SUBMILLIMETER ARRAY TECHNICAL MEMORANDUM

Number :	39
Subject :	Influence of the material on the thermal behaviour of the reflector back-up-structure.
Date :	December 10, 1990
From :	Philippe Raffin

MEMO #39

Reflector Back-up-structure Influence of the material on the Thermal Behaviour.

Philippe Raffin

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A model of a back-up-structure has been made for the SMA 6-meter antennas that is compatible with a structure based on COAST STEEL design for the DRAO 12-meter Radio Schmidt Telescope. Appendix 1 shows this non-conventional Nasmyth mount.

The model is a space frame made of 3D-struts arranged in such a way as to avoid "hard" points in the design, i.e. to fulfil the homology basic requirement, following Von Hoerner[1] principle of equal softness.

A very critical issue in the design phase of an antenna dedicated to millimeter and sub-millimeter observations is its thermal behaviour. Both the reflector (panels and back-up-structure) and the mount are affected by thermal loads. The purpose of this report is an attempt to quantify the deterioration of the dish surface accuracy due to thermal loads on the back-up-structure for different materials. This can be predicted by computing the deformation of the model through a Finite-Element package and then by best-fitting the surface points.

1 Model Description

The primary mirror is assumed to be made of 3 rings of 16 CFRP (Carbon Fiber Reinforced Plastics) panels, each panel being supported at its 4 corners. We have chosen 16 panels per ring as this keeps the max panel size to about 1m. This is a reasonable size for high accuracy panels as far as thermal and mechanical loads (dead-loads, wind loads) are concerned.

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[1] Sebastian Von Hoerner, The Design and Improvements of Tiltable Radio Telescopes, 1967

The panels are not part of the model as we consider only thermal loads.

The interface back-up-structure /mount is highly asymmetric using 3 non equally distributed connections (See Appendix 2) : the elevation bearings (2) and the linear actuator at 90 deg from the elevation axis. In order not to destroy the homologous behaviour of the back-up-structure, this interface needs to be very stiff. A ring is therefore introduced here to support the dish back-up-structure. It is a box-type structure and is modeled as an equivalent beam.

A special arrangement is then made by the way of 3 layers of upside down pyramids (in order to get an equally supported surface) from the panel support points to the ring. The nodes of the pyramids are themselves connected radially and circumferentially in order to be fully triangulated, which allows to model the members as trusses working in a push-pull way only i.e. no bending moment, which is the usual way of designing a reflector in a first stage.

A deeper detailing of this structure is not the purpose of this report. This will be given later and will include wind loads, the quadrupod, and a detailed analysis of the ring. Appendix 3 shows a computer plot of the model. Assuming that this structure has reached a reasonable level of accuracy under gravity loadcases we now use it as a basis on which to apply thermal loads.

I-Deas, the finite-element program from SDRC is used to analyse the structure, and the best-fit paraboloid program used for IRAM's calculations is used to find the parameters of the best-fit paraboloid .[2]

2 Coordinate system

Appendix 2 shows the coordinate system used for the structural analysis of the reflector to give nodal displacements, and for the parameters of the best-fit paraboloid . This coordinate system is *linked to the reflector* and then turns in elevation with it. The origin of the system is located at the *Vertex* of the paraboloid.

- the z−axis is defined outward along boresight axis,

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[2] based on an IRAM internal report, Least Square Fit for Axisymmetric Paraboloids, Jean Delannoy, 1980

- the $y-$axis is perpendicular to El-axis so that the Gravity-Vector is along $-y$ when the reflector is in the horizon looking position,
- the $x-$axis is along the El-axis so that (x, y, z) is right.

3 Thermal Analysis of the back-up-structure

3.1 Assumptions

The coefficient of thermal expansion (CTE) is $12 \times 10^{-6} m/m/^{o}C$ for steel and is taken as $2 \times 10^{-6} m/m/^{o}C$ for CFRP. The CTE of the fiber itself is close to zero and can even be negative, but we introduce here a mean value which takes into account the CTE of the materiel used to connect the struts together, which can be steel (IRAM-15m) or invar (SMT) or even CFRP too.

Regarding the boundary conditions, we assume in this thermal model, that :

- at one of the elevation bearings, the structure is not allowed to expand in any direction,
- at the other elevation bearing, the structure is free to move along the elevation axis, but restrained in the 2 other directions. It is free to rotate about the 3 axis,
- The third mechanical interface is the elevation drive which restrains the structure in the direction of the motion of the linear actuator. For the modelisation, instead of a retrain at this location, we prefer to keep it entirely free to move and instead, we apply the restraint to the 1st elevation bearing : the rotation about the elevation axis is then restrained, the 2 other rotations remaining free.

The following loadcases are applied separately on the back-up-structure. Each case is qualitatively representative of a possible thermal situation. They are based on IRAM-15m. design study where a composite layout has been adopted for the reflectors (CFRP for the surface panels and the radial and circumferential struts, steel for the ball joints, the inclined struts or "pyramids" and the central hub which is a 5000 kg piece connecting the back-up-structure to the elevation part housing the cabin; the back-up-structure is enclosed by the primary mirror panels and aluminum honeycomb insulation panels).

