ALMA Memo No. 557
Thermal Deformation of Shaped Carbon Fiber-Aluminum Core Sandwiched Structures

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ROAD MAP
FOR MEMOS 557,558, and 559

Early in 2000, one type of ALMA antenna BUS design was proposed which involved a channel shaped carbon fiber aluminum honeycore sandwiched structure. This type of structure will change its shape as the temperature changes. For verifying this thermal shape change problem, three internal memos were produced in Aug. 2000. These were reproduced here as ALMA Memo Nos. 557, 558 and 559. Memo No. 557 is the first memo which provides theoretical derivation as well as a simple finite element analysis. The memo pointed out that if the channel width is 1m, the surface deformation will be 33 um. The FEA analysis uses a coarse element size. Memo No. 558 is a refined analysis with different constraint conditions. The analysis results are consistent with the first memo. Memo No. 559 is a detailed analysis of the corner problem area. This corner area has high stress concentration, complex strain, and is the main reason for the shape change of the top surface.

In Sept, 2001, a BUS section was tested to verify its thermal performance. After the test data were processed, an internal report was produced. The title of the report is: Antenna BUS Thermal Test Evaluation Report. In this report, test data were used to check the predictions of the early memos. An estimation of the antenna surface deformation was also made from the measurement. If the early BUS design was used, the surface rms error could reach 28 um. The report also provided the explanation of the adjuster’s preload change as temperature changes. The internal stress level between the BUS and the panels were also estimated. The highest internal force between panel and BUS may reach 50,000N when temperature change is large.

After these analyses, the sandwiched BUS structure design was modified. In the modified design, the stress of the corner part is absorbed. The top surface has little thermal deformation. These modified ALMA BUS structures were also applied to APEX and the South Pole Sub-millimeter Telescope. As these memos and this report played an important role in ALMA antenna design, these memos are reproduced as they were. The report remains out of public domain. However, astronomers could request the report with conditions.

Thermal Deformation of Shaped Carbon Fiber-Aluminium Core Sandwiched Structures

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Abstract

Thermal deformations of T-shaped, L-shaped and channel shaped structures are discussed. The work shows that the deformation could become significant for precison instruments if the width of the top plate is more than 1 m. It also shows that using CFRP beams or tubes to connect the top and the bottom skins of the top sandwiched plate is not a helpful practice. The resultant deformation will be worse than that of the bottom surface of the top plate.

1 Introduction

Thermal deformation is a problem for structures made of materials with different thermal expansion coefficient(CTE). This paper discusses the thermal deformation of some typical sandwiched carbon fiber reinforced plastics(CFRP)-aluminum honeycomb angled structures.

2 Thermal deformation of a T-shaped sandwiched structure

For a T-shaped cross-section as in Figure 1(a), if the skin is made of CFRP plate with near-zero CTE and the core is made of aluminum honeycomb, temperature change will produce a shape change. We consider the two parallel line on both sides of the top sandwiched plate, the top line is all made of CFRP where CTE is near zero, while the bottom line has a break in it of length $2d$ made of high CTE aluminum honeycomb. If the temperature changes, the lengths of top line and bottom line will be different. This difference in length is:

$$2 * \Delta d = 2 * d * \alpha_{Al} * \Delta T$$

where ΔT is the temperature increase and α_{Al} is the CTE of aluminum. To acommodate the increase in bottom side length increase, the top of the T-shaped structure will bend upwards as shown in Figure 1(b). If the height of the top layer is h, then the angle of the bending will be:

$$\theta = \Delta d / h$$

In this section, we have not mentioned the thickness change of the T-shaped structure plates. These changes are straightforward.

3 Thermal deformation of a right angle(L-shaped) structure

Right angle structure is also called an L-shaped structure(Figure 2(a)). The structure could be assumed to be half of the T-shaped structure. If the skin is made of CFRP, the deformation of the top plate will be the same as the T-shaped one except there is a local deformation on the top of the vertical outer skin(Figure 2(b))(Note: From now on, we neglected the angular effect from the h dimension change.). The angle change of the structure is approximately:

$$\theta = \frac{d * \alpha_{Al} * \Delta T}{h}$$

For outer edge CFRP skin of the vertical plate, the length will remain unchanged. The T-shaped structure has its top skin lifted by $\Delta h = h * \alpha_{Al} * \Delta T$. This local effect will increase the θ angle for the top surface.

If the temperature is reduced, the structure angle will be smaller than a right angle and the top surface will be pulled down instead of lifted up.

4 Thermal deformation of a channel-shaped structure

For a channel-shaped sandwiched structure(Figure 3(a)), thermal expansion will change the shape of the structure as well. If both vertical plates are constrained, there will be moment applied on the top plate. The top plate surface will be curved upwards when the temperature change is positive(Figure 3(b)). The radius of the curve is:

$$R = \frac{\sqrt{1+\theta^2} * D}{2 * \theta}$$

The maximum height change for the bottom and the top parts of the plate are:

$$\Delta h_b = R - R * cos\theta$$

$$\Delta h_t = \Delta h_b + h * \alpha_{Al} * \Delta T$$

The bottom deformation is significantly smaller than the top deformation. If the top and bottom surface are joined by a zero expansion CFRP tube, the position change of the tube is just an average deformation of the bottom and top. This deformation is larger than the deformation of the bottom surface when the CFRP connection is not introduced.

