GEM TN-93-350

Gravity Sag of Sandwich Panel Assemblies as Applied to Precision Cathode Strip Chamber Structural Design

John Horvath
Lawrence Livermore National Laboratory

July 12, 1993

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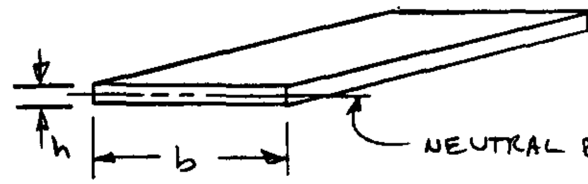
HOW TO CALCULATE THE STIFFNESS OF A STACK OF SLABS

STIFFNESS OF ONE SOLID SLAB
WITH RECTANGULAR CROSS-SECTION

$$I_{SLAB} = \frac{bh^3}{12}$$



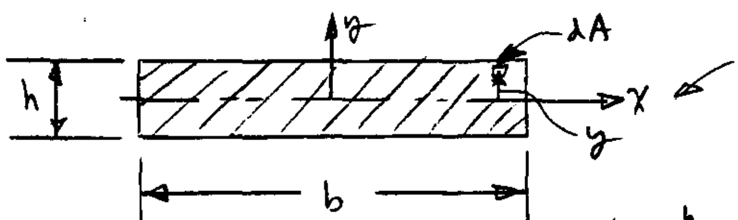
NOTE:

I_{SLAB} IS THE "AREA MOMENT OF INERTIA" OF THE CROSS-SECTION CALCULATED WITH RESPECT TO THE CENTROID OF THE SECTION.

THE DEFINITION OF "I" IS,

$$I = \int_{AREA} y^2 \, dA$$ WHERE y = DISTANCE FROM THE NEUTRAL PLANE TO ELEMENT dA

THE "INERTIA" OF A RECTANGULAR $b \times h$ CROSS-SECTION IS,



THE VERTICAL CO-ORDINATE OF THE CENTROID IS ALSO CALLED THE NEUTRAL PLANE

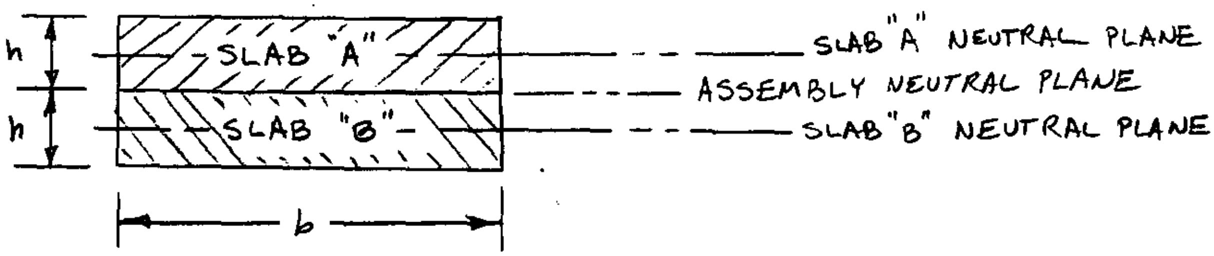
$$I = \int_{AREA} y^2 \, dArea = \int_0^b \int_{-\frac{h}{2}}^{\frac{h}{2}} y^2 \, dy \, dx$$

$$I = \left[\int_{-\frac{h}{2}}^{\frac{h}{2}} y^2 dy \; x \right]_0^b = \left[\left[\frac{y^3}{3} \right]_{-\frac{h}{2}}^{\frac{h}{2}} x \right]_0^b$$

$$I = \frac{(2) h^3 b}{(8)(3)}$$

$$\boxed{I_{RECTANGLE} = \frac{bh^3}{12}}$$ = MOMENT OF INERTIA OF <u>ONE</u> <u>RECTANGULAR</u> <u>SLAB</u>

SUPPOSE THERE ARE TWO SLABS "GLUED" TOGETHER (ASSUME BOTH ARE MADE OF THE SAME MATERIAL.)



INERTIA OF COMPONENTS:

$$I_{"A"} = \frac{bh^3}{12} \quad \text{(ABOUT SLAB "A" NEUTRAL PLANE)}$$

$$I_{"B"} = \frac{bh^3}{12} \quad \text{(ABOUT SLAB "B" NEUTRAL PLANE)}$$

INERTIA OF ASSEMBLY:

SINCE THE TWO SLABS ARE RIGIDLY "GLUED" TOGETHER, THE PARALLEL AXIS THEOREM MAY BE APPLIED.

$$I_{ASSEMBLY} = \sum I_o + \sum A y^2_{N.P.}$$

WHERE I_o IS THE INERTIA OF A COMPONENT ABOUT ITS NEUTRAL PLANE

A IS THE AREA OF A COMPONENT

AND $y_{N.P.}$ IS THE DISTANCE FROM THE ASSEMBLY NEUTRAL PLANE TO THE COMPONENT NEUTRAL PLANE.

THEREFORE,

$$I_{ASSEMBLY} = \left[\frac{bh^3}{12} + \frac{bh^3}{12}\right] + \left[\left(\frac{h}{2}\right)^2 bh + \left(\frac{-h}{2}\right)^2 bh\right]$$

$$I_{ASSEMBLY} = \frac{8bh^3}{12}$$ = MOMENT OF INERTIA OF GLUED ASSEMBLY (OF SLABS OF SAME MATERIAL)

CHECK: FOR THE ASSEMBLY AS ONE COMPONENT,

$$I_{ASSEMBLY} = \frac{b(2h)^3}{12} = {}_2\frac{8\,bh^3}{12}$$

FOR COMPARISON,

SUPPOSE THE TWO SLABS ARE NOT GLUED.

$$I_{ASSEMBLY} = \sum I_o$$

$$I_{ASSEMBLY} = \frac{bh^3}{12} + \frac{bh^3}{12}$$

$$I_{ASSEMBLY} = \frac{2bh^3}{12}$$

SUMMARY:

FOR TWO SLABS OF WIDTH "b" AND HEIGHT "h" STACKED TOGETHER,

IF ALLOWED TO SLIP (i.e. SHEAR IS ALLOWED)

$$I_{ASSEMBLY} = \frac{2bh^3}{12}$$

IF NOT ALLOWED TO SLIP (i.e. "IDEAL" ZERO-SHEAR GLUE)

$$I_{ASSEMBLY} = \frac{8bh^3}{12}$$

CSC OBSERVATIONS:

AS APPLIED TO CATHODE STRIP CHAMBERS, A "SLAB" IS ANALOGOUS TO A SANDWICH PANEL.

THE "GLUE" BOND THAT IS NECESSARY TO PREVENT SLIDING BETWEEN SLABS IS THE "GAP FRAME". IT BONDS TOGETHER THE SANDWICH PANELS.

THE STRUCTURAL PURPOSE OF THE GAP FRAME IS TO PREVENT SLIDING BETWEEN SANDWICH PANELS.

THE GAP FRAME MATERIAL AND GEOMETRIC DESIGN MUST RESIST SHEAR DEFORMATION.

