Extension</td>
<td>X</td>
<td>Irregular</td>
<td>Figure 6</td>
<td>A</td>
</tr>
<tr>
<td>3b.</td>
<td>Straight Beam - Extension</td>
<td>X</td>
<td>Trapezoid</td>
<td>3.000-5</td>
<td>2.985-5</td>
</tr>
<tr>
<td>3c.</td>
<td>Straight Beam - Extension</td>
<td>X</td>
<td>Parallelogram</td>
<td>3.000-5</td>
<td>2.997-5</td>
</tr>
<tr>
<td>4.</td>
<td>Straight Beam - Bending</td>
<td>X</td>
<td>Rectangle</td>
<td>.10810</td>
<td>.097632</td>
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<td>4a.</td>
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<td>Trapezoid</td>
<td>.10810</td>
<td>.007668</td>
</tr>
<tr>
<td>5b.</td>
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<td>Parallelogram</td>
<td>.10810</td>
<td>.008734</td>
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<tr>
<td>6.</td>
<td>Straight Beam - Bending</td>
<td>X</td>
<td>Rectangle</td>
<td>.43210</td>
<td>.42389</td>
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<td>7a.</td>
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<td>Trapezoid</td>
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<td>.41611</td>
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<tr>
<td>7b.</td>
<td>Straight Beam - Bending</td>
<td>X</td>
<td>Parallelogram</td>
<td>.43210</td>
<td>.42216</td>
</tr>
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<td>8a.</td>
<td>Straight Beam - Twist</td>
<td>X</td>
<td>Rectangle</td>
<td>.32086</td>
<td>.30017</td>
</tr>
<tr>
<td>8b.</td>
<td>Straight Beam - Twist</td>
<td>X</td>
<td>Trapezoid</td>
<td>.32086</td>
<td>.03433</td>
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<tr>
<td>9.</td>
<td>Curved Beam</td>
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<td>Rectangle</td>
<td>.067346</td>
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<td>10.</td>
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<td>Rectangle</td>
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<td>11a.</td>
<td>Twisted Beam</td>
<td>X</td>
<td>Regular</td>
<td>.005424</td>
<td>.005373</td>
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<tr>
<td>11b.</td>
<td>Twisted Beam</td>
<td>X</td>
<td>Regular</td>
<td>.001754</td>
<td>.001721</td>
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<tr>
<td>12a.</td>
<td>Rect. Plate (ss-u,N=4,b/a=5)</td>
<td>X</td>
<td>Regular</td>
<td>12.9746</td>
<td>12.6976</td>
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<tr>
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<td>Rect. Plate (ss-c,N=4,b/a=5)</td>
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<td>Regular</td>
<td>16.9613</td>
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<td>Rect. Plate (cc-u,N=4,b/a=5)</td>
<td>X</td>
<td>Regular</td>
<td>2.5625</td>
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<td>12d.</td>
<td>Rect. Plate (cc-c,N=4,b/a=5)</td>
<td>X</td>
<td>Regular</td>
<td>7.2362</td>
<td>5.6828</td>
</tr>
<tr>
<td>13a.</td>
<td>Scordelis-Lo Roof (N=4)</td>
<td>X</td>
<td>Regular</td>
<td>.302446</td>
<td>.31623</td>
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<tr>
<td>13b.</td>
<td>Spherical Shell (N=8)</td>
<td>X</td>
<td>Regular</td>
<td>.094000</td>
<td>.09286</td>
</tr>
<tr>
<td>15a.</td>
<td>Thick-Walled Cylinder v=-.43</td>
<td>X</td>
<td>Regular</td>
<td>5.0399-3</td>
<td>4.2523-3</td>
</tr>
<tr>
<td>15b.</td>
<td>Thick-Walled Cylinder v=-.499</td>
<td>X</td>
<td>Regular</td>
<td>5.0602-3</td>
<td>1.803-3</td>
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<tr>
<td>15c.</td>
<td>Thick-Walled Cylinder v=-.4999</td>
<td>X</td>
<td>Regular</td>
<td>5.0623-3</td>
<td>2.6496E-4</td>
</tr>
<tr>
<td>16a.</td>
<td>Twisted Ribbon (Case A, L=10)</td>
<td>X</td>
<td>Regular</td>
<td>0.0291+</td>
<td>0.02774</td>
</tr>
<tr>
<td>16b.</td>
<td>Twisted Ribbon (Case B, L=10)</td>
<td>X</td>
<td>Regular</td>
<td>0.0291+</td>
<td>0.02774</td>
</tr>
</tbody>
</table>