5 Estimation for maximum height change of the channel sandwich structure

We have calculated thermal deformation of a channel structure with a different width D and where the vertical plate thickness is d=0.02 m and the top plate thickness is h=0.072 m. The maximum bottom and top deformations of the horizen plate are shown in Figure 4 when the temperature increase is 10 degrees C. From the figure, the deformation of the top surface is much greater than that of bottom surface. For a channel structure of 1 m width, the maximum deformation of the bottom skin is only 16 μm while the top deformation could be 33 μm.

6 Computer analysis of the channel sandwich structure

In the above analysis, bending stiffness of the CFRP skin is ignored(It is in fact small.). To include the effect of skin stiffness, a computer model has been built. The section model is part of a slice of a pie-shaped channel. It has an extended angle of 15 degrees. The channel section inner edge to the pie center is 3 m and the outer edge to the pie center is 3.5 m. The channel width of the inner side is therefore D=0.78 m and the outer side is D=0.91 m. The thickness of the top plate is h=0.072 m and that for the vertical plates is d=0.02 m. In the analysis, the skin thickness used is 0.0005 m. The modulus of CFRP skin is E=190 GPa and that for the aluminum core is 270 MPa(Note: After the analysis, I had calculated the modulus of a honeycomb core in three directions. The L direction modulus is $2tE/(11d_c)$, the W direction is $2td_cE/(3{l_c}^2)$ and in vertical direction is $2tE/d_c$, where E is the modulus of aluminum, $d_c = 0.866l_c$, l_c is side length of the hexagonal core, t is the thickness of the core skin. From the calculation, for a core width of $2d_c$=0.00635 m(=1/4 in.) and a skin thickness of t_c=0.0000381 m(=0.0015 in.), the modulus will be 140 MPa, 420 MPa and 168 MPa.). The density of CFRP is 2150 kg/m^3 and that for the core is 83 kg/m^3. The temperature increase is 20 degrees C. Figure 5 shows the coarse channel structure model. The solid elements extended from one side of the sandwich to the other. The solid elements in the model are the core and there are also plate elements which represent the CFRP skins. The constraint is applied at each of the eight bottom nodes. Figure 6 is the result of the computer analysis. The maximum deformation of the bottom surface is about 25 μm for a 20 degrees temperature difference, which agrees with the number in Figure 4(NOTE: In the figure, the temperature difference is 10 degrees C.). However, the maximum deformation of the top surface is a little larger than the calculated number in Figure 4. This is caused by the local edge effect of the additional angle change of the top surface. Figure 7 is a new model which is the same as the earlier model except a number of CFRP beams are inserted between two sides of the sandwiched plates. These beams are all colored yellow. Two are on the side plates and two are on the top plate. Figures 8 and 9 are the analysis results for this model including CFRP short inserts. It seems that the insertion of CFRP beams will not change the big picture of the deformation. The effect of the side CFRP beams on the z direction deformation is very little, while the CFRP beams on the top surface will produce local dents on both sides of the plate. The height deformation at these CFRP beams are the average of the top and bottom surface deformations. Because of these dents, there are also some ripples in the nearby area. Analysis has also been done by lifting up the constraint points on the vertical plates. The pattern of deformation resulted remains the same.

7 Conclusion

The deformations of shaped sandwiched structures are complex and difficult to model. The analytic results are based on very simple calculation. The computer analysis results are better but they are also based on balance of the internal body forces within the structure. However, the thermal expansion of laminated or sandwich structures may not follow the role of the finite element theory. These structures are not isotropic and they involve other forces, for example the bond surface force between plate and core and friction force between fibers and matrix. Therefore, the above calculation can only be used as a general reference. The best way to assess this complex problem is to produce a real structure and to take a measurement.

However, the above work shows the basic deformation patterns of the top plate of a T-shaped, an L-shaped, and a channel shaped structure when the vertical plate is constrained. The work shows that the deformation could become significant for precison instruments if the width of the top plate is more than 1 m. It also shows that using CFRP beams or tubes to connect the top and the bottom skins of the top sandwiched plate is not a helpful practice. The resultant deformation will be worse than that of the bottom surface of the top plate. A very effective way to eliminate the top plate deformation is to free the side constraint of the vertical plates. Over constraint usually produces larger deformation.

Fiber composite material has different thermal properties for different layers in one particular direction. A shaped structure of the composite also produces shape changes as the temperature varies. The deformation pattern is the same as the sandwiched structure.

8 Figures

Figure 1 (a) A T-shaped CFRP aluminum sandwiched struture. (b) Deformed shape of the T-shaped structure when the temperature increases.

Figure 2 (a) An L-shaped CFRP aluminum sandwiched struture. (b) Deformed shape of the L-shaped structure when the temperature increases.

Figure 3 (a) A channel shaped CFRP aluminum sandwiched struture. (b) Deformed shape of the channel structure when the temperature increases.

Figure 4 The height changes of the top and bottom skins of top plate of a channel sandwiched structure when the temperature increases 10 degrees C.

Figure 5 The coarse model of a channel structure which is a part of a slice of pie section.

Figure 6 Deformation of the channel structure when temperature increases 20 degrees C.

Figure 7 The model with CFRP beam insertions.