STIFFNESS OF A STACK OF SLABS

FOR A STACK OF IDENTICAL SLABS OF THE SAME MATERIAL THAT ARE FASTENED TO PREVENT SLIDING,

$$I_{\underset{(\text{NO-SLIP})}{\text{STACK}}} = n^3\, I_{\text{SLAB}}$$

WHERE I_{STACK} = STACK STIFFNESS

I_{SLAB} = SLAB STIFFNESS

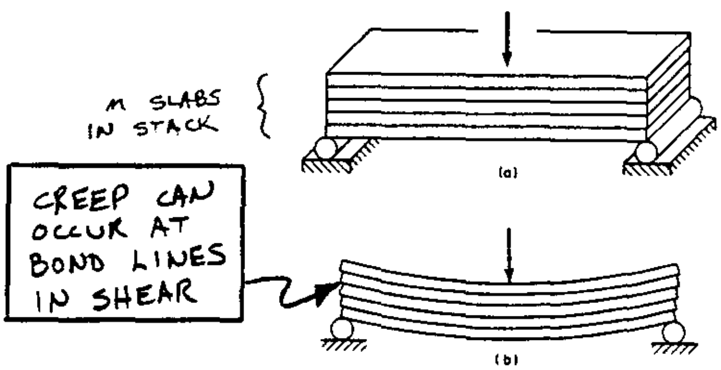
n = NUMBER OF SLABS

FOR SLABS FREE TO SLIDE ON EACH OTHER,

$$I_{\underset{(\text{SLIP})}{\text{STACK}}} = n\, I_{\text{SLAB}}$$

THE RATIO OF $\dfrac{I_{\text{GLUED}}}{I_{\text{SEPARATE}}}$ IS n^2.

When a bending load is applied, the stack will deform as indicated in Fig. 10-13(*b*). Since the slabs were free to slide on one another, the ends do not remain even but become staggered. Each of the slabs behaves as an independent beam, and the total resistance to bending of n



SLABS FASTENED TO PREVENT SLIDING

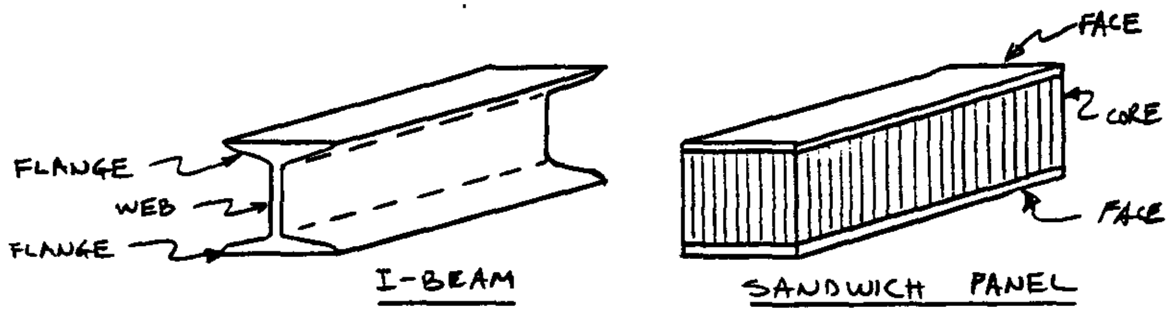
SLABS FREE TO SLIDE ON EACH OTHER

FIG. 10-13

slabs is approximately n times the resistance of one slab alone. If the experiment is repeated after the slabs have been fastened together so as to prevent their sliding on one another, the entire assembly would behave as a single beam having a thickness equal to n times the thickness of one slab. In the case of elastic action, the bending resistance of the assembly would be approximately n^3 times the bending resistance of one slab. From this simple experiment you can see the importance of a beam being able to resist longitudinal shear forces so that this "slipping" will not occur.

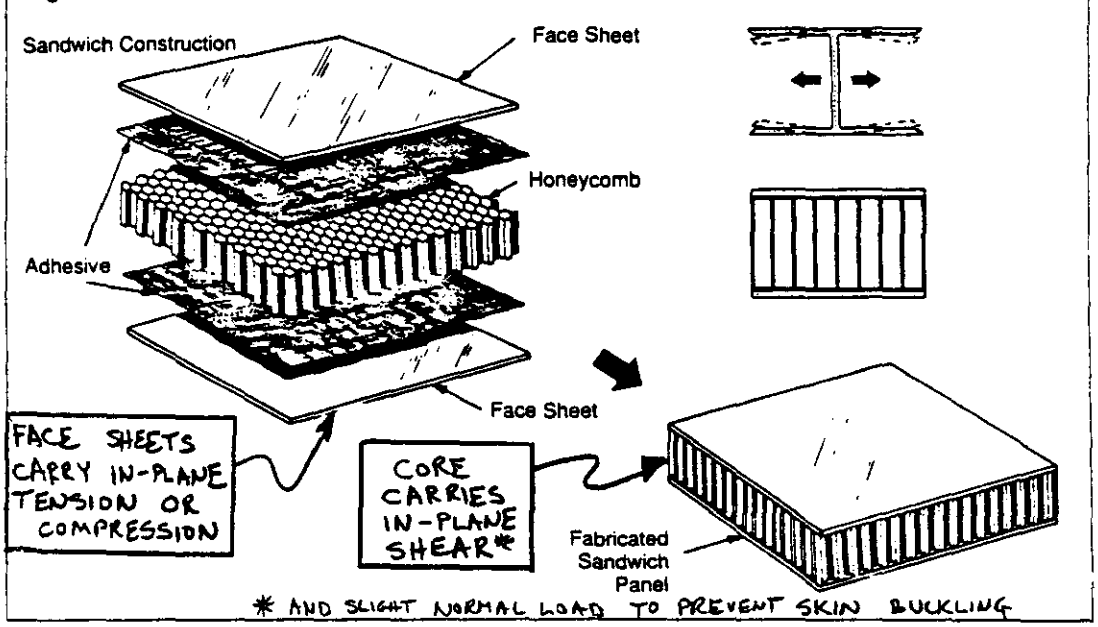
STIFFNESS OF A SANDWICH PANEL

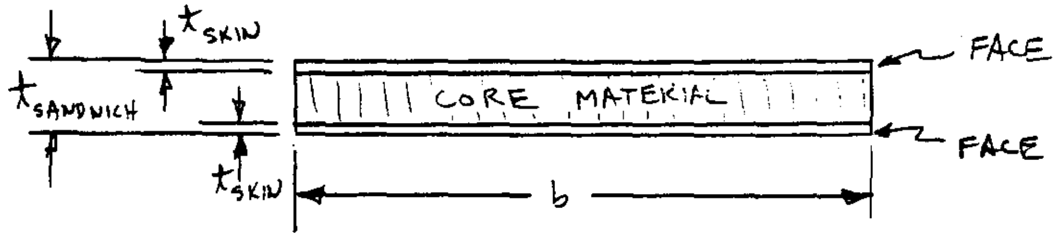
THE CORE OF A SANDWICH PANEL BEHAVES LIKE THE "WEB" OF AN I-BEAM, PREVENTING SLIDING BETWEEN TOP AND BOTTOM FLANGES.