*Regular means that element shape has not been intentionally distorted

Remarks: 1. Letter grades are used to indicate the following error percentages:
   A: Error < 2%; B: 2% < Error < 10%; C: 1% < Error < 20%
   D: 20% < Error < 50%; E: Error > 50%
2. Letter grades shown for problem set numbers 3, 5, 7, 8, 11, 12 and 15 have been assigned by averaging the absolute error for each problem in the set.
TABLE 2. Composite Element Accuracy Test Results

SQUARE PLATE - Statics

Center point deflection of a simply supported square plate due to a sinusoidally varying pressure load

<table>
<thead>
<tr>
<th>Number of Plies</th>
<th>Type of Laminate</th>
<th>Center Point Deflection</th>
<th>Theory</th>
<th>NASTRAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Unsymmetric</td>
<td>0.010029</td>
<td>0.010056</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Symmetric</td>
<td>0.00035347</td>
<td>0.00036245</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Unsymmetric</td>
<td>0.00042175</td>
<td>0.00042622</td>
<td></td>
</tr>
</tbody>
</table>

CYLINDER - Cyclic Symmetry Normal Modes

<table>
<thead>
<tr>
<th>Harmonic Number</th>
<th>Longitudinal Halfwave</th>
<th>FREQUENCY (rad/sec)</th>
<th>Theory</th>
<th>NASTRAN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>18.608</td>
<td>18.576</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>46.605</td>
<td>46.426</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>61.435</td>
<td>60.810</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>9.391</td>
<td>9.377</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>27.219</td>
<td>27.143</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>41.842</td>
<td>41.535</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>6.274</td>
<td>6.230</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>18.895</td>
<td>18.864</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>30.804</td>
<td>30.644</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>4.934</td>
<td>4.893</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>14.578</td>
<td>14.568</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>24.494</td>
<td>24.404</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Geometric and Kinematic Data for CQUAD4 Element
Figure 2. Warped QUAD4 1-2-3-4 in local coordinates xyz.
Figure 3. Geometric and Kinematic Data for CTRIA3 Element
Figure 4. Laminae Identification for $n$-ply Laminate
Figure 5(a): Stress Output for Layered Composite Elements;
<table>
<thead>
<tr>
<th>ELEMENT ID</th>
<th>PLY ID</th>
<th>STRAINS IN FIBRE AND MATRIX DIRECTIONS</th>
<th>PRINCIPAL STRAINS (ZERO SHEAR)</th>
<th>MAX SHEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NORMAL-1</td>
<td>NORMAL-2</td>
<td>ANGLE</td>
</tr>
<tr>
<td>102</td>
<td>7</td>
<td>7.95663E-05</td>
<td>1.301823E-04</td>
<td>3.329711E-01</td>
</tr>
</tbody>
</table>