- a 2 ^oC linear gradient across the reflector (along x-axis), or 0.33 ^oC m^{-1},
- a 2 ^oC linear gradient across the reflector (along y-axis) or 0.33 ^oC m^{-1}. x-axis and y-axis are not equivalent as far as boundary conditions are concerned,
- a 2 ^oC step gradient across the reflector (along y-axis) : half of the reflector has a uniform temperature of 2 ^oC above the ambient (the part being above the elevation axis when the antenna looks versus horizon : y>0 while the other half is at the ambient temperature,
- a 2 ^oC linear gradient from bottom to top of the reflector (along z-axis) or 1.3 ^oC m^{-1}, the height of the truss (over which is applied the gradient) without the ring being 1.6 m,
- a uniform increase of 2 ^oC above the ambient in the whole structure. The ambient temperature is referred to as the temperature with zero deformation. A temperature lower than the ambient would have the same effect on the surface accuracy, but the variation of the focal length would be opposite in sign,
- a uniform increase of 2 ^oC in the ring alone,
- a uniform increase of 2 ^oC for the surface nodes of the back-up-structure i.e. those connected to the primary mirror panels.

Each of these 7 loadcases is applied to the same structure, but with different materials for the reflector constituting elements and the results are given in the 1st table of Section 3.2.

- CFRP : all the structural members are made out of CFRP, including the ring,
- STEEL : all the structural members are made out of steel including the ring,
- DUAL : the radial and circumferential struts as well as the ring are made out of CFRP, whereas the pyramids are made out of steel.

3.2 Results

The following table gives for each loadcase the surface accuracy deterioration σ in μm r.m.s. and the change in focal length df in mm.

	CFRP		STEEL		DUAL	
Loadcases	σ	df	σ	df	σ	df
2 ^oC linear x-gradient	<0.1	-.004	<0.1	-.021	0.9	-.056
2 ^oC linear y-gradient	<0.1	0	<0.1	0	0.7	0
2 ^oC step y-gradient	0.7	0.008	4.5	0.049	10.7	0.091
2 ^oC linear z-gradient	0.1	0.044	0.9	0.262	1.3	0.061
2^oC Global increase	0	0.010	0	0.062	1.7	0.166
2 ^oC in the ring	0.7	-.048	4.1	-.283	0.3	-.023
2 ^oC for surf.nodes	1.3	0.070	7.7	0.422	2.4	0.087

Appendix 4 shows the residual deviations from best-fit paraboloid for some relevant thermal cases for CFRP and steel. These plots are readily comparable as the contour level is the same for each case : $1\mu m$.

Appendix 5 to 8 show plots of the deformed back-up-structure with a very enlarged scale of deformation. The continuous lines are used for the deformed structure, the dashed lines show the undeformed structure. The following cases are plotted :

- Loadcase4 (App.5) : a linear y-gradient of 2^oC , assuming a max displacement of 0.005 mm, one finds a tilt of 0.3" about the elevation axis.
- Loadcase6 (App.6) : a uniform temperature of 2^oC in the ring alone shows a global expansion of the structure, with a max absolute displacement of 0.016 mm in the back-up-structure .
- Loadcase8 (App.7) : a uniform temperature of 2^oC for the front nodes gives also a symmetrical expansion, with a max absolute displacement of 0.019 mm in the back-up-structure .
- Loadcase9 (App.8) : a step gradient of 2^oC in half of the structure shows an internal deformation of the back-up-structure , with a max amplitude of 0.017 mm.

Then, one can combine linearly these elementary loadcases and add the results in a r.s.s. way to have some figure for more realistic cases. 2 cases are shown here.

1. Assuming a transient situation where we can have the following thermal cases adding together :

- the antenna has to work on the full operational range of temperature –30 to $+20^oC$, or $\pm 25^oC$ around a mean temperature,
- a uniform increase in temperature in the ring alone of 4^oC above the ambient due to the different thermal time constant of the ring which is an enclosed structure compared to the truss being an open structure.
- a 4^oC step gradient across the dish,
- an increase of 4^oC above the ambient for the front nodes.

Loadcases	σ (μm r.m.s.)		
	CFRP	STEEL	DUAL
25^oC global change	0	0	21.3
4 ^oC in the ring	1.4	8.1	0.7
4 ^oC step y-gradient	1.5	8.9	21.4
4 ^oC for front nodes	2.6	15.4	4.7
TOTAL r.s.s.	3.3	19.5	30.5

2. Another loadcase can be seen, less degrading, for a more steady-state regime, but much more difficult to obtain, coming to :

- a uniform temperature in the whole dish of 25 ^oC above or below the reference temperature,
- an increase of 2 ^oC above the ambient for the back-up-structure front nodes.
- a 2 ^oC linear gradient in the depth of the dish,
- an increase of 2 ^oC in the ring.

Loadcases	σ (μm r.m.s.)		
	CFRP	STEEL	DUAL
25 ^oC global change	0	0	21.3
2 ^oC for front nodes	1.3	7.7	2.4
2 ^oC linear z-gradient	0.1	0.9	1.3
2 ^oC in the ring	0.7	4.1	0.3
TOTAL r.s.s.	1.5	8.8	21.5

The assumptions taken here are not very drastic, but in order to be more accurate with them, it would be interesting to have more temperature measurements of operational telescopes. We already received data from Cal.Tech and are ready to use them.