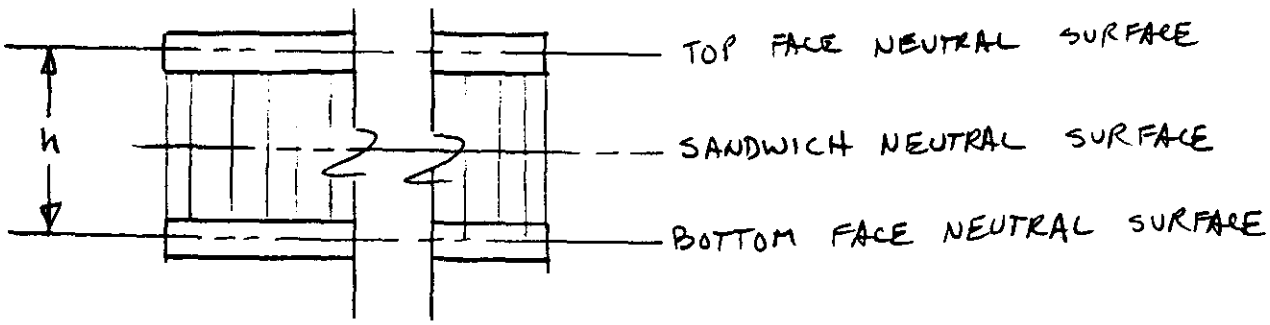
The facings of a sandwich panel used as a beam act similarly to the flanges of an I-beam by taking the bending loads — one facing in compression and the other in tension. Expanding this comparison further, the honeycomb core corresponds to the web of the I-beam. This core resists the shear loads, increases the stiffness of the structure by spreading the facings apart, but unlike the I-beam's web, gives continuous support to the flanges or facings. The core-to-skin adhesive rigidly joins the sandwich components and allows them to act as one unit with a high torsional and bending rigidity.

Figure 1





SINCE THE CORE MATERIAL IS "SOFT" COMPARED TO THE FACE MATERIAL, IT IS <u>IGNORED</u> IN THE INERTIA CALCULATION.



DEFINE "h" AS THE CENTROID DISTANCE BETWEEN THE FACES (DISTANCE BETWEEN NEUTRAL SURFACES)

$$I_{SANDWICH} = \sum I_0 + \sum A y^2$$

$$= \left[\frac{b\,t_{SKIN}^3}{12} + \frac{b\,t_{SKIN}^3}{12}\right] + \left[b\,t_{SKIN}\left(\frac{h}{2}\right)^2 + b\,t_{SKIN}\left(\frac{-h}{2}\right)^2\right]$$

$$= \frac{2\,b\,t_{SKIN}^3}{12} + \frac{2\,b\,t_{SKIN}\,h^2}{4}$$

$$\boxed{I_{SANDWICH} = \frac{b\,t_{SKIN}^3}{6} + \frac{b\,t_{SKIN}\,h^2}{2}}$$

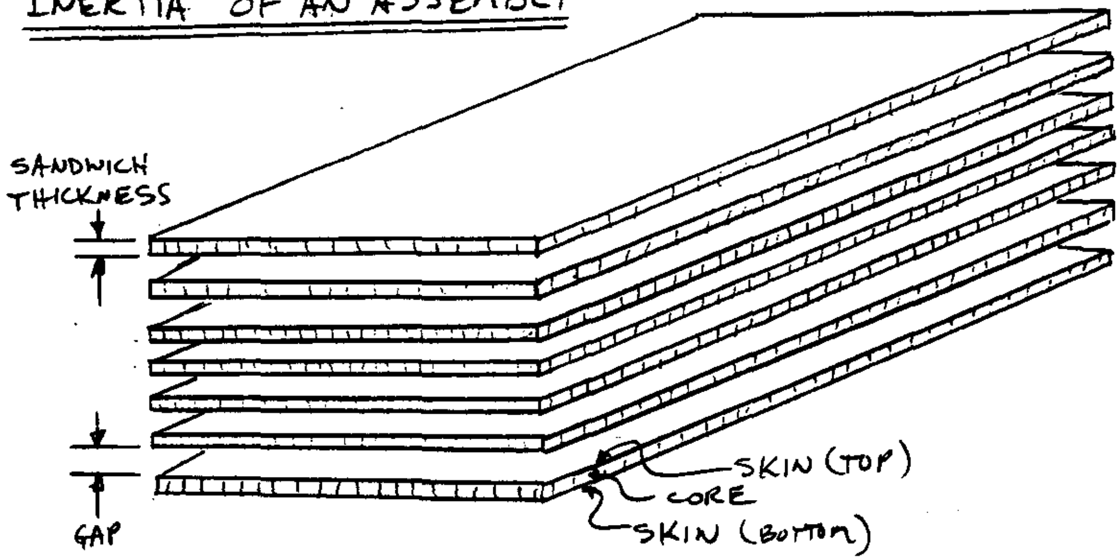
SINCE THE SKIN THICKNESS (t_{SKIN}) IS USUALLY SMALL, THE FIRST TERM CONTRIBUTES VERY LITTLE TO THE PANEL STIFFNESS.

THEREFORE INCREASING "t_{SKIN}" SHOULD HAVE A SMALL EFFECT ON STIFFNESS,

AND INCREASING "h" SHOULD HAVE A LARGER EFFECT.

ALSO, CORE MATERIAL SHEAR STIFFNESS IS NEEDED TO LINK SKINS, BUT ITS CORE WEIGHT IS <u>DEAD</u> <u>LOAD.</u>

"INERTIA" OF AN ASSEMBLY



ASSUME, 7 EQUALLY SPACED SANDWICH PANELS (DIMENSIONS AS SHOWN)

"IDEALLY" PREVENTED FROM SLIPPING BY PERFECT MASSLESS GLUE.

TREAT EACH SKIN (7 SANDWICHES × 2 SKINS/SANDWICH = 14 SKINS) AS A COMPONENT.

$$I_{ASSEMBLY} = \sum_{i=1}^{14} I_i + \sum_{i=1}^{14} A_i y_i^2$$

WHERE $I_i = \dfrac{b\,t_{SKIN}^3}{12}$

$A_i = b\,t_{SKIN}$

y_i = DISTANCE FROM NEUTRAL SURFACE OF ASSEMBLY TO NEUTRAL SURFACE OF THE i-th SKIN

THIS ARITHMETIC HAS BEEN PROGRAMMED INTO A SPREADSHEET MODEL.

THE SPREADSHEET CALCULATES $I_{ASSEMBLY}$ USING THE PARALLEL AXIS THEOREM, THE SAME AS ABOVE.

THE SPREADSHEET MODEL PROVIDES RAPID CALCULATION OF ASSEMBLY STIFFNESS AS A FUNCTION OF VARIOUS PARAMETER VALUES.

PARAMETRIC ANALYSIS

- STACK OF 7 SANDWICH PANELS
- SANDWICH PANEL THICKNESS = 20 mm (CONSTANT)

PARAMETERS:

- SANDWICH PANEL SKIN THICKNESS ($0.5\,mm \le t \le 10\,mm$)
- GAP BETWEEN SANDWICH PANELS ($0.0 \le GAP \le 20\,mm$)
- SLIP OR NO-SLIP (GLUED) BETWEEN PANELS

THE RESULTS OF THE ABOVE ANALYSES ARE PLOTTED ON THE FOLLOWING PAGE.