Figure 5(b): Strain Output for Layered Composite Elements
<table>
<thead>
<tr>
<th>ELEMENT ID</th>
<th>FAILURE ID</th>
<th>THEOREM</th>
<th>PLY ID</th>
<th>FP (FAILURE INDEX FOR PLY)</th>
<th>FB (FAILURE INDEX FOR BONDING)</th>
<th>FAILURE INDEX FOR ELEMENT</th>
<th>FLAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>0.0013</td>
<td>0.0014</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.0025</td>
<td>0.0021</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2</td>
<td>0.0013</td>
<td>0.0031</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>2</td>
<td>0.0002</td>
<td>0.0041</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>2</td>
<td>0.0002</td>
<td>0.0031</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>2</td>
<td>0.0021</td>
<td>0.0021</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>2</td>
<td>0.0064</td>
<td>0.0014</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>2</td>
<td>0.0193</td>
<td>0.0193</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5(c): Failure Index Table for Layered Composite Elements
Membrane Boundary Conditions:
\[ U = (x + \frac{1}{2}y) \times 10^{-3} \quad V = (\frac{1}{2}x + y) \times 10^{-3} \]

Bending Boundary Conditions:
\[ W = \frac{1}{2}(x^2 + xy + y^2) \times 10^{-3} \]
\[ \Theta_x = \frac{2W}{x} = (\frac{1}{2}x + y) \times 10^{-3} \quad \Theta_y = \frac{2W}{y} = (x + \frac{1}{2}y) \times 10^{-3} \]

Test Results:

<table>
<thead>
<tr>
<th>Element Output Quantity</th>
<th>Theory</th>
<th>NASTRAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-Plane Strains ( \varepsilon_x, \varepsilon_y, \gamma )</td>
<td>( 1.0 \times 10^{-3} )</td>
<td>( 1.0 \times 10^{-3} )</td>
</tr>
<tr>
<td>Stresses ( \sigma_x, \sigma_y )</td>
<td>1333</td>
<td>1333</td>
</tr>
<tr>
<td>Shear Stress ( \tau_{xy} )</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Bending Moment per unit length ( M_x = M_y )</td>
<td>( 1.111 \times 10^{-7} )</td>
<td>( 1.111 \times 10^{-7} )</td>
</tr>
<tr>
<td>Bending Moment per unit length ( M_{xy} )</td>
<td>( 0.333 \times 10^{-7} )</td>
<td>( 0.333 \times 10^{-7} )</td>
</tr>
<tr>
<td>Surface Stresses ( \sigma_x, \sigma_y )</td>
<td>( \pm 0.647 )</td>
<td>( \pm 0.647 )</td>
</tr>
<tr>
<td>Surface Shear Stress ( \tau_{xy} )</td>
<td>( \pm 0.200 )</td>
<td>( \pm 0.200 )</td>
</tr>
</tbody>
</table>

Figure G. Element Patch Test Results - CQUAD4
Length = 12.0 m
Width = 1.1 m
Depth = 0.32 m
Twist = 90° (root to tip)
$E = 29.0 \times 10^6 \text{ N/m}^2 \quad \nu = 0.22$

Applied Loads: Unit forces at tip

<table>
<thead>
<tr>
<th>Tip Direction Load</th>
<th>Displacements in Loaded Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoretical</td>
</tr>
<tr>
<td>In-plane Shear</td>
<td>0.005424</td>
</tr>
<tr>
<td>Out-of-plane Shear</td>
<td>0.001754</td>
</tr>
</tbody>
</table>

Figure 7. CQUAD4 Twisted Beam Test Results
Simply Supported Composite Square Plate Subjected to Sinusoidally Varying Pressure Loading of the form

\[ p(x, y) = \frac{1}{2} \sin \left( \frac{\pi x}{L} \right) \sin \left( \frac{\pi y}{L} \right) \]

Finite Element Model

3x3 ¼ Symmetric QUAD4 Mesh

- \( E_1 = 20 \times 10^6 \)
- \( E_2 = 5 \times 10^6 \)
- \( G_{12} = 2.5 \times 10^6 \)
- \( \nu_1 = 0.25 \)
- \( \nu_2 = 0.00425 \)
- \( t = 0.2 \)

Figure 8. Simply Supported Composite Plate Example
• 20 QUAD4 Elements
  Bending, Membrane and Transverse Shear Effects

