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User's Guide for the Computer Program COPANO version 2.4

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The Computer Program COPANO

The acronym COPANO stands for COrrugated Panel ANalysis & Optimization. The program is developed for the design of corrugated panels of composite or conventional material under in-plane loads (shear load in particular). This user’s guide explains the features of the program, gives instructions for use and provides an example of the required input and resulting output.
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1 INTRODUCTION

The interactive computer program COPANO is one of the recent results of research into the design of structural corrugated panels for aerospace applications. The panels are in general made of composite material, but isotropic material can be used as well. COPANO is intended to be used in the preliminary design, when only the loading and general requirements on the structure are given while the actual form and layup have yet to be defined. It combines elements of the analysis of such panels with an optimization routine to define an optimum design. (By varying the corrugation shape and the layup - orientation and thickness of the layers - COPANO looks for a panel of least mass.) The optimization method to guide the user towards panels with low mass is an essential feature, because the design of composite panels can involve a large number of design variables.

This document explains briefly the elements of the program and helps the user prepare the necessary input, and interpret its results. Next to this user’s manual the PhD thesis of the author can be seen as the theoretical manual of the program, explaining and justifying the various formulae involved. Note that in this thesis the background of a similar program SAPANO, for sandwich panels, is covered as well. Together, COPANO and SAPANO form a set of programs for the design of a complete structural wing box, using the sandwich panel as top and bottom cover and using the corrugated panel as the web of the front and rear spar. The different sections of this manual present in increasing detail the possibilities of the program and the way data are organized; first, in section 2 the features of the program COPANO are described. Section 3 introduces the user interface and in section 4 an example is presented in detail. Section 5 illustrates the available extra output at the end of the program and finally section 6 describes the composition of the material data file.

2 PROGRAM DESCRIPTION

COPANO is an interactive design tool to analyse and optimize corrugated panels that have flat faces (the term face is used to denote separate flat surfaces of the panel), as drawn in Figure 1. The corrugated panel is modeled as a long rectangular panel, with the height h as the only relevant overall dimension. It is simply-supported on all four sides. The corrugated cross-section is defined by the widths $b_1$ and $b_2$ of the faces, and

![Diagram of corrugated panel]

Figure 1 Example of a corrugated panel (other materials and loads can also be used)
by the angle $\beta$ between them. Both faces are made of the same laminate of up to 20
different layers; each layer is of one (user-defined) material and has a thickness and
orientation with respect to the panel axes. Here the term laminate is used, even though
it is of course possible to use only one layer of isotropic material. The user defines the
number of different layers in the panel and assigns a material to each of them. The
shape of the corrugation and the orientation and thickness of every layer are then the
variables that can be used in the optimization in order to find the panel of least mass.
Of course, the user can also interactively define different panels to assess the influence
of some parameters, in this way performing an optimization 'by hand'. If the panel is
symmetric, only half of the laminate, up to the mid-plane, has to be specified. The
thickness of every layer is given a discrete value that is a multiple of the physical ply
thickness of the material of which the layer is made. This physical ply thickness is part
of the data of the material. The fibre orientation is also discrete because in the
manufacturing process the orientation can be defined only up to limited precision.
Further data for one case are the panel dimensions and the (up to 10) load
combinations, each of which can have non-zero direct loads $N_x$, $N_y$ and shear load
$N_{xy}$. Only in-plane loads are considered.

The idea behind a corrugated panel is to fold a plate in order to obtain a higher out-of-
plane stiffness. A secondary effect of this is to introduce a warping restraint which also
increases its stiffness against overall deformations. Corrugated panels are suitable to
resist compressive forces parallel to the folds and shear loads. The buckling analysis of
corrugated panels is a complex matter, because instability can occur not only for the
panel as a whole (in an overall mode), but also in the separate faces (in a local mode).
Furthermore, mode interaction between local and overall buckling under shear load is
possible as well. All of these are covered in COPANO.