(EACH POINT ON THE GRAPH REPRESENTS ONE SPREADSHEET ANALYSIS RUN.)

CONCLUSIONS DRAWN FROM GRAPH:

THERE IS A FACTOR OF 39 INCREASE IN ASSEMBLY STIFFNESS BETWEEN A "SLIP" AND A "NO-SLIP" STACK OF 7 PANELS WITH 10 mm GAPS BETWEEN PANELS ($t_{SKIN} = 0.5\,mm$)

THE "RULE OF THUMB" GRAPH OF $I_{NO\text{-}SLIP} = n^2 I_{SLIP\text{-}ALLOWED}$

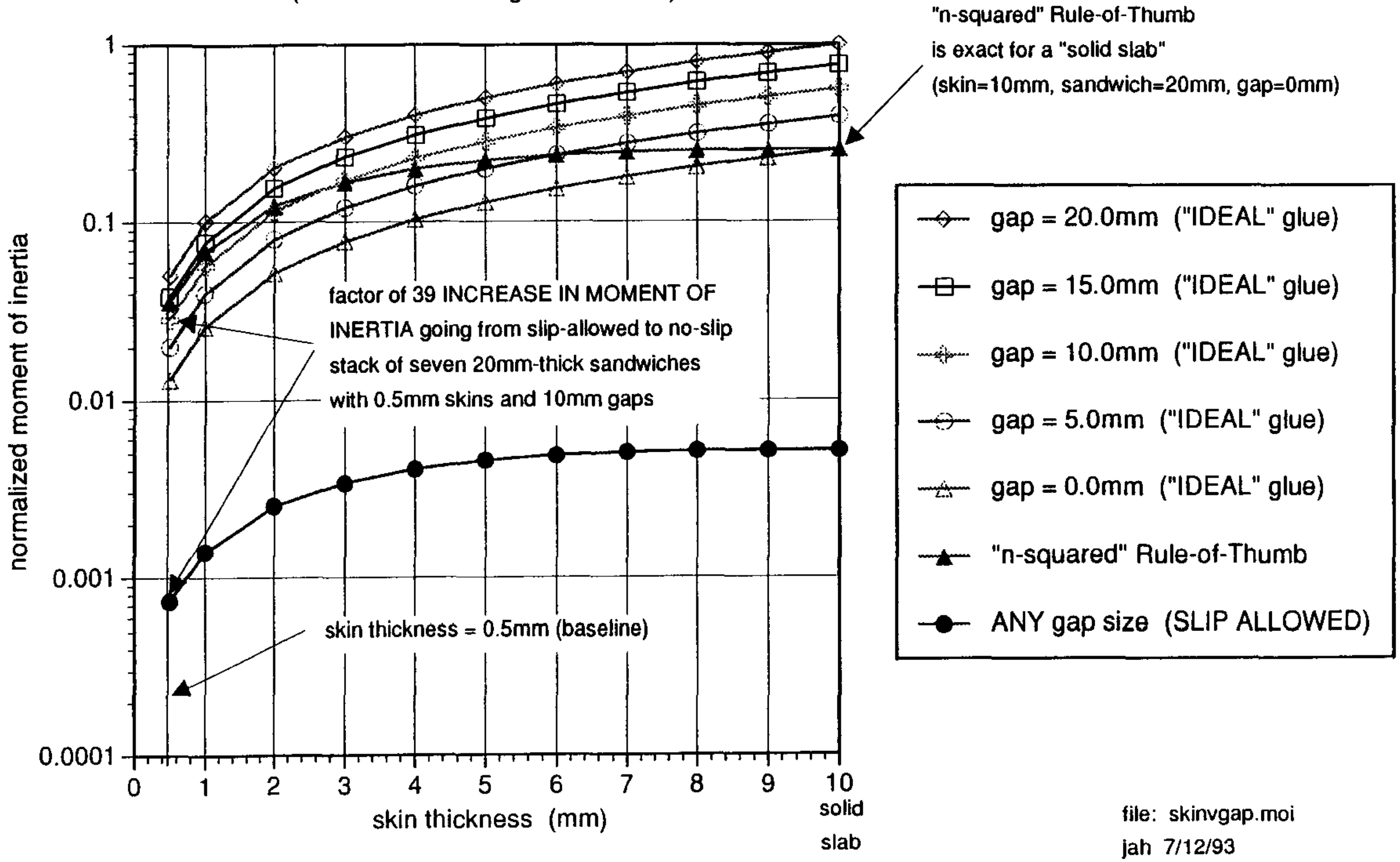
IS SEEN TO FALL ACROSS GRAPHS FOR VARIOUS GAP SIZES OF NO-SLIP ASSEMBLIES. THE "RULE OF THUMB" IS FOR A SOLID PANEL. SANDWICH PANELS BEHAVE DIFFERENTLY.

THE SPECIAL CASE OF A STACK OF 7 20 mm-THICK SANDWICH PANELS WITH 10 mm SKINS AND GAP=0.0 REPRODUCES THE $I_{NO\text{-}SLIP} = n^2 I_{SLIP\text{-}ALLOWED}$ VALUE EXACTLY.

(TWO 10 mm SKINS ON A 20 mm SANDWICH IS A SOLID PANEL. GAP=0.0 IS A SOLID ASSEMBLY.)

IN GENERAL, THERE IS A DECREASING PAYOFF FOR INCREASING SKIN THICKNESS FOR A FIXED SANDWICH THICKNESS. (NOTE: STIFFNESS AXIS IS LOGARITHMIC.)

Normalized Moment of Inertia
Vs. Skin Thickness, Gap Thickness, & Gap "Slip"
Seven 20.0mm-thick Sandwich Panels
("ideal" zero-shear glue assumed)



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GRAVITY SAG OF AN ASSEMBLY OF SANDWICH PANELS

THE CALCULATION OF STIFFNESS AS A FUNCTION OF SKIN THICKNESS IS NOT DIRECTLY APPLICABLE TO CHAMBER DESIGN.

STIFFNESS WOULD BE DIRECTLY APPLICABLE IF CHAMBER WEIGHT WAS AN INSIGNIFICANT FRACTION OF THE TOTAL LOAD ON THE CHAMBER.

FOR CATHODE STRIP CHAMBERS, THE WEIGHT OF THE STRUCTURAL COMPONENTS IS ABOUT 90% OF THE TOTAL LOAD. (NON-STRUCTURAL ELECTRONICS, UTILITIES AND ALIGNMENT HARDWARE COMPRISE THE REST.)

> SINCE INCREASING PANEL SKIN THICKNESS NOT ONLY INCREASES ASSEMBLY STIFFNESS, BUT ALSO INCREASES CHAMBER WEIGHT, THE IMPORTANT INDICATOR FOR CHAMBER STRUCTURAL DESIGN FOR STIFFNESS IS GRAVITY SAG.

THE FOLLOWING PAGE CONTAINS BEAM DEFLECTION EXPRESSIONS FOR VARIOUS SUPPORT LOCATIONS.

THE MOST CONSERVATIVE (LARGEST GRAVITY SAG) OCCURS FOR SIMPLE SUPPORTS AT THE EXTREME END POINTS.