• Boundary Conditions
  Edge ab:
  \( U_\theta = 0 \)
  \( \Theta_r = \Theta_\theta = 0 \)

  Edge cd: Simply Supported
  \( u_r = u_\theta = 0 \)
  \( \Theta_\theta = 0 \)

• Wall thickness = 0.5
• 72 Segments

Figure 7. Simply Supported Composite Cylinder Example
Composite laminate details:

8-ply Graphite/Epoxy (T 300/5208)
(0/+45/-45/90) Symmetric

Constraints:

Element Stress: Hill's Criteria

Displacements: ± 0.02 at center and corners of plate

(Number denote element IDs. Numbers in circles denote element groups by design variable linking.)

(a) Rectangular Plate: Loading and Supports.

(b) Finite Element Model.

Figure 10. Rectangular Plate for Optimum Design
(Values denote total thickness of 8-ply graphite/epoxy laminate (mass = 0.8879 lbs). Values in parentheses denote thickness for aluminum (mass = 2.0135 lbs.).)

(c) Plate Thickness for Optimum Design.

Figure 16. Rectangular Plate for Optimum Design with Stress and Displacement Constraints. (Cont.)
APPENDIX

CSA/NASTRAN Bulk Data Card Descriptions
CSA/NASTRAN BULK DATA DECK

Input Data Card  CQUAD4  Quadrilateral Element Connection

Description: Defines a quadrilateral plate element (QUAD4) of the structural model. This is an
isoparametric membrane-bending element.

Format and Example:

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>CQUAD4</td>
<td>EID</td>
<td>PID</td>
<td>G1</td>
<td>G2</td>
<td>G3</td>
<td>G4</td>
<td>θ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CQUAD4</td>
<td>1213</td>
<td>745</td>
<td>92</td>
<td>103</td>
<td>76</td>
<td>1001</td>
<td>32.4</td>
<td>C04</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T1</td>
<td>T2</td>
<td>T3</td>
<td>T4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>.78</td>
<td>.63</td>
<td>.60</td>
<td>.70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Field   Contents

EID   Element identification number (unique integer > 0)

PID   Identification number of a PSHELL or PCOMP property card (Integer > 0 or blank, default is EID)

G1,G2,G3,G4 Grid point identification numbers of connection points (Integers > 0, all unique)

θ   Material property orientation specification (Real or blank; or 0 < Integer < 1,000,000). If Real or blank, specifies the material property orientation angle in degrees. If Integer, the orientation of the material x-axis is along the projection onto the plane of the element of the x-axis of the coordinate system specified by the integer value. The sketch below gives the sign convention for θ.

T1,T2,T3,T4 Membrane thickness of element at grid points G1 through G4. (Real > 0, or blank, not all zero. See Remark 4 for default.)

![Sketch of quadrilateral element](image-url)
Remarks:

1. Element identification numbers must be unique with respect to all other element identification numbers.

2. Grid points G1 through G4 must be ordered consecutively around the perimeter of the element.

3. All the interior angles must be less than 180°.

4. The continuation card is optional. If it is not supplied, then T1 through T4 will be set equal to the value of T on the PSHELL data card.

5. Stresses are output in the element coordinate system.
CSA/NASTRAN BULK DATA DECK

Input Data Card   TRIA3 Triangular Element Connection

Description: Defines a triangular plate element (TRIA3) of the structural model. This is an isoparametric membrane-bending element.