Once the case is suitably defined by the appropriate data, an analysis can be performed.
The user can specify which aspects are to be examined, for example whether or not a
strain analysis is to be included. Every analysis begins with a calculation of the
laminate; with classical laminate theory the so-called $ABD$-matrix (with extension,
shear, bending and twisting stiffnesses) is calculated, assuming Kirchhoff-Love type
deformation. If the panel is not symmetric, reduced bending stiffnesses $D^{**}$ are
considered, also on the basis of cylindrical bending. Also, the transverse shear stiffnesses
$S_{xz}$ and $S_{yz}$ are calculated. Various mechanical analyses are then performed (if
specified by the user):

* for static failure, the (modified) Tsai-Hill stress criterion is adopted (this analysis
  is always performed);
* impact damage is covered on the basis of a fibre strain criterion (the extensional
  strain in the main (fibre) direction of a layer is checked against a maximum
  allowable value for that material, given in the material data file);
* instability is covered amply in COPANO, as mentioned higher; for compressive
  loads parallel to the folds of the corrugation, buckling loads are calculated in an
  overall and a local mode:
  - the overall mode considers the panel as a wide column buckling in an
    'Euler' mode;
  - the local mode considers the faces separately and calculates the lower of
    the buckling loads of the faces (rectangular, simply-supported orthotropic
    plates). This mode is the only of COPANO that includes the reduction in
    buckling load due to transverse shear effects.

The shear buckling analysis also comprises an overall and a local mode:
  - the overall mode considers the corrugated panel as a long, narrow
orthotropic plate (with very different bending stiffnesses in the two principal directions). As mentioned higher, the corrugation produces an extra warping restraint, which is included in this analysis;
- the local mode evaluates the buckling load of the two faces coupled to each other.

Furthermore, interaction between compression and shear is analyzed by means of the parabolic interaction formula, both for the overall and local modes. Note that for the overall mode the formula can be up to 10% conservative.

* It is also possible to check whether mode interaction (between overall and local buckling in shear) could occur, with the stiffness parameter SP of which the value should be higher than SP=1500. to prevent mode interaction.

Furthermore it is possible to specify certain constraints that affect only the optimization; these are not mechanical analyses, yet can pose some extra constraint on the design:
* orthotropic design (where some or all '16' and '26' elements of the ABD-matrix are zero) can be favoured;
* the user can specify minimum thicknesses for some layers;
* a maximum laminate thickness can be specified as well.

With this set of data a case is fully described. When the layup and the corrugation shape are defined an analysis (and possibly an optimization) can be performed. Extensive output of the analysis of the panel can be examined. Also, when the panel satisfies the constraints (i.e. is feasible), an optimization can be performed, in which the computer tries to define a better panel (i.e. with lower mass) than the one the user has given, while still satisfying the selected constraints.

Optimization is performed by the Complex method, a zero order (not using function derivatives) direct method (without penalty terms for the constraints), it takes into account the discrete nature of some variables (thickness of the different layers, and orientation of the layers with respect to the panel axes). Generally the default parameter settings (echoed by the program at the start of the optimization) will do, but it is possible to specify other values. The course of the optimization can be followed on screen.

3 USER’S INSTRUCTIONS

COPANO is a Fortran77 program of some 5000 lines of code. Executable forms of the program are available for SUN and PC computers, but the source code has only few commands specific to these computers, making the program highly portable.

Two kinds of data files are provided with the program, a material data file (typically with the extension 'MAT') and a file with data specifically associated with the case (typically with the extension 'DAT'). Both are plain text files that can be edited by the user; however, the case data file can best be generated by the program itself at the end of a run. Note that the case data file is not required to run the program, while the material data file is. Therefore, the material data file is described in a later section.

The program has an interactive text-type user interface; the user is asked to reply to questions, for which the set of possible answers is listed. For example, at the start of the program the user is asked whether to read data from a file, as follows:
read data from file?
select:
   no - [n]
   yes; file supplied by user - [u]
   yes; file supplied by sapano - [*]

Note the possible replies for the user, given between the square brackets. The '*' indicates the default answer. This is chosen if you do not enter any of the specifically listed answers (here 'n' or 'u'), or if you just press enter with no character at all.