(THE OPTIMUM LOCATIONS FOR SUPPORTING A UNIFORM BEAM ARE AT POINTS 0.223 L FROM THE ENDS. THIS IS CASE 4 ON THE CHART)

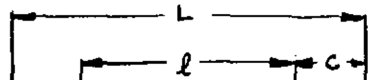
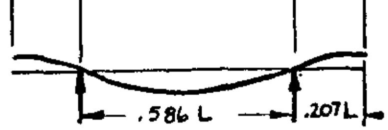
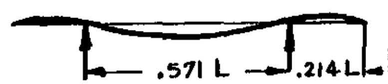
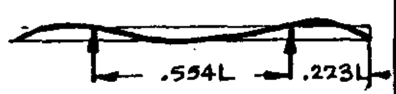
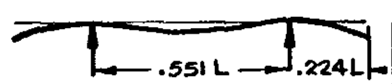
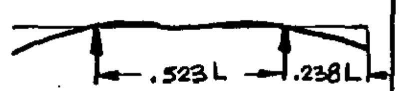
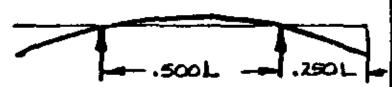
> THE GRAVITY SAG OF AN ASSEMBLY OF SANDWICH PANELS SUPPORTED AT THE EXTREME ENDS (MOST CONSERVATIVE CASE) HAS BEEN CALCULATED USING A SPREADSHEET.

NEW PARAMETERS ARE NOW INTRODUCED.

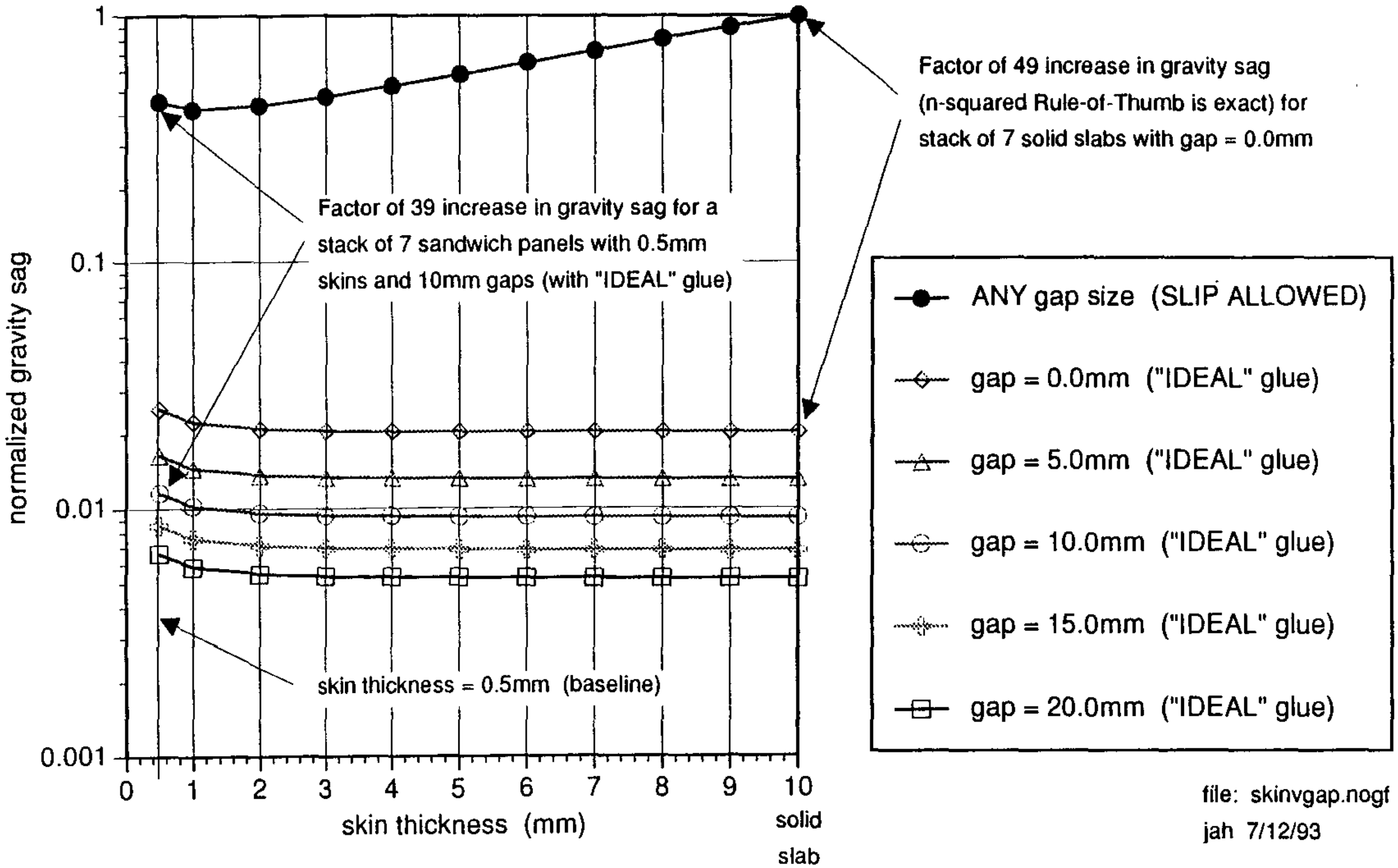
THE CROSS-SECTION INERTIA WAS A FUNCTION OF CROSS-SECTION DIMENSIONS ONLY.

THE BEAM GRAVITY SAG IS A FUNCTION OF THE CROSS-SECTION MOMENT OF INERTIA (PREVIOUSLY CALCULATED), MATERIAL MODULUS, MATERIAL DENSITY, BEAM LENGTH, AND SUPPORTS.

BEAM CALCULATIONS - SPECIAL CASES OF SYMETRICAL OVERHANGING BEAMS WITH UNIFORM LOAD w = UNIT LOAD (e.g. lbs/in)

SPECIAL CASE / CASE #		DISTANCE EACH WAY FROM CENTER TO INFLECTION POINT (POINT OF ZERO MOMENT) $=\sqrt{\frac{\ell^2}{4}-c^2}$	MOMENT AT CENTER $=\frac{w(c^2-\frac{\ell^2}{4})}{2}$	MOMENT AT SUPPORTS (MAX. MOMENT) $=\frac{wc^2}{2}$ = MAX. MOMENT	DEFLECTION AT ENDS $=\frac{wc}{24EI}(3c^2(c+2\ell)-\ell^3)$ PLUS = DOWN MINUS = UP	DEFLECTION AT CENTER $=\frac{w\ell^2}{384EI}(5\ell^2-24c^2)$ PLUS = DOWN MINUS = UP
						