Figure 8 Deformation of the channel structure with CFRP beam insertions when temperature increases 20 degrees C(top view).

Figure 9 Deformation of the channel structure with CFRP beam insertions when temperature increases 20 degrees C(bottom view).

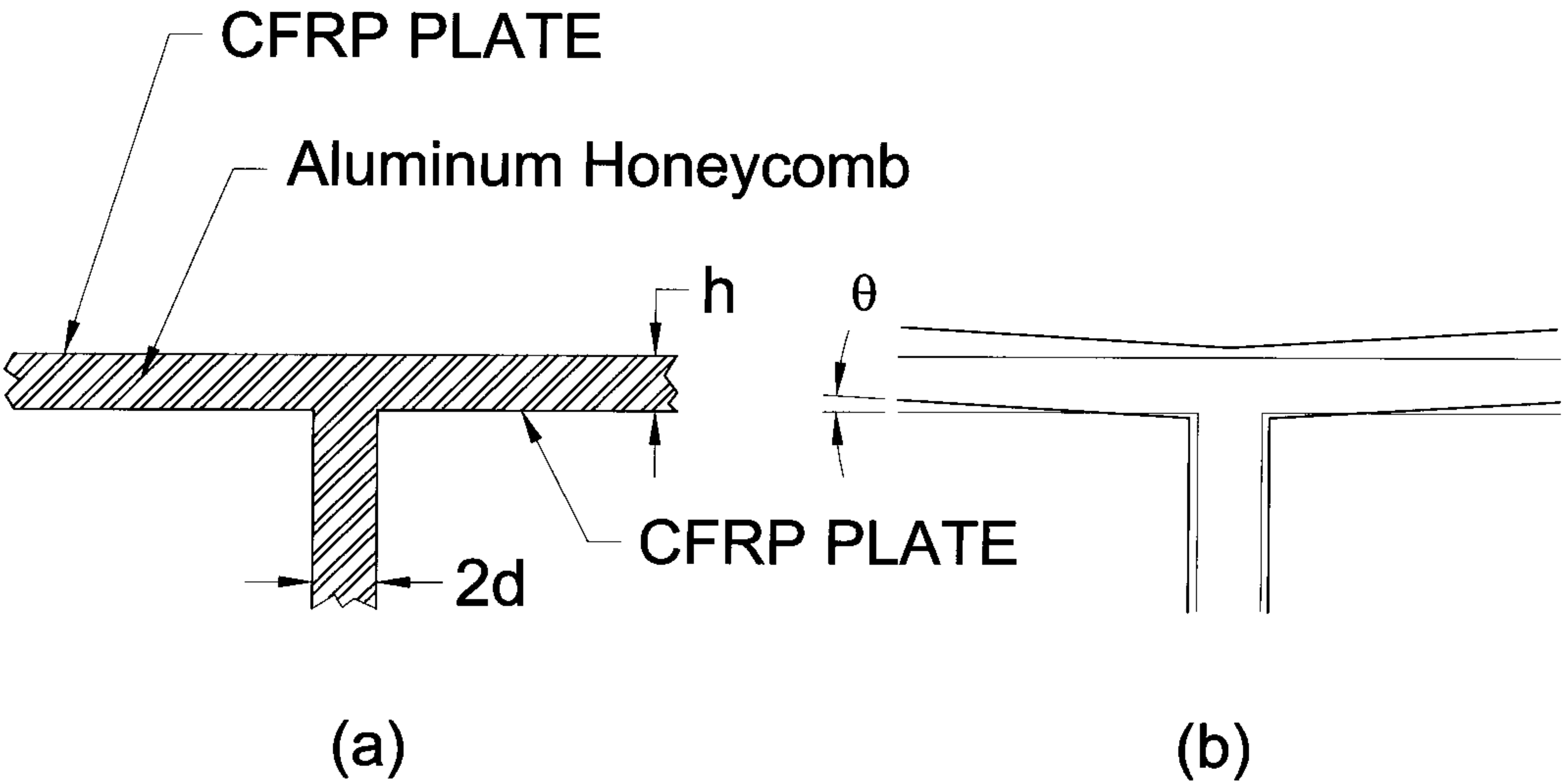