It would even be more interesting to obtain data from telescopes that use the techniques and materials that we are considering for the SMA antennas (IRAM, Nobeyama).

Anyway it appears that CFRP is the candidate for the back-up-structure, or at least a material with a low thermal expansion coefficient, but certainly not steel if one does not want to be involved in a tremendous temperature control business to track a fraction of a degree C.

It is certain that the layout for the back-up-structure /mount interface adopted for this design helps a lot to cope with thermal loads : the deterioration of the surface accuracy is very limited, however every non symmetrical loading will give a pointing error that has to be corrected.

The CFRP/steel combination for the struts doesn't look very attractive at first glance for this particular design. For the IRAM 15-meter dish design, it was much more interesting in a sense that it allowed to save money as half of the struts only needed to be made out of CFRP in order to have a very good thermal behaviour. Having a whole CFRP reflector wouldn't improve the thermal behaviour, however would reduce the weight, which is relevant too but for other reasons. The explanation is that IRAM 15-meter dish is behaving as a sandwich; 2 CFRP "skins" of struts (the radials and circumferentials) enclosing a steel "core" : the central hub and the inclined struts. Thus low CTE is not necessary for the "core" but only for the "skins"

The result has to be inserted into a global error budget of 15μm r.m.s.

for the dish assuming a CFRP reflector. The following table for the SMA antennas is in between the ERT tables produced so far[3] and as a comparison it shows the error budget for the SMT-10 meter antenna.[4]

	Source	SMA	SMT
		(μm r.m.s.)	
PANELS			
	Manufacturing	5.0	6.0
	Alignment	8.0	10.0
	Gravity	3.0	
	Wind	3.0	5.5[x]
	Thermal	3.0	
BACK-UP-STRUCTURE			
	Gravity	6.0	4.2
	Wind	6.0	3.7
	Thermal	3.5	6.1
TOTAL r.s.s.		14.2	15.3

[x] *includes gravity, wind, thermal*

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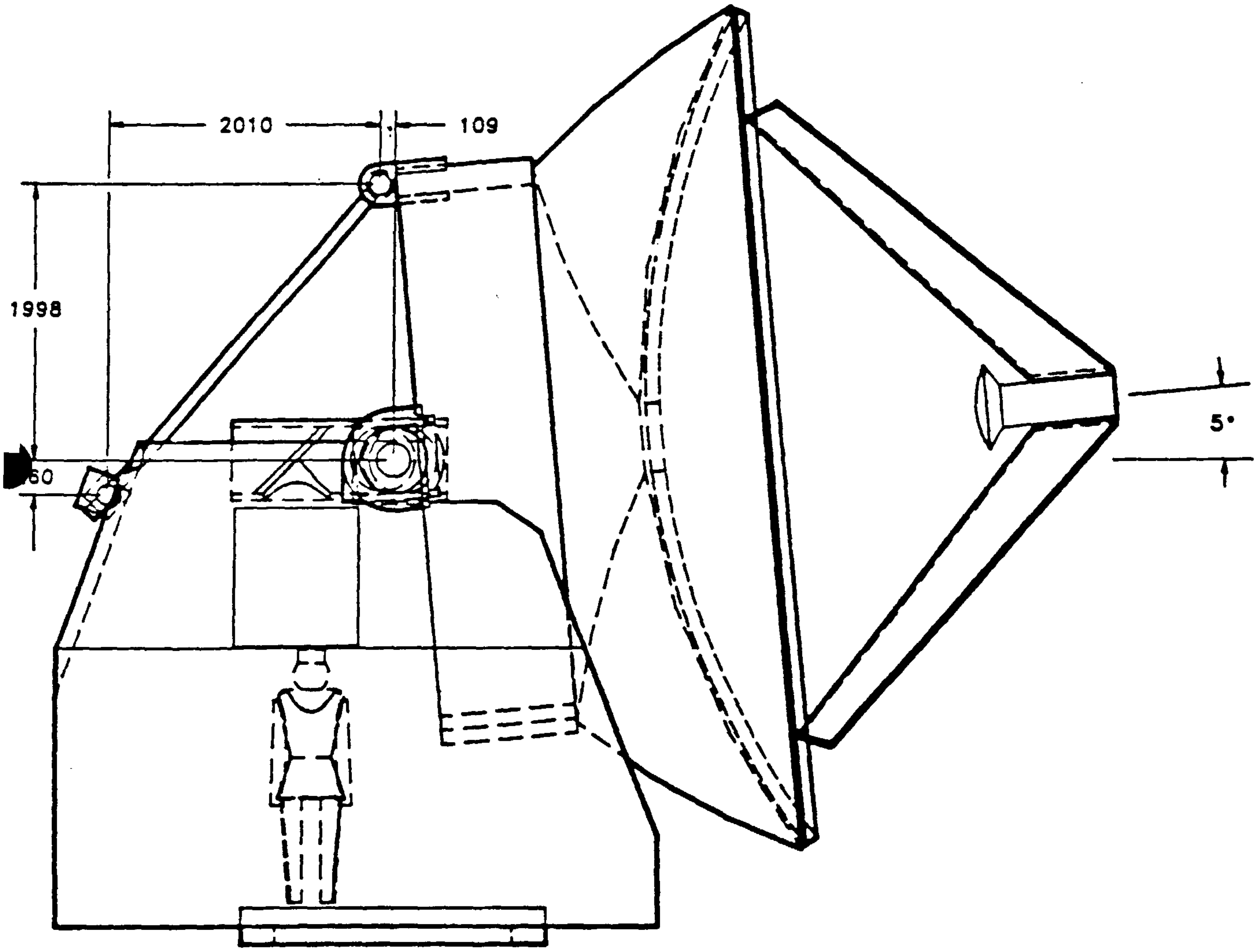
[3] SMA Tech.memo 17: Aluminum Panel Study, by B.Bruckman and B.Davis