The user dialogue is set up such that, if you always select the default answer, the program will read the standard data file, perform an analysis (no optimization) of the panel, show the basic output data and stop the execution of the program.

The program execution proceeds as given in Figure 2. At the end of the program it is possible to return to one of the earlier modules in order to modify some data, or to perform another analysis and/or optimization. In this way a flexible interactive computer program is obtained.

4 EXAMPLE OF CORRUGATED PANEL DESIGN

As an example a simple composite corrugated panel is designed; it is 500 mm deep, made of a CFRP±45° laminate. Data from the standard material data file
(COPANO.MAT) are used (section 6 describes the format of the data in the material data file). There is a single loadcase with a shear load Nxy=500 N/mm. First a corrugated panel is only analyzed, and later an optimization is performed to find the panel of least mass for this design requirement.

4.1 Analysis with COPANO

When the program is started (by typing the name of the executable file) an introductory screen appears with the title and version number of the program:

```
read data from file?
select: no - [n]
    yes; file supplied by user - [y]
    yes; file supplied by copano - [*]
<Enter>
reading data...
...general data read
reading material data ...
enter filename:
<Enter>
opening copano.mat
... material data read

CASE: Example case: 1 layer-laminate

GENERAL: layers [ 1 ] | MATERIALS: | LOADS: |
symmetry [ no ] | 1 CFRP45 | 1 .00  .00  100.00 [N/mm]
depth [ 500.00 mm ] |

CONSTRAINTS:|
stress [x] |
strain [ ] |
buckling [x] |
local buckling p [ ] |
orthotropy [ ] |
max thickness [ ] |
min thickness [ ] |
select: modify comment text - [t]
general data - [g]
constraints - [c]
materials - [m]
ok - [*] loads - [l]

q
(enter l to modify) - GENERAL: layers [ 1 ]
```
Enter a number 3

enter the depth of the panel [in mm]:
1000

(enter 1 to modify) – GENERAL: layers [1]
(enter 2 to modify) – symmetry [no]
(enter 3 to modify) – depth [1000.00 mm]

<Enter>

==DATA==========================================================================
(rest omitted; the new panel depth would be visible)
<Enter>

initial design=====================================================================

layer material orient [deg] thickness [mm]
1 CFRP45 0 50.00 * .20

width of face 1 [mm] = 100.00
width of face 2 [mm] = 100.00
corrugation angle [deg] = 90.00

select: OK – [*]
modify laminate – [no of layer]
corrugation shape – [c]

<Enter>

panel satisfies constraints
select: get results –[*]
optimize – [o]

<Enter>

results of analysis================================================================

layer material orient | thickness | mass = 3.200 g/cm2
| [deg] | [mm] | max stress: loadcase 1 / layer 1
| CFRP45 | .0 | 50.00 * .20 | reserve factor 56.60000
| | | | max strain: loadcase / layer
| | | | fibre strain

| buckling: px local = 14096.69 N/mm
| euler = 4227.15 N/mm
| pxy local = 27717.96 N/mm
| overall = 4895.72 N/mm

| constraints: | FEASIBLE
| stress [x] |
| strain [ ] | max thickness [ ]
| buckling [x] | min thickness [ ]
| local buckling parameter [ ]

width of face 1 [mm] = 100.00 # Do you want more output? no – [*]
width of face 2 [mm] = 100.00 
| corrugation angle [deg] = 90.00 # stress-[s] strain-[e] stiffness-[d]

end of program
select: quit – [*]
save case – [s]
modify panel – [p]
modify data – [d]
new case – [n]

goodbye ...
4.2 Optimization with COPANO

When a feasible initial panel has been defined by the user (see above and Figure 2) it is possible to perform an optimization by selecting 'o' after the analysis of the initial panel. The optimization proceeds as follows:

(as before)
panel satisfies constraints
select: get results - [*] 
 optimize - [o]

optimization parameters:

complex method: reflection factor = 2.00
number of points = 10
optimization output = 1
design variables:
ply or ply th flange1 flange2 corrug
ply:   1 1
min: .00 .00 1.00 1.00 10.00
max: .00 50.00 200.00 200.00 90.00
step: .00 .20 1.00 1.00 1.00
start: .00 10.00 100.00 100.00 90.00

select: o.k. - [*]
modify Complex method parameters - [c]
modify Orientation: fixed or free - [o]
modify Thicknesses: min & max & step - [t]
modify Flange parameters - [f]
modify corrugation Angle parameters - [a]

optimizing:

<table>
<thead>
<tr>
<th>#</th>
<th>obj</th>
<th>ply or ply th flange1 flange2 corrug</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.200</td>
<td>.00 10.00 100.00 100.00 90.00</td>
</tr>
<tr>
<td>10</td>
<td>908</td>
<td>.00 4.00 43.00 54.00 62.00</td>
</tr>
<tr>
<td>15</td>
<td>767</td>
<td>.00 4.60 111.00 58.00 28.00</td>
</tr>
<tr>
<td>17</td>
<td>741</td>
<td>.00 3.60 87.00 60.00 63.00</td>
</tr>
<tr>
<td>19</td>
<td>478</td>
<td>.00 2.60 81.00 75.00 43.00</td>
</tr>
<tr>
<td>23</td>
<td>377</td>
<td>.00 2.00 104.00 88.00 48.00</td>
</tr>
<tr>
<td>25</td>
<td>353</td>
<td>.00 2.00 109.00 79.00 39.00</td>
</tr>
<tr>
<td>31</td>
<td>310</td>
<td>.00 1.60 88.00 78.00 51.00</td>
</tr>
<tr>
<td>32</td>
<td>307</td>
<td>.00 1.60 90.00 97.00 47.00</td>
</tr>
<tr>
<td>33</td>
<td>285</td>
<td>.00 1.40 79.00 86.00 54.00</td>
</tr>
<tr>
<td>41</td>
<td>272</td>
<td>.00 1.40 87.00 84.00 50.00</td>
</tr>
<tr>
<td>48</td>
<td>270</td>
<td>.00 1.40 86.00 85.00 49.00</td>
</tr>
<tr>
<td>49</td>
<td>264</td>
<td>.00 1.40 88.00 85.00 46.00</td>
</tr>
<tr>
<td>51</td>
<td>261</td>
<td>.00 1.40 88.00 84.00 45.00</td>
</tr>
<tr>
<td>52</td>
<td>261</td>
<td>.00 1.40 90.00 83.00 45.00</td>
</tr>
</tbody>
</table>
To verify any obtained optima, the process repeats itself at the end.

Panel #55 is the best result of the optimization up to now.

optimization stopped after 55 points and 156 analyses
#; obj = ply or ply th flange flange2 corrug
55; .257; .00 1.40 87.00 87.00 42.00

A sound signal indicates that the optimization has ended.

optimization stopped after 97 points and 287 analyses

<Beep>

This panel is the optimum panel.

This panel is defined by coincident mode buckling and not by stress failure; this is confirmed by the numeric output above:

* both buckling loads are very near to the applied load:
  pxy local=100.49 N/mm, and pxy overall=102.78 N/mm
* the reserve factor for stress failure equals reserve factor=7.924 (hence an applied load of 7.942 times the current load is required to make stress critical)

Within a run of COPANO, different optimization paths are followed even if identical starting points are chosen; however, every new run of COPANO repeats the previous optimization paths if the same starting point is used again.

It is advisable to repeat the optimization, both from the obtained optimum panel, and from the initial panel. In this way alternative optima can be found, but also in some cases the overall optimum is not immediately found. Because the optimization method has a random feature different optimization paths will be followed from identical starting points.
5 EXTRA OUTPUT

At the end of the program a number of extra output screens can be viewed (if the associated constraints are selected). These are selected by entering the appropriate characters (see the result screen on page 9):

s (s for sigma) stresses in every layer, for every loadcase
e (e for epsilon) strains in fibre direction in every layer, for every loadcase
d (d for ABD) the ABD-matrix of the laminate, the D**-matrix of the laminate and also the stiffness parameter SP (if calculated)

Below some of these are covered separately.