Figure 1

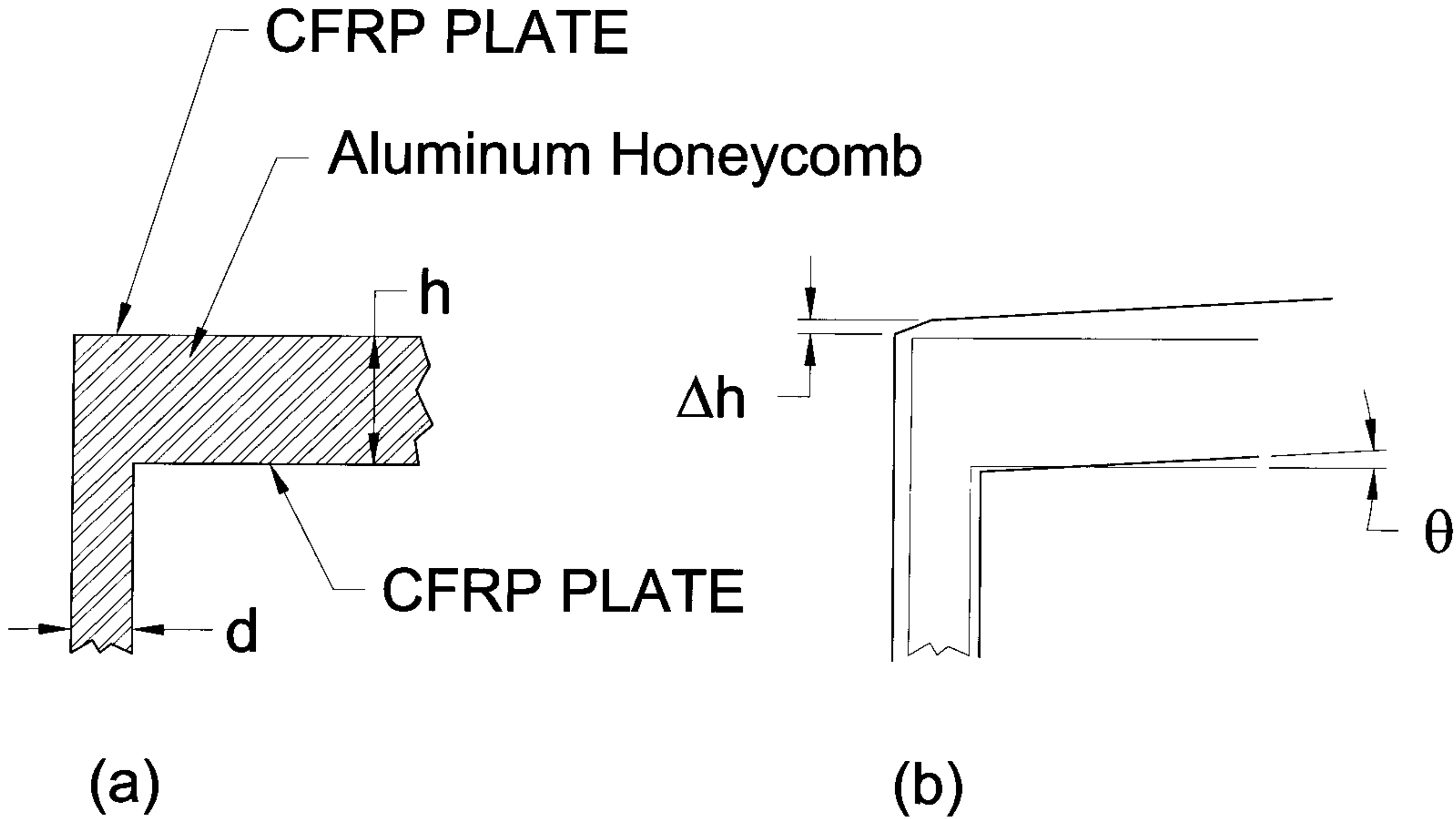


Figure 2

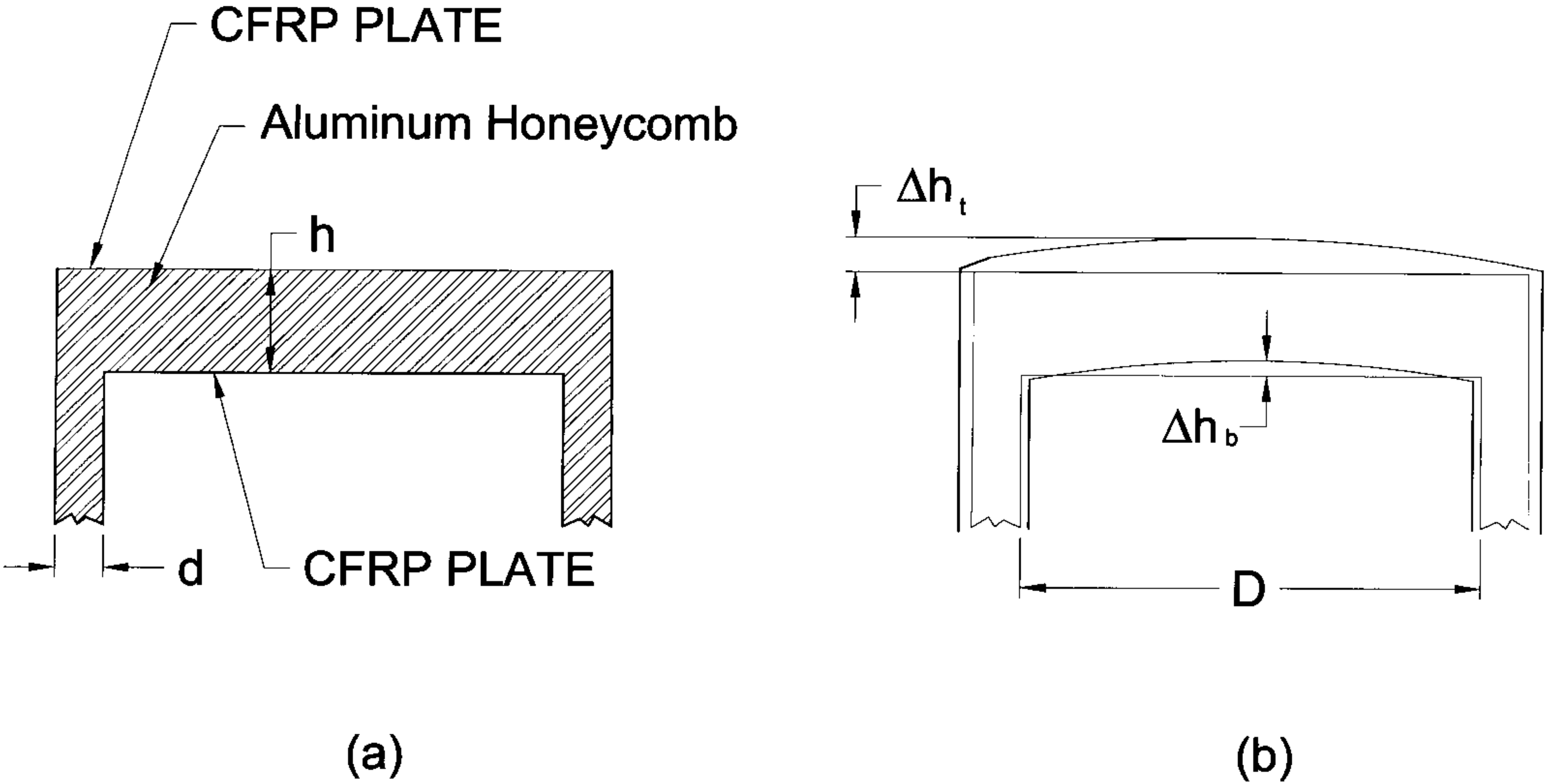
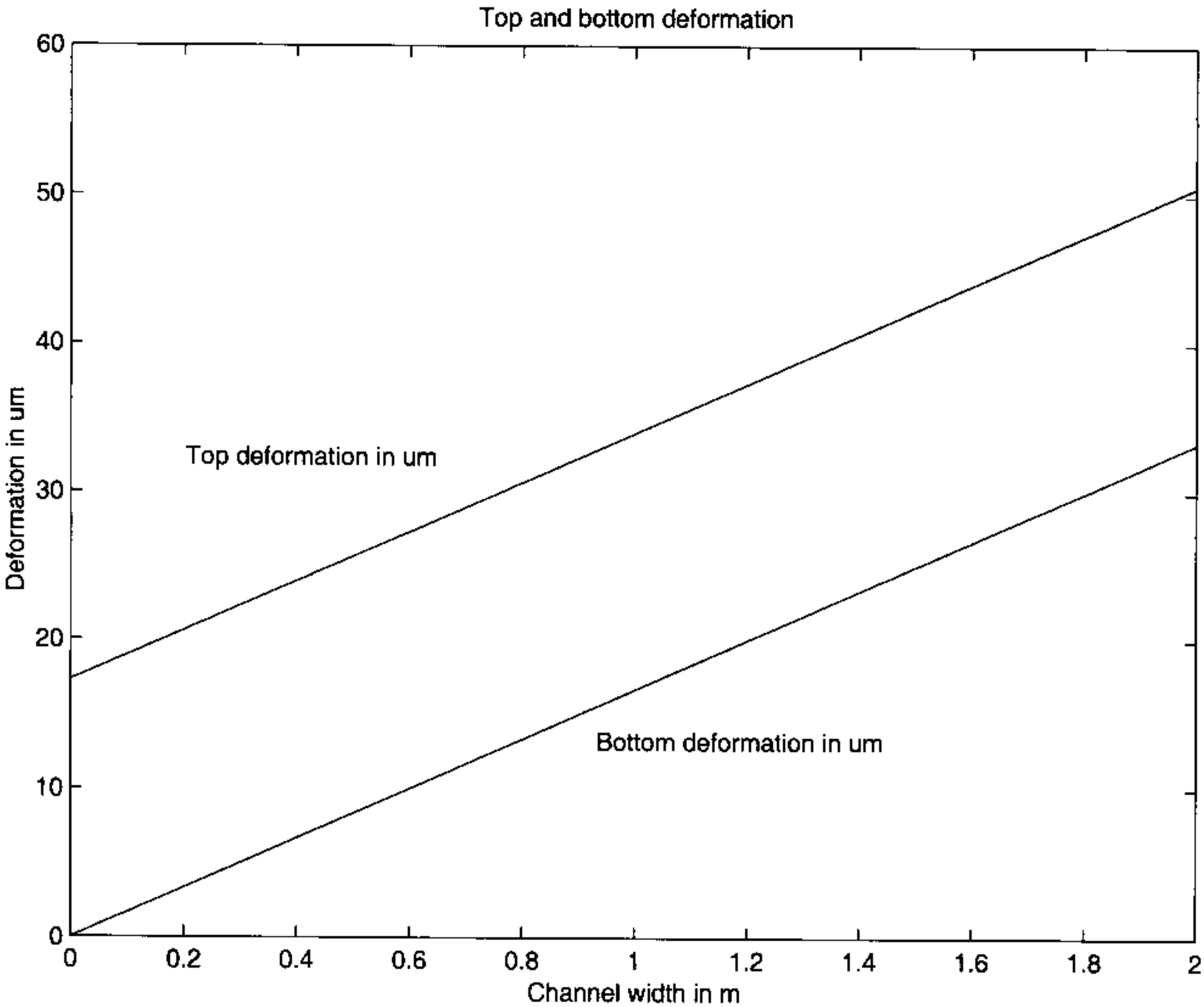