① EQUAL MOMENTS AT SUPPORTS & CENTER		.207 L	$.0214\,wL^2$	$.0214\,wL^2$	$-.00021\,\frac{wL^4}{EI}$	$.000615\,\frac{wL^4}{EI}$
② ZERO SLOPE AT ENDS		.196 L	$.0192\,wL^2$	$.0223\,wL^2$	$-.000078\,\frac{wL^4}{EI}$	$.000512\,\frac{wL^4}{EI}$
③ NO END DEFLECTION		.183 L	$.0177\,wL^2$	$.0230\,wL^2$	0	$.000446\,\frac{wL^4}{EI}$
④ END & CENTER DEFLECTIONS EQUAL. MINIMUM OVERALL DEFLECTION		.164 L	$.0135\,wL^2$	$.0248\,wL^2$	$.000268\,\frac{wL^4}{EI}$	$.000268\,\frac{wL^4}{EI}$
⑤ ZERO SLOPE AT SUPPORTS		.159 L	$.0126\,wL^2$	$.0252\,wL^2$	$.000317\,\frac{wL^4}{EI}$	$.000237\,\frac{wL^4}{EI}$
⑥ NO CENTER DEFLECTION		.106 L	$.0057\,wL^2$	$.0284\,wL^2$	$.000759\,\frac{wL^4}{EI}$	0
⑦ INFLECTION POINT AT CENTER MAX. DEFLECTION AT CENTER ZERO MOMENT AT CENTER		0	0	$.0312\,wL^2$	$.00113\,\frac{wL^4}{EI}$	$-.000162\,\frac{wL^4}{EI}$

Normalized Gravity Sag
Vs. Skin Thickness, Gap Thickness, & Gap "Slip"
Seven 20.0mm-thick Sandwich Panels
("IDEAL" massless zero-shear gap frame and glue assumed)



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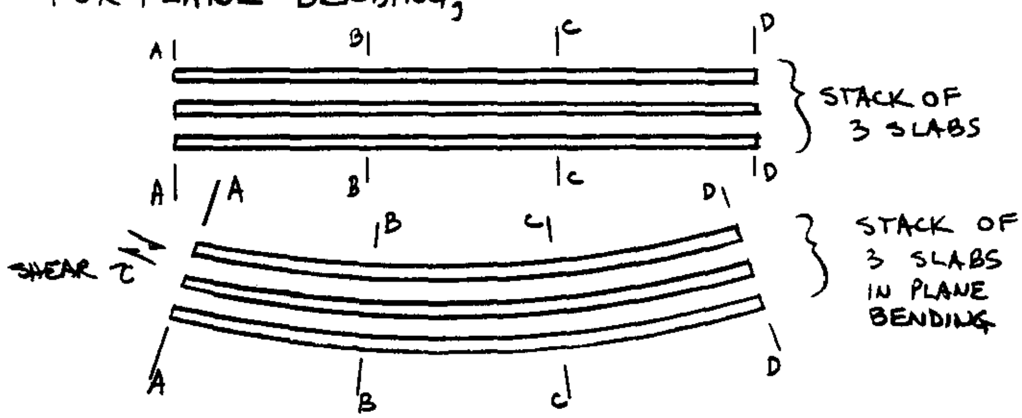
THE EFFECT OF GAP FRAMES ON DEFLECTION

IN THE PREVIOUS ANALYSIS THE STACK OF SANDWICH PANELS (WITH GAPS BETWEEN PANELS) WAS ASSUMED BONDED ACROSS THE GAPS WITH "IDEAL" MASSLESS GLUE.

IN MECHANICS, THIS BENDING ANALYSIS ASSUMPTION IS STATED AS "CROSS-SECTIONS REMAIN FLAT DURING BENDING"

FOR PLANE BENDING,

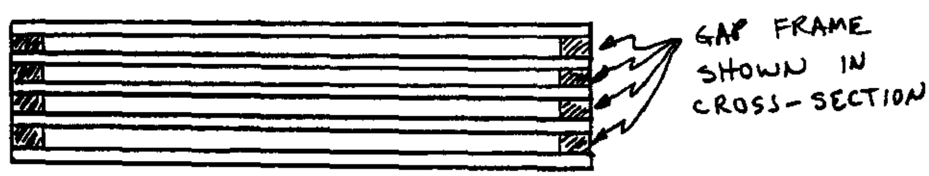


ALL CROSS-SECTION PLANES (A-A, B-B, ...) REMAIN FLAT DURING BENDING

TO ACHIEVE THIS LINKING BETWEEN SLABS THE GAPS MUST BE SPANNED AT SUFFICIENT LOCATIONS AND IN A MANNER THAT RESISTS THE SHEAR LOAD INDUCED BETWEEN SLABS.

SHEAR BETWEEN SLABS CAUSES THE ABOVE SECTION PLANES TO WARP. THIS RESULTS IN AN ADDITIONAL COMPONENT OF SAG CALLED "SHEAR DEFLECTION."

THE SANDWICH PANELS ARE LINKED TOGETHER INTO A "SANDWICH OF SANDWICHES" BY THE GAP FRAME. IDEALLY THE GAP FRAME SHOULD PREVENT SHEAR DEFORMATION (SLIPPING).



THE EFFECT OF GAP FRAME WIDTHS AND MATERIALS ON ASSEMBLY GRAVITY SAG IS CALCULATED USING ANOTHER SPREADSHEET[13] AS FOLLOWS:

THE EFFECT OF GAP FRAMES (CONTINUED)

$$\text{"EFFECTIVE STIFFNESS"} = \frac{E\ I}{\text{WEIGHT / UNIT LENGTH}}$$

THE MODULUS OF ELASTICITY OF THE GAP FRAME MATERIAL IS A MATERIAL PROPERTY.

THE "MOMENT OF INERTIA" OF THE GAP FRAME IS A FUNCTION OF THE AMOUNT AND THE LOCATION OF THE GAP FRAME (GEOMETRIC DISTRIBUTION).

THE WEIGHT/UNIT LENGTH OF THE GAP FRAME MATERIAL IS A FUNCTION OF BOTH THE MATERIAL AND THE GEOMETRIC DISTRIBUTION.

THE GAP FRAME WILL "LOAD" THE SANDWICH PANELS IF THE GAP FRAME EFFECTIVE STIFFNESS IS LOWER THAN THE SANDWICH PANEL E.S.