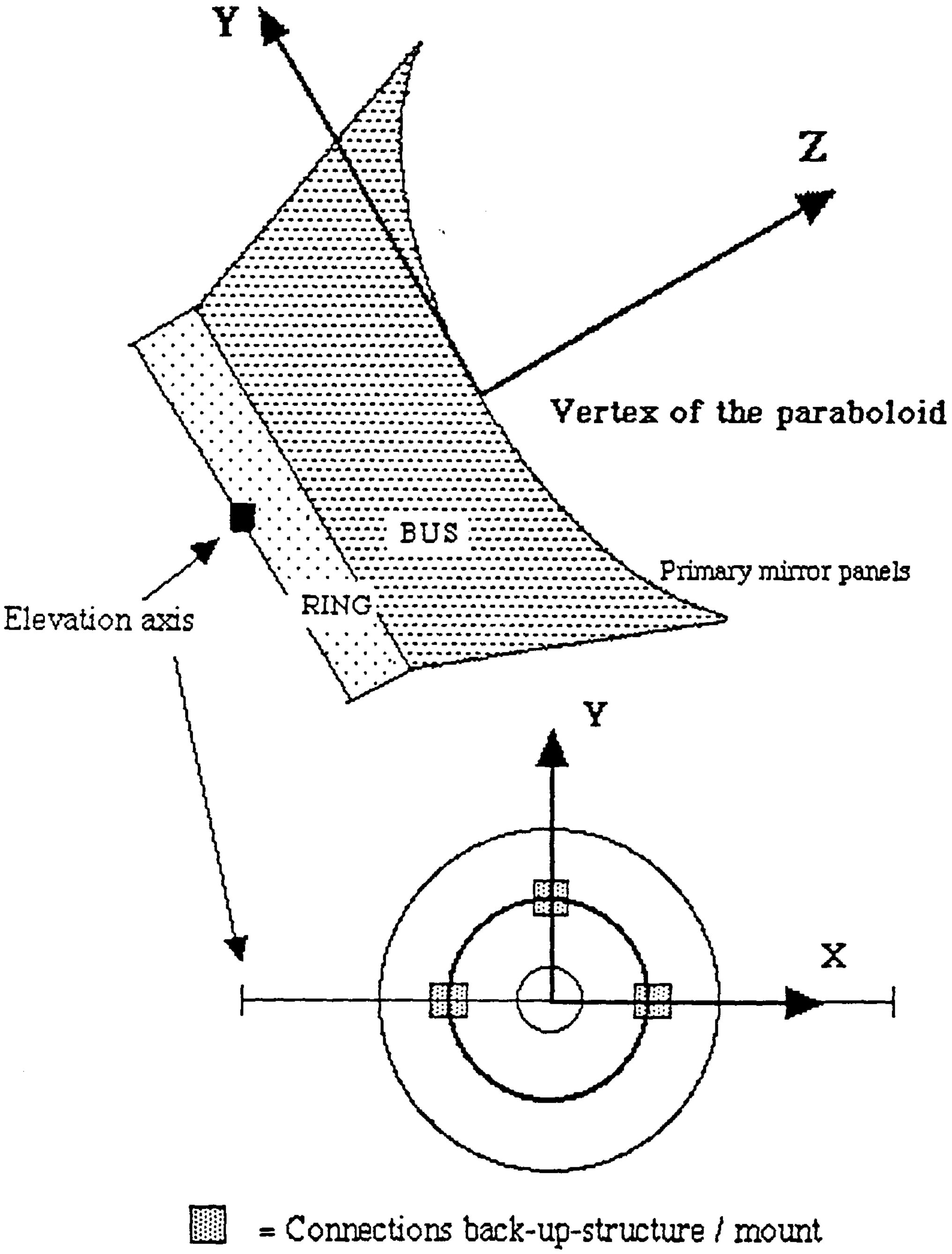
[4] The Submillimeter Telescope Project, R.N.Martin, JWM Baars, SPIE Vol 1235 VII (1990)