Figure 3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60
50
40
30
20
10
0
Deformation in um
Top deformation in um
Bottom deformation in um
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0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Channel width in m

FIGURE 4

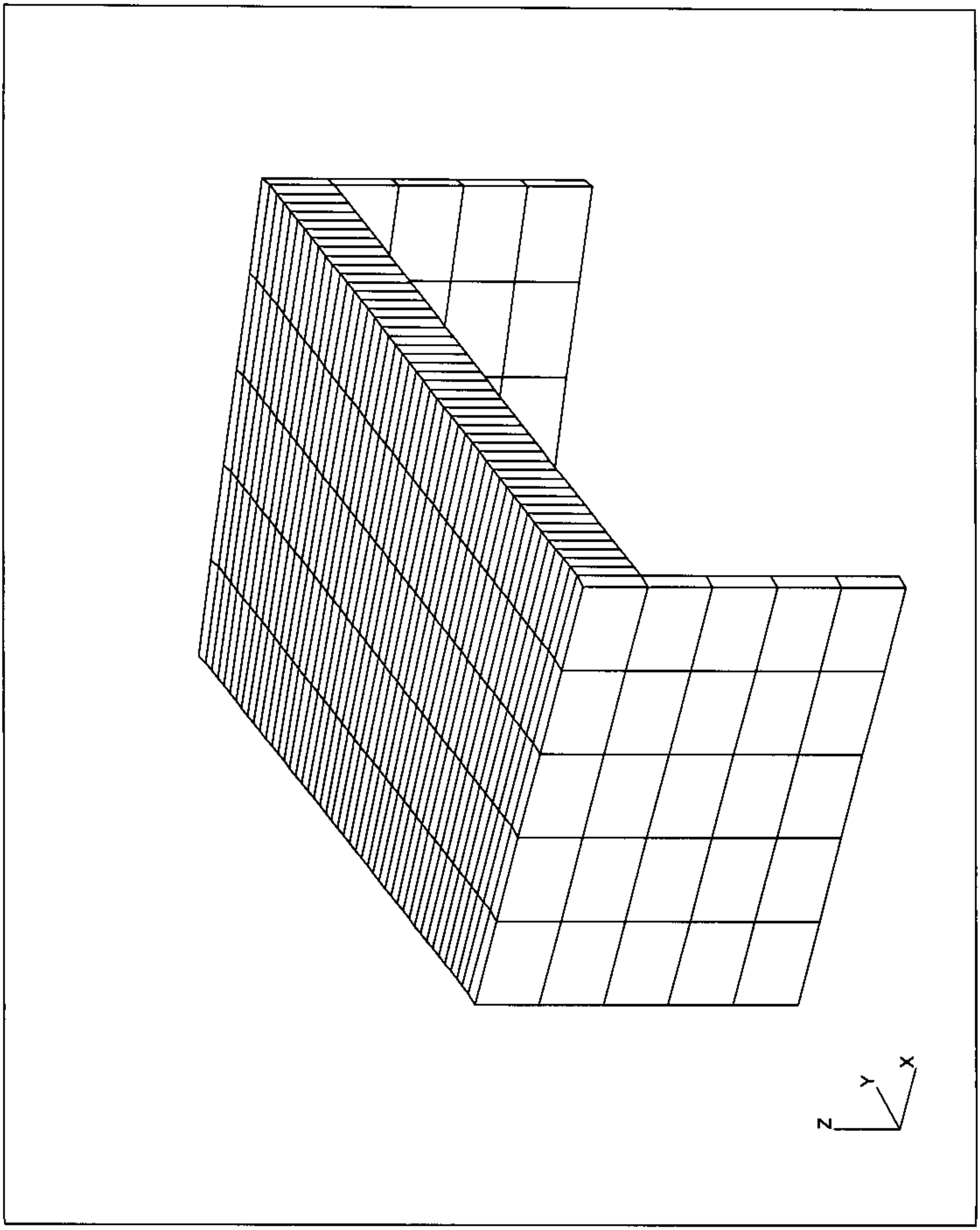

FIGURE 5

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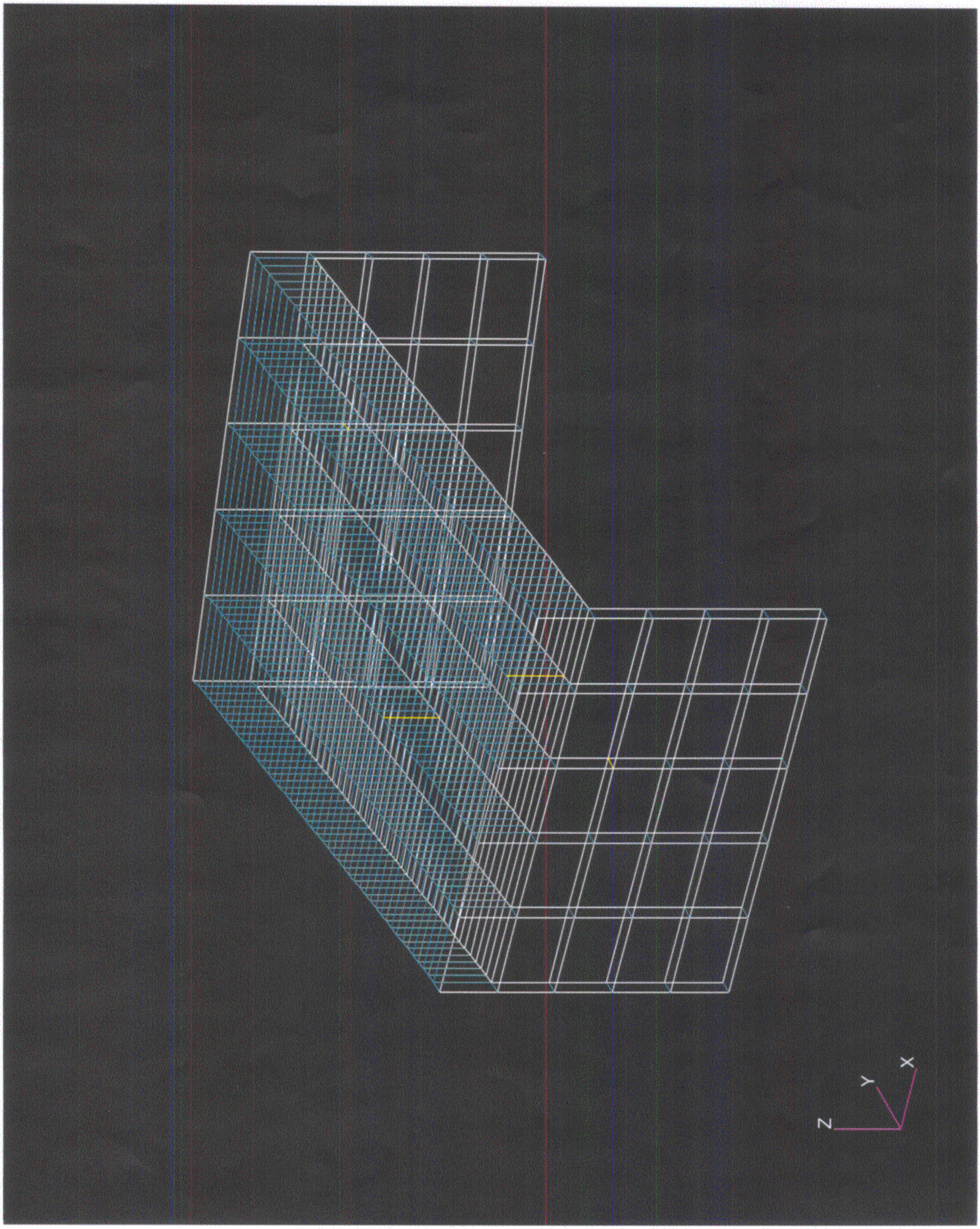
FIGURE 6