Format and Example:

<table>
<thead>
<tr>
<th>Field</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>EID</td>
<td>Element identification number (Unique Integer &gt; 0)</td>
</tr>
<tr>
<td>PID</td>
<td>Identification number of a PSHELL property card (Integer &gt; 0 or blank, default is EID)</td>
</tr>
<tr>
<td>G1, G2, G3</td>
<td>Grid point identification numbers of connection points (Integers &gt; 0, all unique)</td>
</tr>
<tr>
<td>( \theta )</td>
<td>Material property orientation specification (Real or blank; or 0 &lt; Integer &lt; 1,000,000). If Real or blank, specifies the material property orientation angle in degrees. If Integer, the orientation of the material x-axis is along the projection on to the plane of the element of the x-axis of the coordinate system specified by the integer value. The sketch below gives the sign convention for ( \theta ).</td>
</tr>
<tr>
<td>T1, T2, T3</td>
<td>Membrane thickness of element at grid points G1, G2, and G3 (Real &gt; 0, or blank, not all zero. See Remark 2 for default.)</td>
</tr>
</tbody>
</table>

![Sketch showing the sign convention for \( \theta \)]

(Continued)
Remarks: 1. Element identification numbers must be unique with respect to all other element identification numbers.

2. The continuation card is optional. If it is not supplied, then T1 through T3 will be set equal to the value of T on the PSHELL data card.
CSA/NASTRAN BULK DATA DECK

Input Data Card  MAT8  Material Property Definition, Form 8

Description: Defines the material property for an orthotropic material

Format and Example:

<table>
<thead>
<tr>
<th>Field</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>MID</td>
<td>Material ID (1,000,000 &gt; Integer &gt; 0)</td>
</tr>
<tr>
<td>E1</td>
<td>Modulus of elasticity in longitudinal direction (also defined as fibre direction or 1-direction) (Real ≠ 0.0)</td>
</tr>
<tr>
<td>E2</td>
<td>Modulus of elasticity in transverse direction (also defined as matrix direction or 2-direction) (Real ≠ 0.0)</td>
</tr>
<tr>
<td>μ12</td>
<td>Poisson's ratio (e2/e1 for uniaxial loading in 1-direction). Note that μ12 * E1/E2 is uniaxial loading in 2-direction is related to μ12, E1, E2 by the relation μ12 = E1E2 / μ12.</td>
</tr>
<tr>
<td>G12</td>
<td>Inplane shear modulus (Real &gt; 0.0)</td>
</tr>
<tr>
<td>G12</td>
<td>Transverse shear modulus for shear in 1-Z plane (Real &gt; 0.0 or blank)</td>
</tr>
<tr>
<td>G22</td>
<td>Transverse shear modulus for shear in 2-Z plane (Real &gt; 0.0 or blank)</td>
</tr>
<tr>
<td>RHO</td>
<td>Mass density (Real)</td>
</tr>
<tr>
<td>A1</td>
<td>Thermal expansion coefficient in 1-direction (Real)</td>
</tr>
<tr>
<td>A2</td>
<td>Thermal expansion coefficient in 2-direction (Real)</td>
</tr>
</tbody>
</table>

(Continued)
CSA/NASTRAN BULK DATA DECK

MAT8 (Continued)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TREF</td>
<td>Thermal expansion reference temperature (Real)</td>
</tr>
<tr>
<td>X_T, X_C</td>
<td>Allowable stresses in tension and compression, respectively, in the longitudinal direction. Required if failure index is desired. (Real &gt; 0.0)</td>
</tr>
<tr>
<td>Y_T, Y_C</td>
<td>Allowable stresses in tension and compression, respectively, in the transverse direction. Required if failure index is desired. (Real &gt; 0.0)</td>
</tr>
<tr>
<td>S</td>
<td>Allowable stress for in-plane shear (Real &gt; 0.0)</td>
</tr>
<tr>
<td>G_E</td>
<td>Structural damping coefficient (Real)</td>
</tr>
<tr>
<td>F_{12}</td>
<td>Interaction term in the tensor polynomial theory of Tsai-Wu (Real). Required if failure index by Tsai-Wu theory is desired and if value of F_{12} is different from 0.0.</td>
</tr>
</tbody>
</table>

Remarks: 1. If G_{1,2} and G_{2,2} values are not supplied, the in-plane shear modulus will be used.
**CSA/NiSTRAH BULK DATA DECK**