App-1



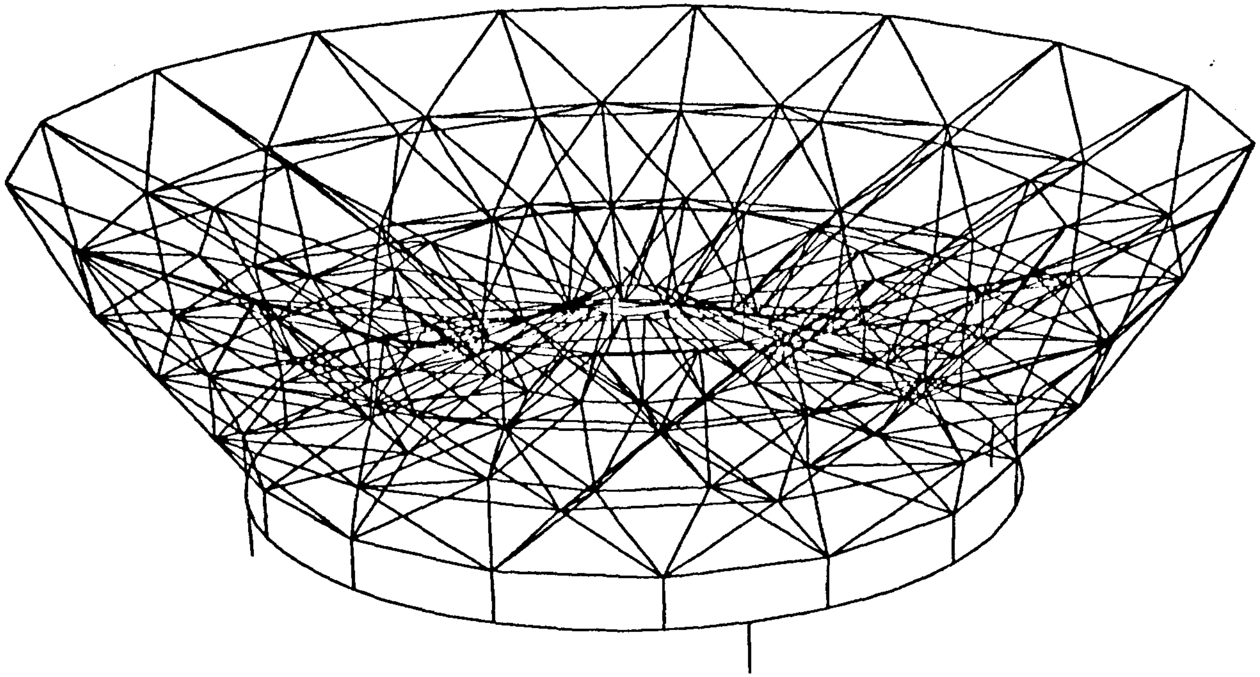
NASMYTH LAYOUT

App. 2



▨ = Connections back-up-structure / mount

Coordinate system for the reflector.

