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FACE WRINKLING AS A FUNCTION
OF SURFACE WAVINESS

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GENERAL DYNAMICS | FORT WORTH



ERR-FW-196

FACE WRINKLING AS A FUNCTION OF SURFACE WAVINESS

C. W. Rogers

6 May 1963

RESEARCH & ENGINEERING DEPARTMENTS

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GENERAL DYNAMICS | FORT WORTH

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NOTATION

- A_0 - Amplitude of initial waviness contained within a critical half-wave length
- A_t - Amplitude of the total initial waviness
- b - Thickness of core
- E_c - Young's modulus of core in a direction perpendicular to faces
- E_f - Young's modulus for faces
- G_c - Shear modulus of core
- K - Modulus of foundation
- l - Length of initial waviness
- l_1 - Critical half-wave length of wrinkling
- l_2 - Length of changing waviness
- t - Thickness of face
- N_{cr} - Critical load per inch
- F_c - Ultimate tensile or compressive strength of core or bond
- F_s - Ultimate shear strength of core
- I - Moment of inertia
- σ_{fw} - Critical face-wrinkling stress
- W - Depth of effective core for one face
- $w&l$ - Subscripts indicating transverse or longitudinal direction of core
- σ_0 - Numerator of critical wrinkling equation

SUMMARY

An attempt was made to establish the correlation between surface waviness of honeycomb core panels and the face wrinkling attendant upon the panels when subjected to compressive forces. Tests were conducted with honeycomb sandwich edgewise compression specimens with controlled initial surface waviness. A survey of the literature disclosed that previous investigations furnished an excellent base for advancing the state of the art of this widely used form of construction. Although previous researchers had suggested methods of predicting the effects of surface waviness on skin wrinkling when considering only a small degree of waviness, the current testing indicated that by extrapolation these predictions could be applied to panels having a large degree of waviness. Further investigation must be conducted to obtain an empirical constant that will eliminate the problem of estimating or measuring the initial surface waviness.

1. INTRODUCTION

The structural concept described by the term "sandwich" has been well defined analytically (Ref. 1) in all of its local modes of failure with the exception of the term "face wrinkling". The currently accepted method of analysis outlined by Kuenzi (Ref. 2) does not apply throughout the range of present-day usage.

"Face wrinkling" is a very localized buckling of one face only. The wrinkle may go into or away from the core, depending on the strength of the core and the core-to-face bond.

S. Yusuff (Ref. 3) proposed a solution based on the "beam on an elastic foundation" theory. The basic buckling equation is shown by Hetenyi (Ref. 4) to be

$$N_{cr} = 2 \sqrt{KEI}. \quad (1)$$

Yusuff relates the parameters of the above equation in terms of the sandwich components and includes the effect of initial waviness on the failing stress.

In this paper we will discuss the solution proposed by Yusuff and present the results of a recent series of tests designed to explore the effect of surface waviness.

2. DISCUSSION

The results of Yusuff's work are presented here for discussion purposes.

$$W = 0.72 t \sqrt[3]{\frac{E_f E_c}{G_c^2}} ; \quad (2)$$

if $b < 2W$ (thin core)

$$\sigma_{fw} = \frac{\sqrt{\frac{2}{3} E_f E_c \frac{t}{b}}}{1 + \frac{2 A_o E_c}{F_c b}} ; \quad \text{(for core compression or tension failure)} \quad (3)$$

if $b > 2W$ (thick core)

$$\sigma_{fw} = \frac{.96 \sqrt[3]{(E_f E_c G_c)}}{1 + \frac{E_c A_o}{W F_c}} ; \quad \text{(for core compression or tension failure)} \quad (4)$$

$$\sigma_{fw} = \frac{.96 \sqrt[3]{E_f E_c G_c}}{1 + \frac{A_o G_c}{F_s \ell_1}} ; \quad \text{(for shear failure of the core)} \quad (5)$$

The critical half-wave length of wrinkling, as expressed by Hetenyi, is:

$$\ell_1 = \frac{\pi}{\sqrt[4]{\frac{G E_c}{b E_f t^3}}} \quad (6)$$

In order to apply the above theory, a practical definition of waviness must be established. The writer has found that two distinct forms of surface waviness predominate; however, many others exist. These two are defined as follows:

Case 1 - Simple wrinkle

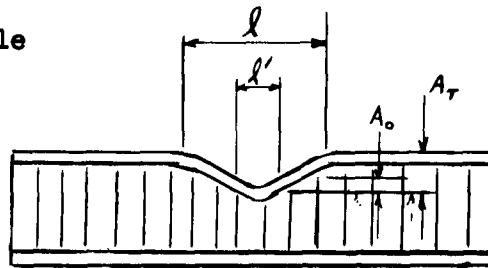


Figure 1 WRINKLE GEOMETRY CASE 1

by inspection

$$A_o = A_t \frac{l_1}{l} \quad (7)$$

Case 2 - Compound wrinkle

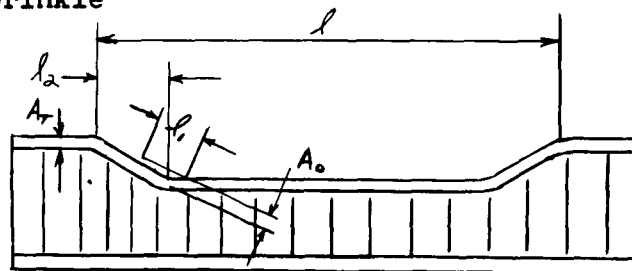


Figure 2 WRINKLE GEOMETRY CASE 2

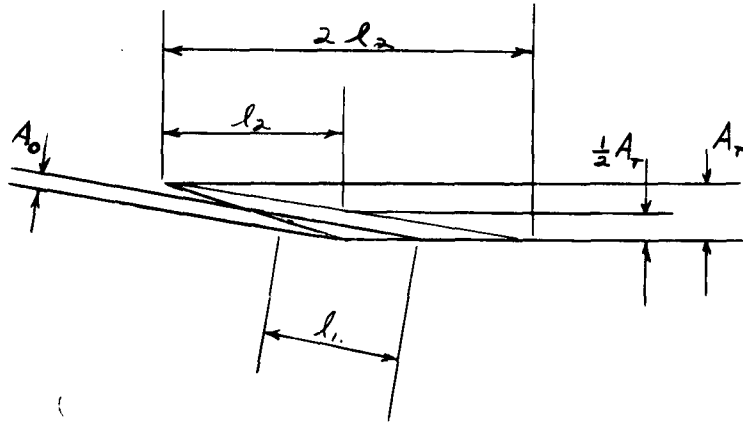


Figure 3 A_0 RELATIONSHIP CASE 2

Using the geometrical relationships shown in Figure 3, the following approximation can be made.

$$\frac{A_0}{l_1} = \frac{1/2 A_T}{2 l_2} ,$$

then

$$A_0 = \frac{A_T l_1}{4 l_2} . \quad (8)$$

The significant point brought out by the definition of A_0 for both Case 1 and Case 2 is that the critical amplitude, A_0 , is the amplitude of the surface waviness contained within a critical half-wave length. This point is one of the basic assumptions in Yusuff's derivation.

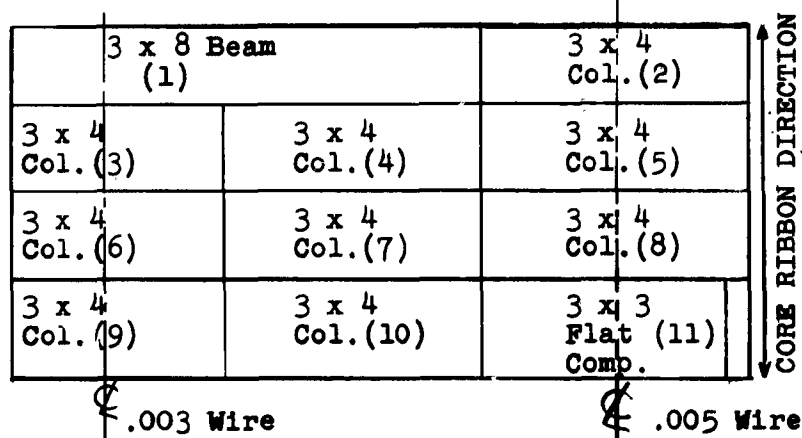
2.1 Test Specimens

Considerable experience has been gained in testing small 3- by 4-inch edgewise compression specimens of sandwich construction. These specimens have proven particularly valuable in evaluating the critical face-wrinkling stress for a particular type of sandwich. It is necessary to fill the loaded edges of the specimen with a suitable filler to prevent local failure. Hetenyi shows that the critical buckling stress for a semi-infinite column on an elastic foundation is half that of an infinite column because of the lack

of face moment continuity. This relationship is applicable to the loaded edge of a sandwich specimen and must be overcome by increasing the foundation stiffness. If the core cell size is relatively large, the sides must be filled also.

Twelve-inch-square sandwich panels were fabricated with the face material and core shown in Figure 4 and Table 1. Metlbond 408 was selected as the adhesive because of its excellent strength and wetting properties. This adhesive flows to the cell wall-face juncture to form a strong fillet without the aid of a glass cloth carrier. Consequently, there is no added stiffness in the faces because of the adhesive. Adhesives with a glass cloth carrier appreciably increase the apparent stiffness of relatively thin faces.

In an effort to obtain a controlled waviness, two wires were placed on the platen side of each panel as shown in Figure 4. The wires were .003 inch and .005 inch in diameter.