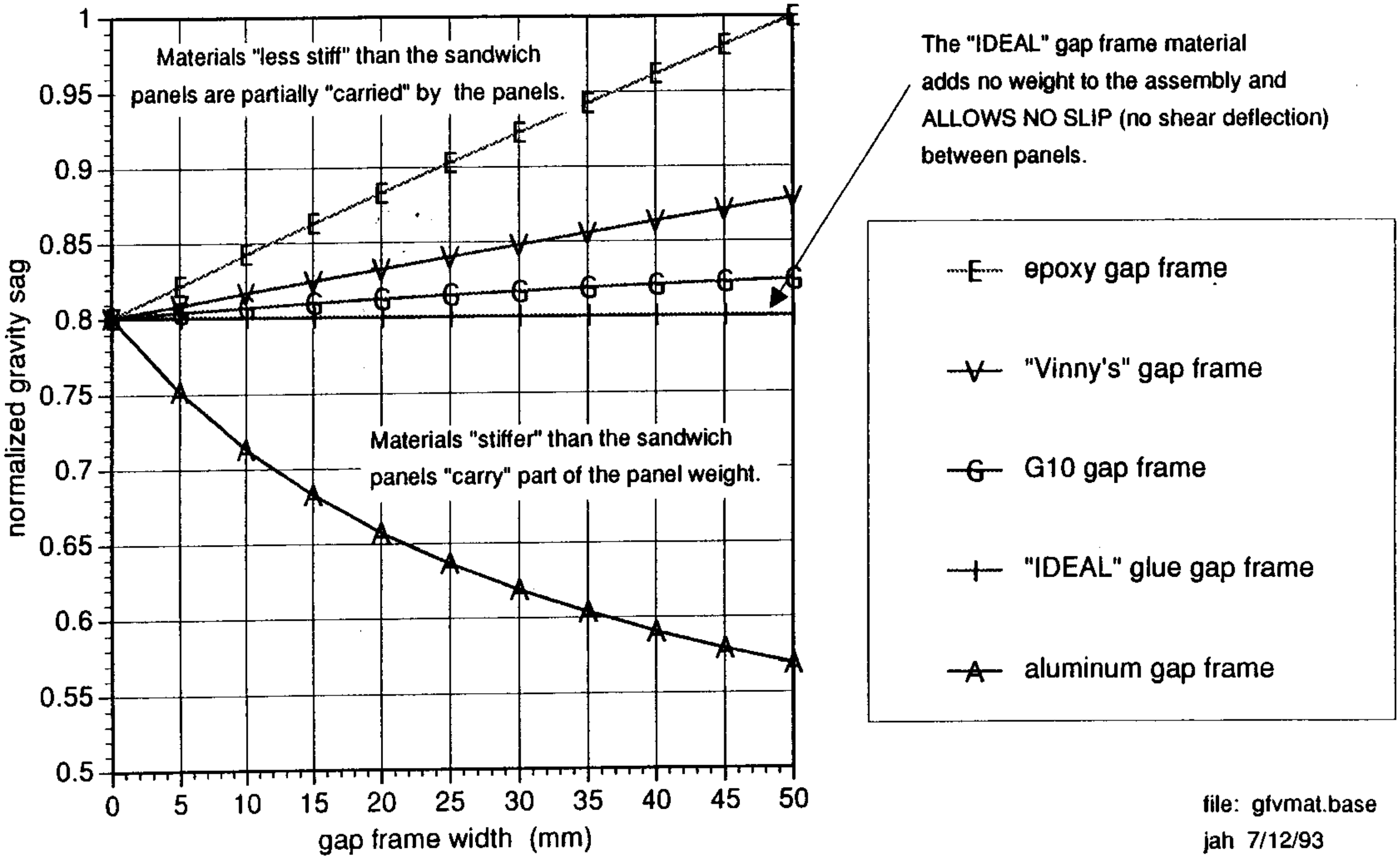
THE GAP FRAME WILL "CARRY" PART OF THE SANDWICH PANEL WEIGHT IF THE GAP FRAME E.S. IS HIGHER THAN THE SANDWICH PANEL E.S.

HOWEVER, THE ASSUMPTION THAT "CROSS-SECTIONS REMAIN FLAT" WILL NOT BE TRUE IF THE GAP FRAME ALLOWS SHEAR DEFORMATION TO OCCUR.

THE ABOVE ANALYSIS ASSUMES THAT EVEN THE MOST NARROW AND SOFT GAP FRAME WILL NOT SHEAR.

FOR SANDWICH ASSEMBLIES, THE EFFECT OF SHEAR DEFORMATION IN THE HONEYCOMB CORE MUST BE CONSIDERED, AS WELL AS THE GEOMETRY AND PROPERTIES OF THE GAP FRAMES.

Normalized Gravity Sag
Vs. Gap Frame Width & Gap Frame Material
Seven 20.0mm-thick Sandwich Panels, No Core Edge Filler,
Skin Thickness = 0.5mm, Gap Height = 10mm, NO SLIP ALLOWED



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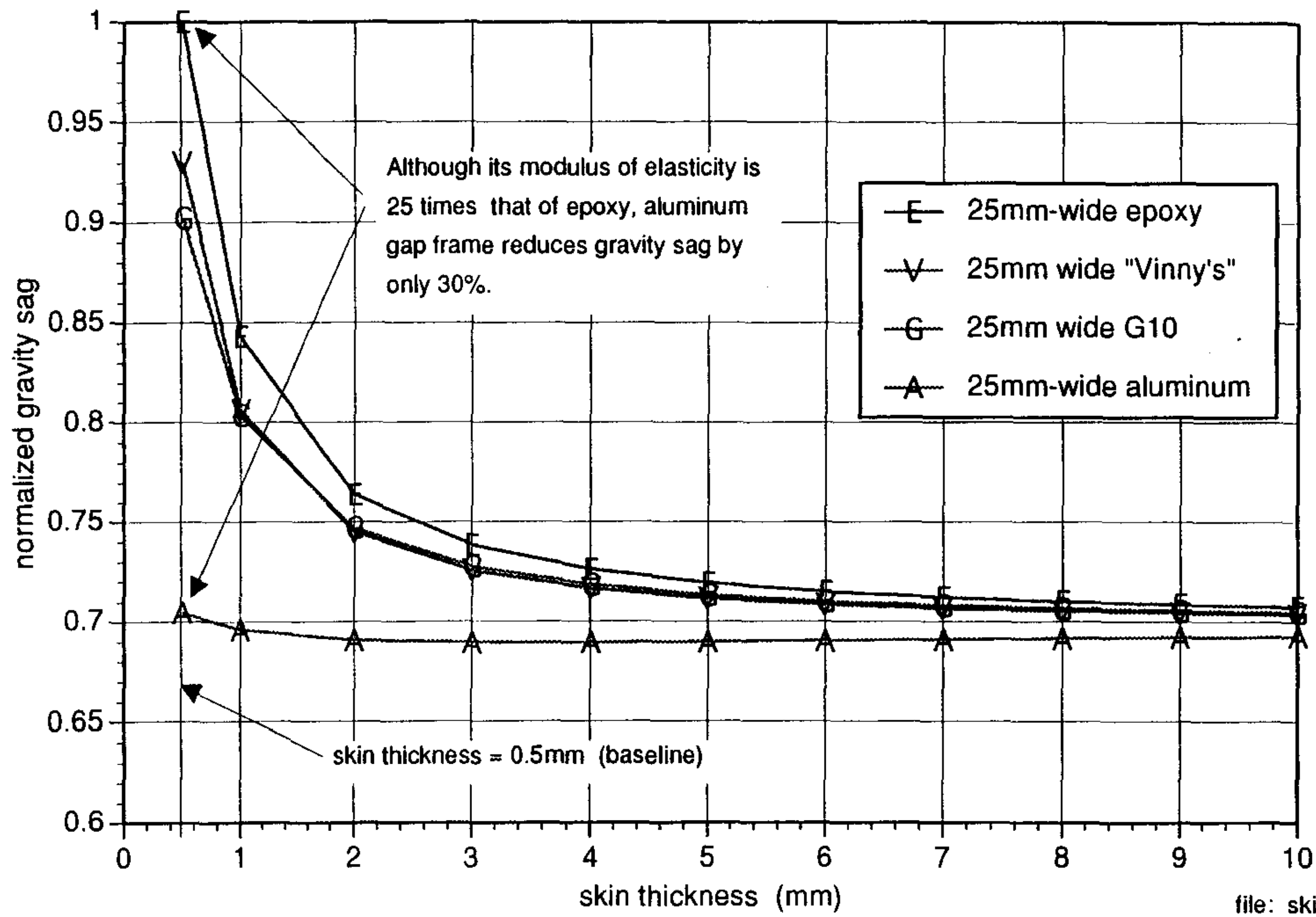
Normalized Gravity Sag
Vs. Skin Thickness & Gap Frame Material
Seven 20mm Sandwich Panels, 10mm Gaps, 25mm Gap Frame, No HC Core Edge Filler,
("IDEAL" zero-shear glue assumed)