5.1 Strain

Strains are calculated in the 0°-direction of the material of the layers. When a ±45° material is used, as in the example, the 0°-direction is at ±45° to the fibres. Then a fibre strain criterion is not useful.

5.2 Stiffness output

When extra stiffness output is requested the following data are displayed:

```
the ABD-matrix of the panel is:
<p>|  429113.89  359168.32  0.00  0.00  0.00 |
|  429113.89  0.00  0.00  0.00 |</p>
<table>
<thead>
<tr>
<th>[N/mm]  370160.00 [N]  0.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>3575949.05  2993069.35  0.00</td>
</tr>
<tr>
<td>3575949.05  0.00</td>
</tr>
<tr>
<td>[N/mm]  3084666.67</td>
</tr>
</tbody>
</table>
```

```
the D**-matrix of the panel is:
|  3575949.05  2993069.35  0.00 |
|  3575949.05  0.00 |
| [N/mm]  3084666.67 |
```

```
the transverse shear stiffnesses of the panel are:
Sxz = 20833.33 N/mm  Syz = 20833.33 N/mm
```

```
the local buckling parameter value is: 0.0
```

The local buckling parameter is equal to zero, because it was not included in the analysis.
6 MATERIAL DATA FILE

Without the material data file it is not possible to run COPANO. A default file is included with the program (COPANO.MAT) with a number of materials. The layout of this file is discussed below (to allow the user to develop its own version) and the material data of the default file given.

E and G are the elastic and shear modulus respectively; axes x,y,z are the length, width and through-the-thickness directions respectively.

c material data for COPANO

c version dd. Oct 20 94

c number of materials

7

c Material Name [up to 6 chars]
c Material Description [up to 60 chars]
c Ex Ey uzx Gxy Gxz Gyz [all in MPa]
c UTSx UCSx UTsy UCsy Shear [all in MPa]
c EPS/ EPSc Density[g/cm3] Thickness[mm]

CFRPUD

UNIDIRECTIONAL CFRP, FIBRE VOLUME 60%

145000. 7000. 0.3400 3500. 3500. 1500.

1750.0 -1350.0 63.0 -210.0 80.0

0.0040 -0.0040 1.6000 0.2000

ARAMUD

UNIDIRECTIONAL ARAMID, FIBRE VOLUME 60% (Du Pont)

75000. 10000. 0.3400 2100. 2100. 1500.

1380.0 -275.0 30.0 -140.0 60.0

0.0040 -0.0040 1.3800 0.2000

CFRP45

+-45 CFRP, DATA FROM 2-Ply STACKING OF UD. CFRP

12849. 12849. 0.8370 37016. 2500. 2500.

157.0 -158.0 157.0 -158.0 566.0

1.e6 -1.e6 1.6000 0.2000

ARAM45

+-45 ARAMID (Du Pont)

6500. 6500. 0.8230 20960. 2500. 2500.

97.0 -126.0 97.0 -126.0 193.0

1.e6 -1.e6 1.3800 0.2000

GLAS45

+-45 E-GLASS IN EPOXY, FIBRE VOLUME 33%

10000. 10000. 0.7000 8000. 2500. 2500.

185.0 -122.0 185.0 -122.0 137.0

1.e6 -1.e6 1.9200 0.2000

GLAS2

+-45 E-GLASS IN EPOXY, FIBRE VOLUME 45%, MOD OF GLAS45

10000. 10000. 0.7000 11000. 2500. 2500.

185.0 -122.0 185.0 -122.0 187.0

1.e6 -1.e6 1.9200 0.3000

AL2024

AL2024 T351, UNCLAD, UP TO 4MM, ULT. STRENGTH, A-VALUES

72500. 72500. 0.3300 27500. 27500. 27500.

445.0 -445.0 445.0 -445.0 265.0

1.e6 -1.e6 2.7700 0.1000

uxy is the Poisson’s ratio (contraction in y-direction due to extension in x-direction)

UTSx is the Ultimate Tensile Strength in x-direction, UCSx is the Ultimate Compressive Strength in x-direction and Shear is the in-plane shear strength.

EPS/ and EPSc are allowable fibre strains, set to arbitrary high values for materials for which this is not relevant.