**Input Data Card PCOMP** Layered Composite Element Property

**Description:** Defines the properties of an n-ply composite material laminate

**Format and Example:**

<table>
<thead>
<tr>
<th>Field</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID</td>
<td>Property ID (1,000,000 &gt; Integer &gt; 0)</td>
</tr>
<tr>
<td>Z_0</td>
<td>Distance from the reference plane to the bottom surface (Real) (Default = (-1/2) the thickness of the element)</td>
</tr>
<tr>
<td>NSM</td>
<td>Non-structural mass per unit area (Real)</td>
</tr>
<tr>
<td>S_d</td>
<td>Allowable shear stress of the bonding material (allowable inter-laminar shear stress). Required if failure index is desired. (Real &gt; 0.0)</td>
</tr>
<tr>
<td>F.T.</td>
<td>Failure theory to be used to test whether the element fails or not (BCD). The following theories are presently allowed:</td>
</tr>
<tr>
<td></td>
<td>HILL for the Hill theory</td>
</tr>
<tr>
<td></td>
<td>HOFF for the Hoffman theory</td>
</tr>
<tr>
<td></td>
<td>TSAI for the Tsai-Wu theory</td>
</tr>
<tr>
<td></td>
<td>STRESS for maximum stress theory</td>
</tr>
<tr>
<td></td>
<td>STRAIN for maximum strain theory</td>
</tr>
<tr>
<td>TREF</td>
<td>Reference temperature (Real)</td>
</tr>
<tr>
<td>GE</td>
<td>Damping coefficient (Real)</td>
</tr>
</tbody>
</table>

(Continued)
CSA/NASTRAN BULK DATA DECK

PCOMP (Continued)

OPT

Lamination generation option codes (integer > 0)

Code        Description
0           all plies are specified
1           ply layup specified is symmetrical; only the plies on one side of the
            cr .line are specified
2           a "stack" of membrane-only elements will be generated for each element
            that references this PCOMP card.

Options may be combined by adding the specific code values

MID1

Material ID of the various plies. MID1 > 0, MID2.....MIDn > 0, or blank. The
plies are identified by serially numbering them from 1 at the bottom layer. The
MIDs must refer to MAT1, MAT2, or MAT8 bulk data cards. (Integer > 0)

T1

Thicknesses of the various plies (Real; T1 > 0.0, T2, T3,...> 0.0 or blank)

Theta

Orientation angle of the longitudinal direction of each ply with the material
axis of the element. (If the material angle on the element connection card is
0.0, the material axis and side 1-2 of the element coincide). The plies are to
be numbered serially starting with 1 at the bottom layer (the bottom layer is
defined as the surface with the largest -Z value in the element coordinate
system). (Real)

SOUT1

Stress output required (YES) or not (NO) for the various plies (BCD) (Default = NO)

Remarks:

1. The default under MID2, MID3, ...., is the last defined Mat card, in this case MID1;
   so for T2, T3, ...., all these thicknesses will be equal to T1.

2. At least one of the four values (MID1, T1, Theta, SOUT1) must be present for a ply
to exist.

3. TREF given on the PCOMP card will be used for all plies of the element; it will
   override values supplied on material cards for individual plies.

4. CE given on the PCOMP card will be used for the element; it will override values
   supplied on material cards for individual plies.
CSA/NASTRAN 3DULK DATA DECK

Input Data Card   PCOMP1  Layered Composite Element Property - Alternate Form 1

Description: Defines the properties of an n-ply composite material laminate, all plies being of equal thickness.