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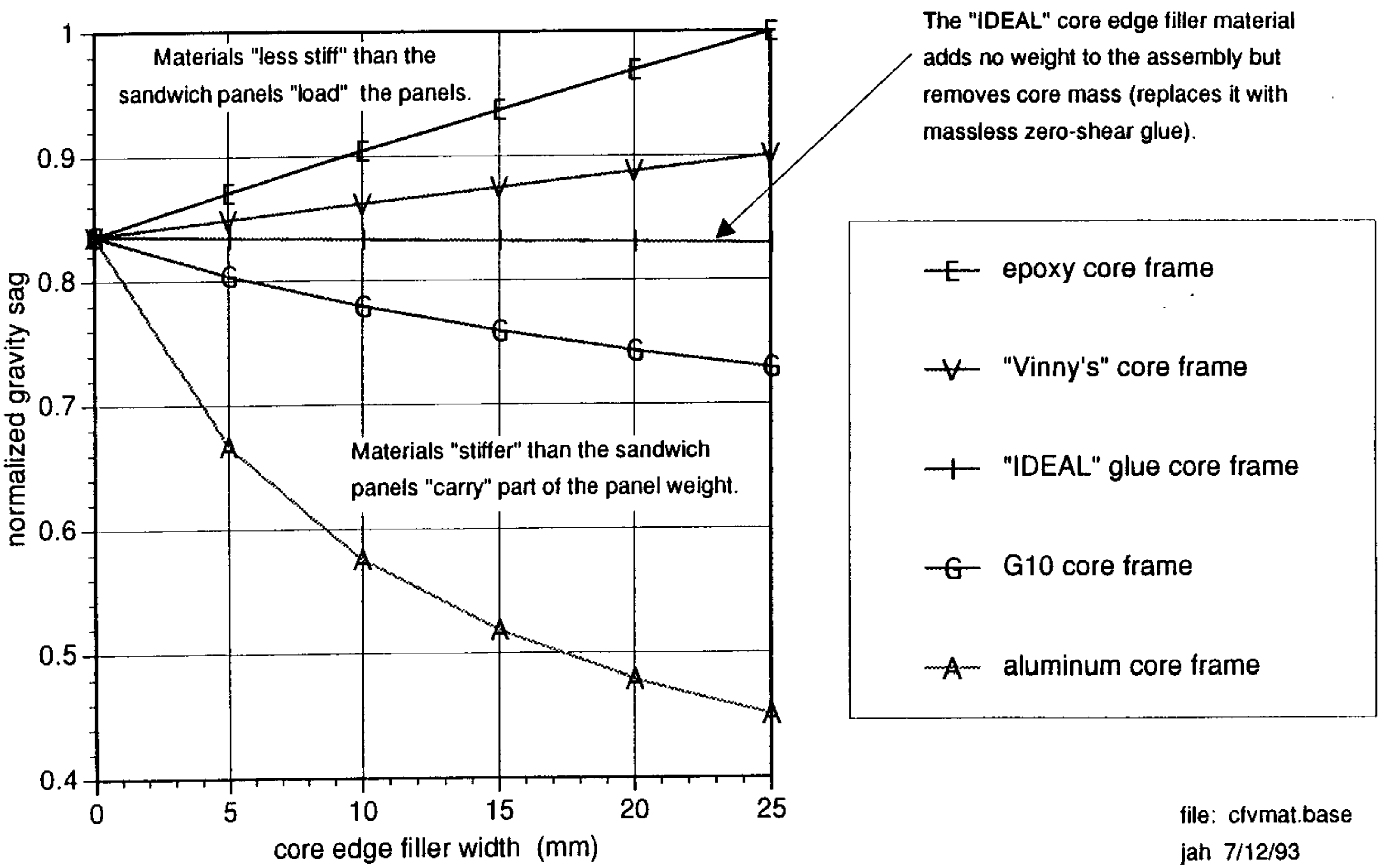
THE EFFECT OF SANDWICH CORE EDGE FILLER

CORE EDGE FILLER IS SIMPLY A SUBSTITUTE FOR THE SANDWICH CORE MATERIAL.

ITS EFFECT ON DEFLECTION IS PROPORTIONAL TO ITS RELATIVE "EFFECTIVE STIFFNESS" (AS DISCUSSED IN RELATION TO GAP FRAME EFFECTS).

THE ONLY MINOR DIFFERENCE IS THAT CORE EDGE FILLER DISPLACES HONEYCOMB MATERIAL. SINCE HONEYCOMB HAS ~~ZERO~~ MODULUS IN THE PLANE OF THE PANELS, LIGHT AND STIFF EDGE FILLERS SUCH AS G10 PROVIDE SOME BENEFIT, BUT ADD MASS.

Normalized Gravity Sag
Vs. Sandwich Core Edge Filler Width & Core Edge Filler Material
Seven 20.0mm-thick Sandwich Panels, 25mm-wide Epoxy Gap Frame,
Skin Thickness = 0.5mm, Gap Height = 10mm, NO SLIP ALLOWED



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Assumed Material properties

The following material properties were used in the normalized gravity sag calculations:

material	elastic modulus (psi)	mass density (lb sec^2/in^4)	elastic modulus (MPa)	mass density (g/cm^3)
G10 laminate	3,300,000	0.000180	22,759	1.926
epoxy	400,000	0.000111	2,759	1.190
"Vinny's"	98,395	0.000039	679	0.420
aluminum	10,000,000	0.000254	68,966	2.718
Nomex core	- - -	0.000003	- - -	0.029

Effect of Support locations

The normalized gravity sag graphs assume some constant support point locations. The chamber mass is assumed to be uniformly distributed along its length. The chart of beam deflection expressions shows that the maximum gravity sag is reduced by a factor of 48.6, i.e. (5/384)/0.000268, by going from support at the extreme ends to support at points 0.223L from the ends. Actual chamber sag will fall between these limits to the extent that weight is evenly distributed along the chamber length and shear deflection is prevented by proper panel-to-panel connection.

Conclusions

The magnitude of chamber sag is highly dependent on chamber support location and design of the gap frame. The gap between sandwich panels must be able to resist shear deformation. The major component of gravity sag is due to beam bending if shear deflection can be avoided. Gravity sag increases by a factor of 39 going from an "ideal" shear connection to slip-allowed between sandwich panels.

The mechanical connection between panels (gap frame and posts) will determine the magnitude of additional gravity sag introduced due to shear deflection. The design parameters that influence this value are the geometry of the gap frames around the perimeter of the panel, its mechanical properties, and the reliability of the panel-to-panel attachment technique (preloaded bolts, adhesives, pins, etc.)