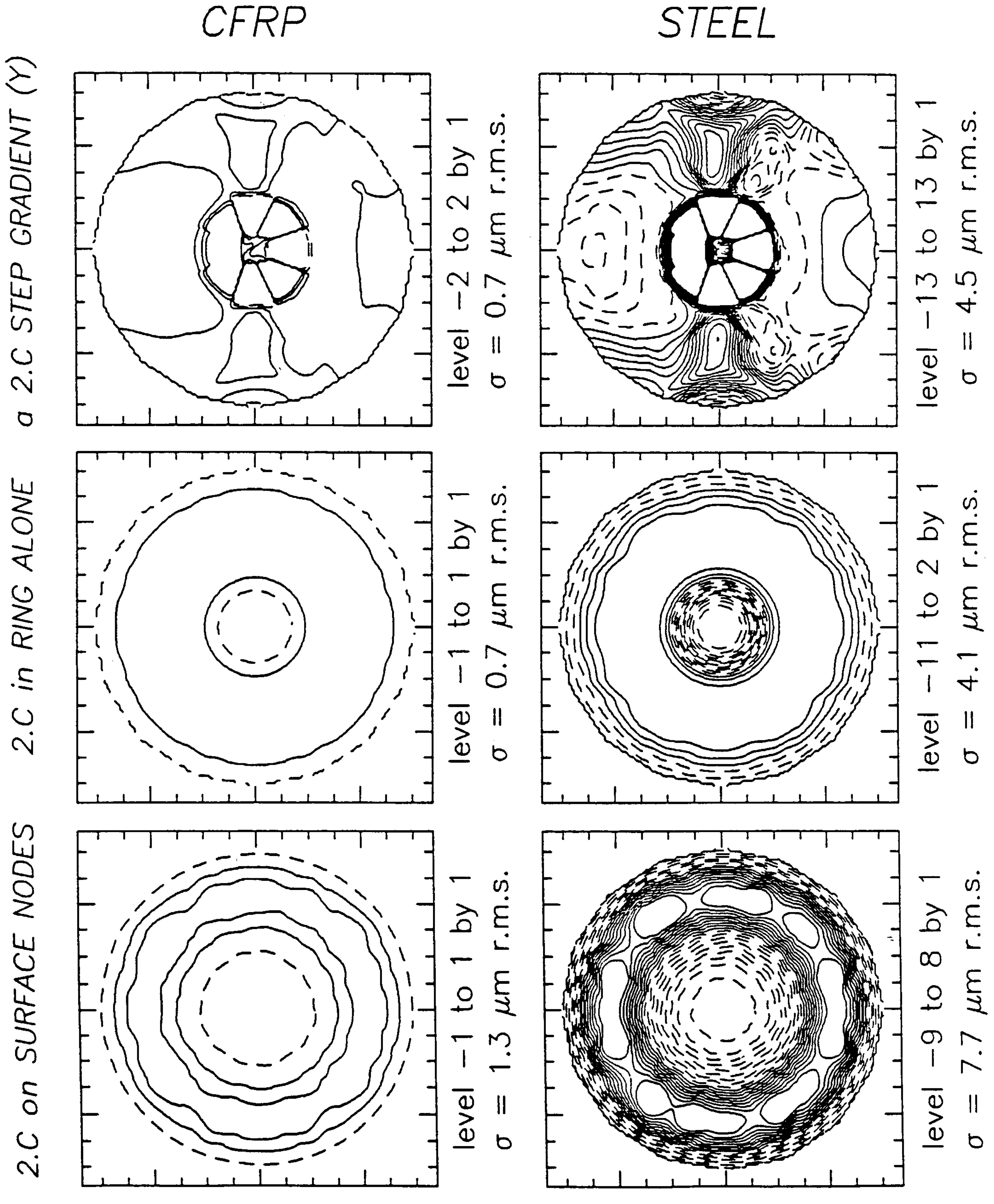


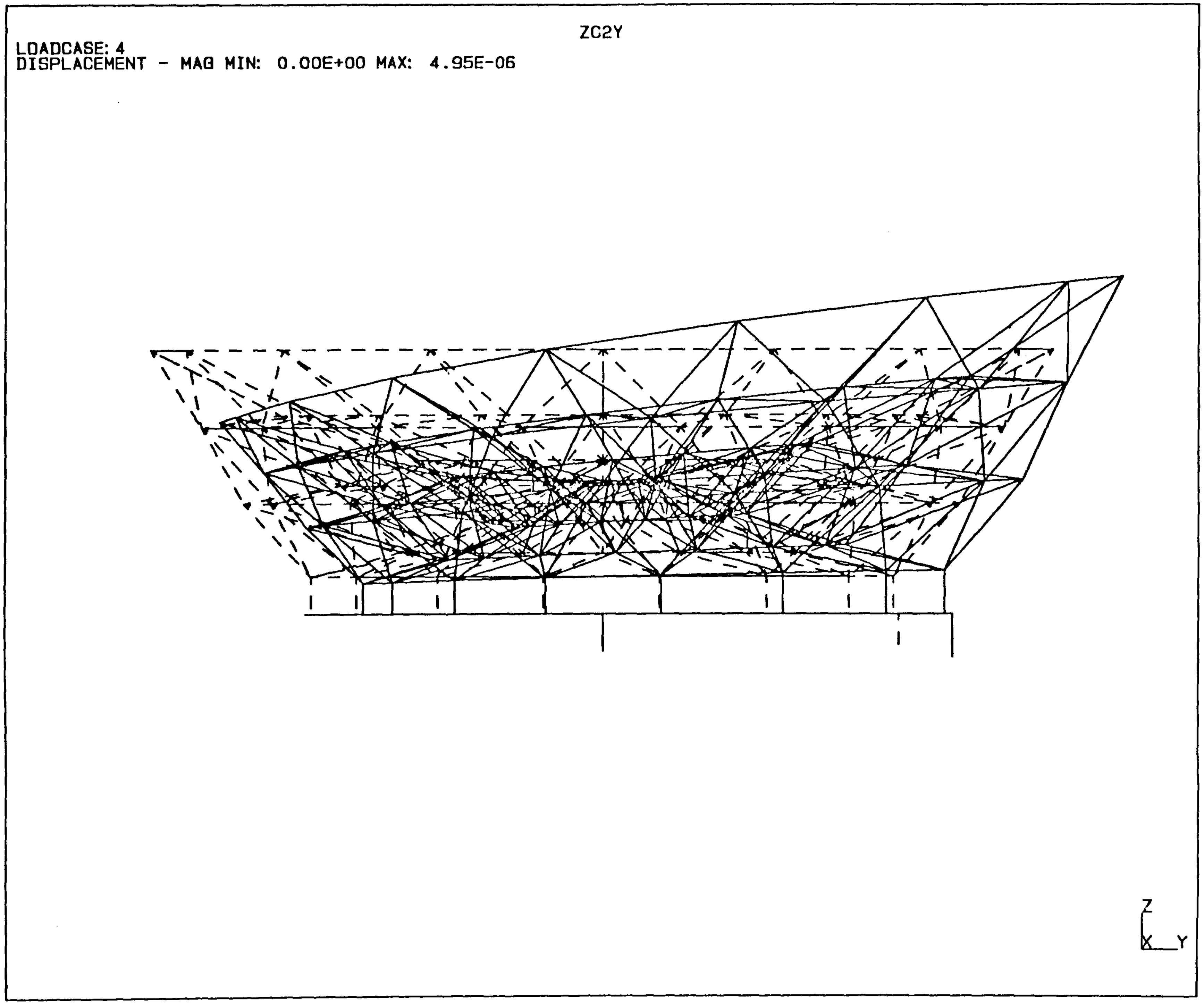
I-DEAS MODEL OF THE DISH.