Format and Example:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCOMP</td>
<td>PID</td>
<td>Z₀</td>
<td>MSM</td>
<td>S₀</td>
<td>F.T.</td>
<td>MID</td>
<td>T</td>
<td>OPT</td>
<td>+ABC</td>
<td></td>
</tr>
<tr>
<td>PCOMP</td>
<td>891</td>
<td>-1.0</td>
<td>18.7</td>
<td>4.5</td>
<td>STRAIN</td>
<td>10</td>
<td>0.25</td>
<td></td>
<td></td>
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</table>

<table>
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<th>Θ₂</th>
<th>Θ₃</th>
<th>Θ₄</th>
<th>Θ₅</th>
<th>Θ₆</th>
<th>Θ₇</th>
<th>Θ₈</th>
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<tbody>
<tr>
<td>+ABC</td>
<td>0.0</td>
<td>+45.</td>
<td>-45.</td>
<td>+90.</td>
<td>-90.</td>
<td>-45.</td>
<td>+45.</td>
<td>0.0</td>
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</tbody>
</table>

Field                      Contents
PID                        Property ID (1,000,000 > Integer > 0)
Z₀                         Distance from the reference plane to the bottom surface (Real) (Default = -1/2 the thickness of the element)
MSM                       Non-structural mass per unit area (Real)
S₀                         Allowable shear stress of the bonding material (allowable inter-laminar shear stress). Required if failure index is desired. (Real > 0.0)
F.T.                       Failure theory to be used to test whether the element fails or not (BCD). The following theories are presently allowed:
                           HILL for the Hill theory
                           HOFF for the Hoffman theory
                           TSAI for the Tsai-Hu theory
                           STRESS for maximum stress theory
                           STRAIN for maximum strain theory
MID                        Material ID of each ply. The plies are identified by serially numbering them from 1 at the bottom layer. The MID must refer to MAT1, MAT2, or MAT8 bulk data cards. (Integer > 0)
T                          Thickness of each ply. All plies have the same thickness. (Real > 0.0)

(Continued)
CSA/NASTRAN BULK DATA DECK

PCOMP1 (Continued)

OPT

Lamination generation option codes (Integer ≥ 0)

Code
0 all plies are specified
1 ply layup specified is symmetrical; only the plies on one side of the centerline are specified.
2 a "stack" of membrane only elements will be generated for each element that references this PCOMP card

Options may be combined by adding the specific code values

θ_i

Orientation angle of the longitudinal direction of each ply with the material axis of the element. (If the material angle on the element connection card is 0.0, the material axis and side 1-2 of the element coincide). The plies are to be numbered serially starting with 1 at the bottom layer (the bottom layer is defined as the surface with the largest z value in the element coordinate system). (Real)

Remarks:
1. Stress and strain output will be generated for all plies if a case control STRESS request is present. See the PCOMP card description for a method of reducing the amount of output generated.
CSA/NASTRAN BULK DATA DECK

Input Data Card PCOMP2 Layered Composite Element Property - Alternate Form 2

Description: Defines the properties of an n-ply composite material laminate

Format and Example:

<p>| | | | | | | | | | |</p>
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</tr>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T1  θ1  T2  θ2  T3  θ3  T4  θ4</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ABC  .25  0.0  .25  45.0  -45.0  +90.0  +DEF</td>
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</tr>
<tr>
<td></td>
<td>T5  θ5  T6  θ6  T7  θ7  T8  θ8</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>+DEF  +90.0  -45.0  45.0  0.0</td>
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</tbody>
</table>

Field     Contents
PID     Property ID (1,000,000 > Integer > 0)
Z0     Distance from the reference plane to the bottom surface (Real) (Default = -1/2 the thickness of the element)
NSM     Non-structural mass per unit area (Real)
S0     Allowable shear stress of the bonding material (allowable inter-laminar shear stress). Required if failure index is desired. (Real > 0.0)
F.T.     Failure theory to be used to test whether the element fails or not (BCD). The following theories are presently allowed:
          HILL for the Hill theory
          HOFF for the Hoffman theory
          TSAL for the Tsai-Wu theory
          STRESS for maximum stress theory
          STRAIN for maximum strain theory
MID     Material ID of the various plies. The plies are identified by serially numbering them from 1 at the bottom layer. The MID must refer to MAT1, MAT2, or MAT8 bulk data cards. (Integer > 0)