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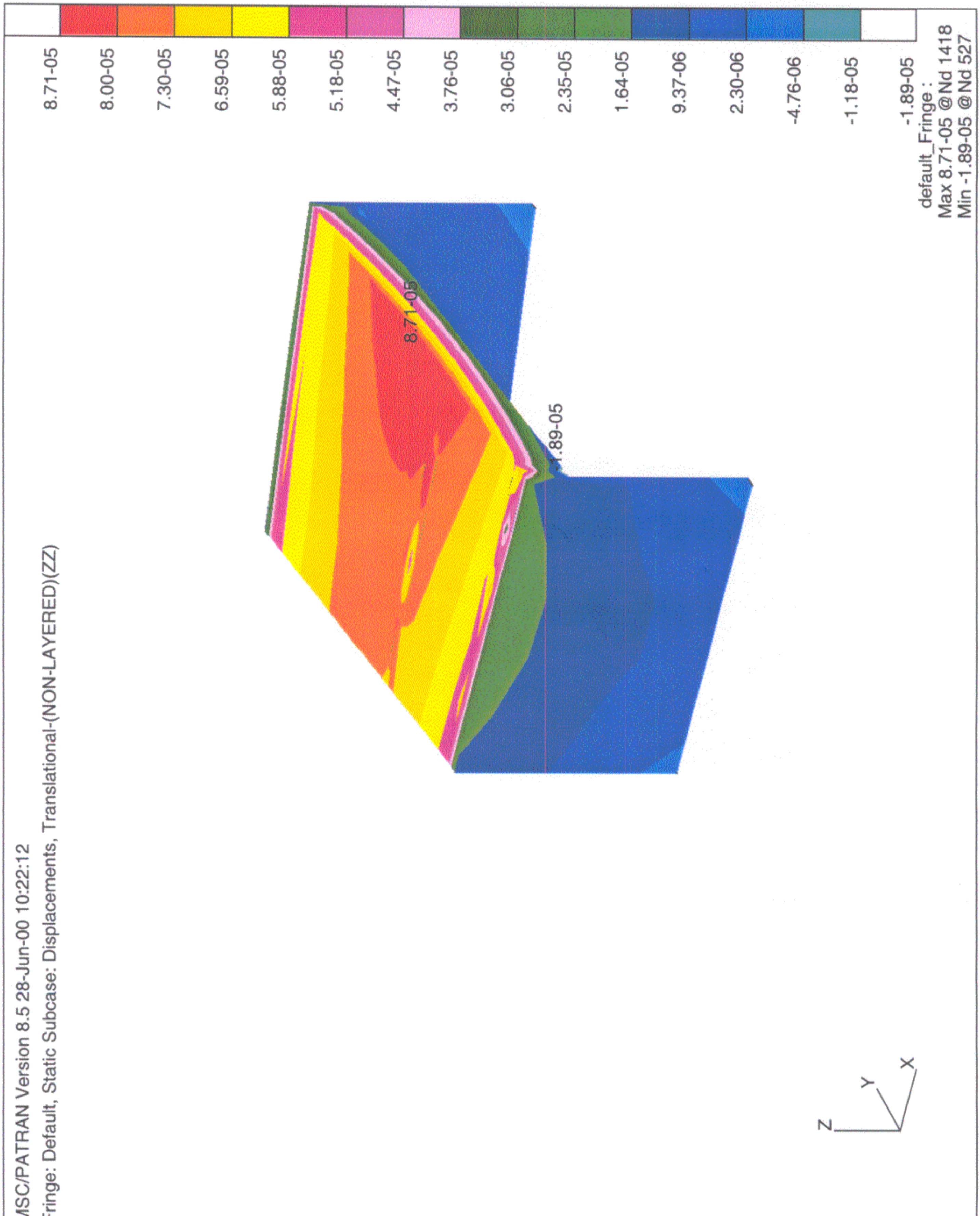
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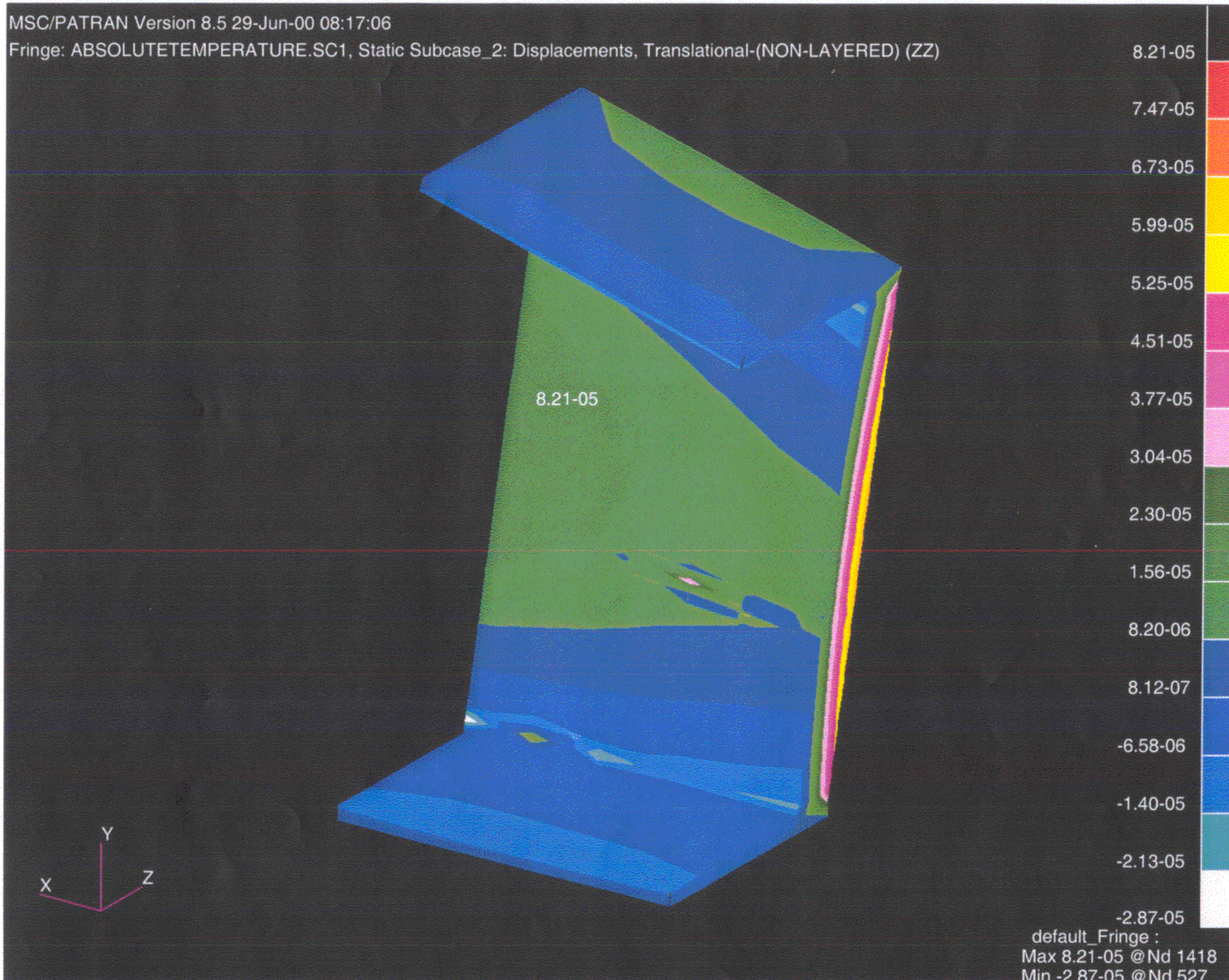
FIGURE 8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