App.4

*RESIDUALS from BFP * CONTOURS in μm*

*ref. Model myg06o * THERMAL LOADCASES*





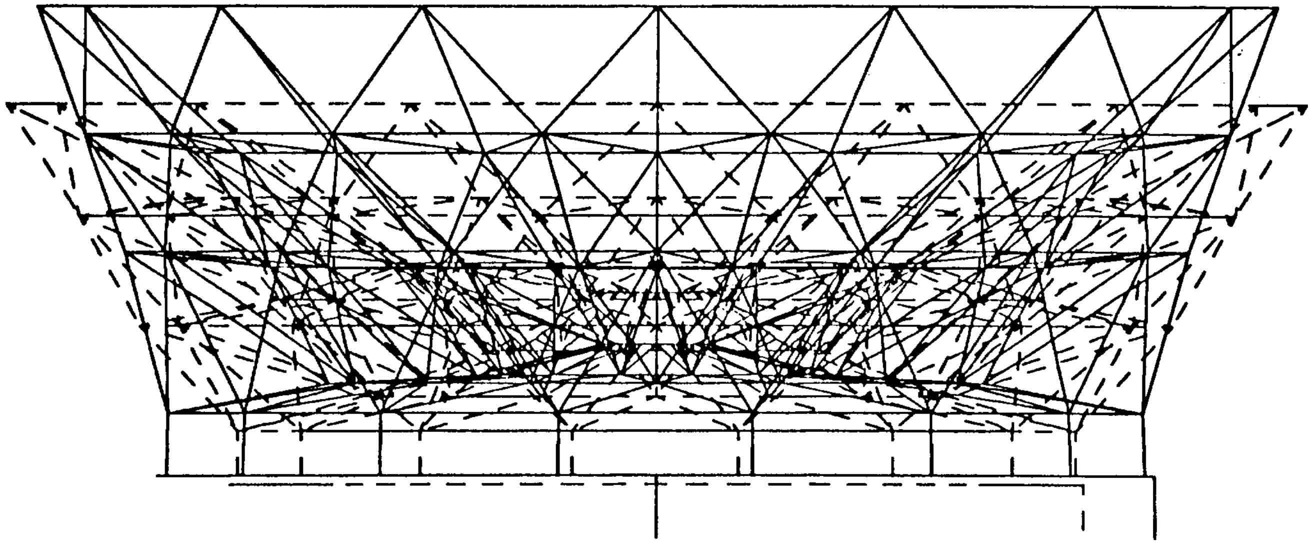
ZC2Y

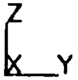
LOADCASE: 4
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 4.95E-06