(Continued)
CSA/NASTRAN BULK DATA DECK

PCOMP2 (Continued)

OPT

Lamination generation option codes (Integer > 0)

Code

0     All plies are specified
1     Ply layup specified is symmetrical; only the plies on one side of the centerline are specified
2     A "stack" of membrane only elements will be generated for each element that references this PCOMP card

Options may be combined by adding the specific code values

Ti

Thickness of the various plies (Real; T1 > 0.0, T2, T3,... > 0 or blank)

θi

Orientation angle of the longitudinal direction of each ply with the material axis of the element. (If the material angle on the element connection card is 0.0, the material axis and side 1-2 of the element coincide). The plies are to be numbered serially starting with 1 at the bottom layer (the bottom layer is defined as the surface with the largest -Z value in the element coordinate system). (Real)

Remarks:

1. At least one of the two values, (Ti, θi) must be present for a ply to exist.
2. Stress and strain output will be generated for all plies if a care control STRESS request is present. See the PCOMP card description for a method of reducing the amount of stress output generated.
CSA/NASTRAN BULK DATA DECK

Input Data Card  PSHELL  Shell Element Property

Description: Defines the membrane, bending, transverse shear, and coupling properties of thin shell elements.

Format and Example:

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
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</thead>
<tbody>
<tr>
<td>PSHELL</td>
<td>PID</td>
<td>MID1</td>
<td>T</td>
<td>MID2</td>
<td>MID3</td>
<td>TS/T</td>
<td>NSM</td>
<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

Field  | Contents
--- | ---
PID  | Property identification number (Integer ≥ 0)
MID1  | Material identification number for the membrane (Integer ≥ 0 or blank)
T  | Default value for the membrane thickness (Real)
MID2  | Material identification number for bending (Integer ≥ 0 or blank)
121/T³  | Bending stiffness parameter (Real or blank, default = 1.0)
MID3  | Material identification number for transverse shear (Integer ≥ 0 or blank), must be blank unless MID2 > 0, default = MID2.
TS/T  | Transverse shear thickness divided by the membrane thickness (Real or blank, default = .833333)
NSM  | Nonstructural mass per unit area (Real)
Z1, Z2  | Fiber distances for stress computation. The positive direction is determined by the righthand rule and the order in which the grid points are listed on the connection card. (Real or blank, see Remark 11 for defaults).
MID4  | Material identification number for membrane-bending coupling (Integer ≥ 0 or blank, must be blank unless MID1 > 0 and MID2 > 0, may not equal MID1 or MID2).

Remarks:

1. All PSHELL property cards must have unique identification numbers.
2. The structural mass is computed from the density using the membrane thickness and membrane material properties.

(Continued)
The results of leaving an MID field blank are:

- **MID1**: No membrane or coupling stiffness
- **MID2**: No bending, coupling, or transverse shear stiffness
- **MID3**: MID2 will be used as default for MID3
- **MID4**: No bending-membrane coupling

4. The continuation card is not required.

5. The structural damping (for dynamics rigid formats) uses the values defined for the MID1 material.

6. The MID4 field should be left blank if the material properties are symmetric with respect to the middle surface of the shell. If the element centerline is offset from the plane of the grid points, the MID4 field may be used for modeling the offset but it involves laborious calculations that produce physically unrealistic stiffness matrices ("negative terms on factor diagonal") if done incorrectly.

7. This card is used in connection with the CTRIA3 and CQUAD4 cards.

8. For structural problems, PSHELL cards may reference MAT1, MAT2 or MAT8 material property cards.

9. If the transverse shear material, MID3, references a MAT2 data card, the G1, G12 and G22 values will be used to obtain the symmetric 2x2 \([G3]\) matrix for the element.

10. For heat transfer problems, PSHELL cards may reference MAT4 or MAT5 material property cards.

11. The default for Z1 is \(-T/2\), and for Z2 is \(+T/2\), where \(T\) is the local plate thickness.