App. 5

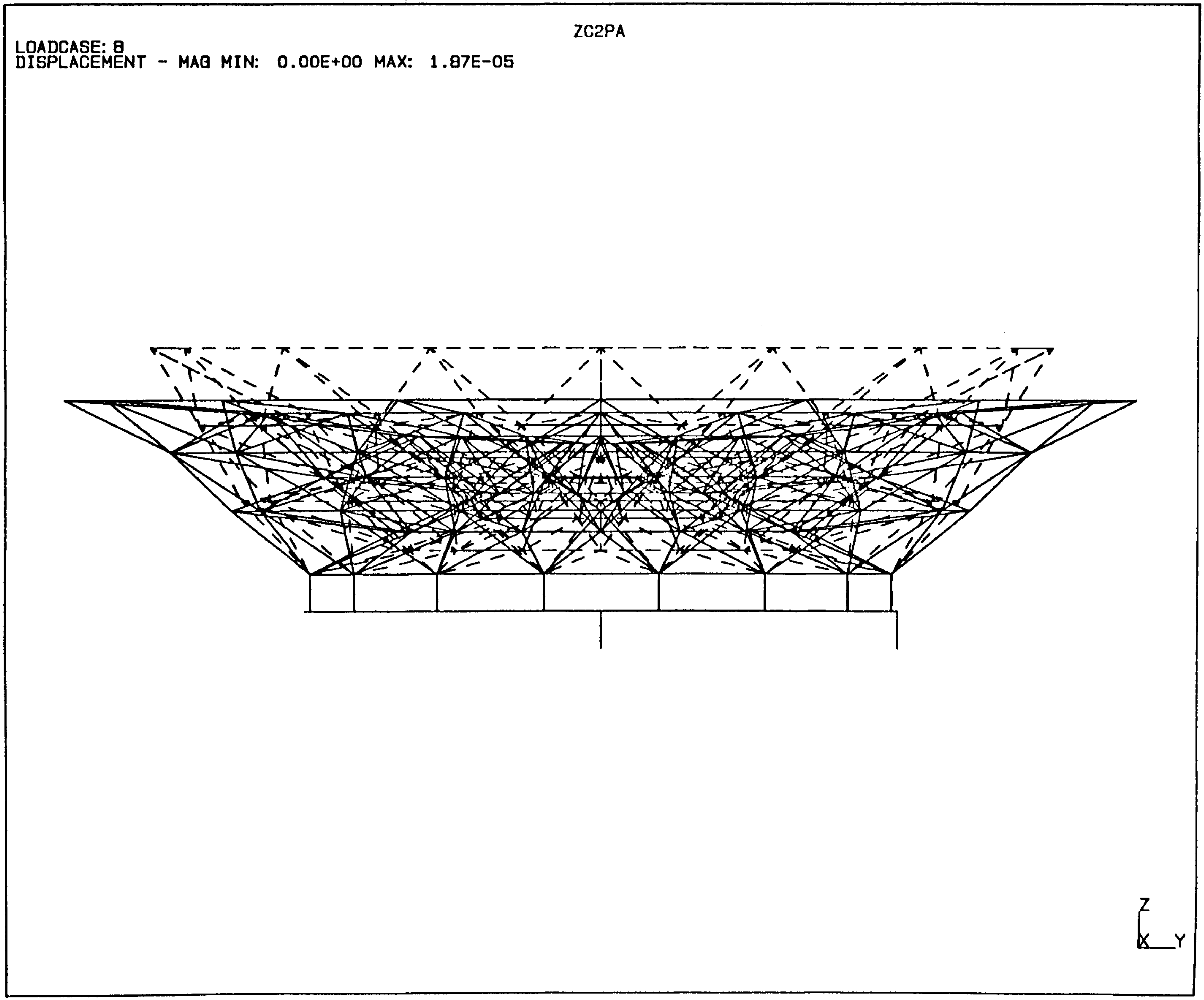
ZC2RG

LOADCASE: 6
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.61E-05





App. 6



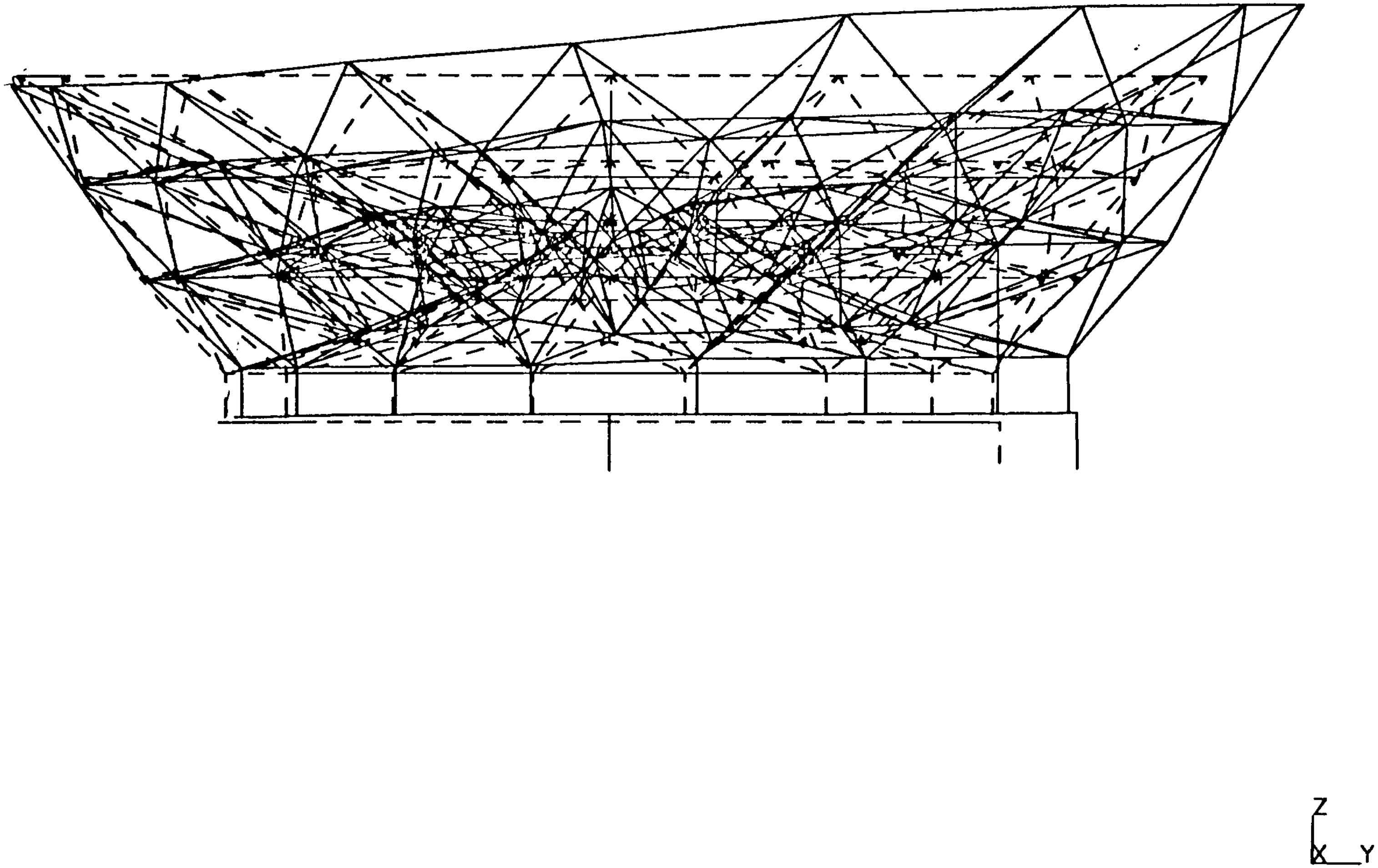
ZC2PA

LOADCASE: 8
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.87E-05

App.7

ZCFRP

LOADCASE: 9
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.74E-05



App. 8