CORE PROPERTIES (Ref. 5)

TYPE IA 5052 ALUMINUM

- $F_{sw} = 120 \text{ psi}$
- $F_{sL} = 210 \text{ psi}$
- $F_c = 270 \text{ psi}$
- $E_c = 130,000 \text{ psi}$
- $G_{ow} = 21,500 \text{ psi}$
- $G_{cL} = 31,500 \text{ psi}$

- NOTES:**
1. Numbers in () are specimen numbers
 2. Beam flex test specimens are 3- by 8- inches
 3. Column compression test specimens are 3- by 4- inches
 4. Flatwise compression specimens are 3- by 3-inches

Figure 4 FACE-WRINKLING PANELS CUTTING PLAN

Table 1
TEST SPECIMENS CONFIGURATION

PANEL	FACE MATERIAL	GAGE	CORE THICKNESS	COMPUTED		
				σ_0	λ_1	W
A	7075 T6	.010	0.50	295,000	0.16	0.104
B	7075 T6	.010	0.50	295,000	0.16	0.104
C	7075 T6	.010	0.20	210,000	0.128	0.104
D	7075 T6	.010	0.20	210,000	0.128	0.104
E	17-7 PH (TH 1050)	.008	0.50	418,000	0.1775	0.116
F	17-7 PH (TH 1050)	.008	0.50	418,000	0.1775	0.116
G	17-7 PH (TH 1050)	.008	0.25	294,000	0.149	0.116
H	17-7 PH (TH 1050)	.008	0.25	294,000	0.149	0.116

Thin, high-strength faces combined with minimum stiffness core were selected in an effort to obtain wrinkling failures when the face stresses were still in the elastic range. Core thicknesses were arbitrarily set to evaluate both thick and thin core solutions.

Up to this point in the program, everything proceeded as planned. Because of the nature of the problem, an extremely fragile specimen construction was required. The problems resulting from specimen preparation were greater than estimated; three major discrepancies were found in the completed specimens. First, the faces did not remain parallel when the core was removed from the ends for filling. The ends were generally spread or not filled to a sufficient depth. Second, the sawing operations on the steel-faced specimens damaged the core cells adjacent to the saw cut, necessitating filling of all edges. Third, a large number of specimens were crushed during machine milling of the loading ends.

In spite of the bad specimen preparation, all but three specimens were tested. Prior to testing, the surface waviness was measured on a flat granite table with a supported dial gage. At least three traverses were made on each side and any significant waviness was recorded on the face of the specimen. Both length and depth were noted.

The specimens were all tested at room temperature in a 12,000-pound Baldwin hydraulic test machine at a load rate of 1,200 pounds per minute. No loading jigs were used.

2.2 Test Results

The results of the waviness survey, together with failing load, description, and a computed A_0 , are shown in Tables 2 through 5. A plot of the actual failing stress versus the computed A_0 , together with a curve as computed by the appropriate equation, are shown for each type of panel in Figures 5 through 8. All results are shown except for those cases wherein the failures did not occur at a measured irregularity and were unquestionably caused by improper edge preparation.

TEST RESULTS - PANELS A & B

SPEC. NO.	WIDTH	TOP		BOTTOM		LOAD IN POUNDS	PSI	FAILURE		ID
		T	L ₁	T	L ₂			LOCATION	TYPE	
A-2	2.70	0	-	2.0	0.33/0.3	2300	41,400	Bot @ 10	FW	.0022
A-3	2.70	0	-	0.2	-	2900	2,200	End	-	.0006
A-3	2.78	0	-	0.2	-	3930	71,000	End *	-	.0008
A-4	2.78	.011/	-	-	0.4/	2250	40,000	Both @ 40	FW	.0011
A-5	2.78	.012/.007	1.5	0.2	-	2970	23,400	Both "	FW	.0011B
A-6	2.78	.021/	-	-	0.40/	1950	3,400	Both 1	FW	.0021B
A-7	2.78	.020/	-	-	0.40/	2010	36,100	Both 10	FW	.0021B
A-8	2.78	.009/.013	2.25	Corner	-	2130	36,600	Top @ 10	CS	.0012T
A-9	2.78	.002/	0.50	0.3 end	-	2800	46,600	End	-	.0036B
A-9	2.78	.002/	0.50	-	-	3250	58,300	Top @ 10*	FW	.0011
A-10	2.78	.008/	-	-	0.30/	3060	22,100	Both @ 10	FW	.0009T
B-2	2.83	1.010/	-	-	0.25/	1850	32,700	Bot @ 10	CS	.0032B
B-3	2.83	.003/	1.0	0	-	3720	26,000	Top @ 10	FW	.0005
B-4	2.83	.012/.004	1.10	-	0.30/	1910	33,600	Bot @ 10	FW	.0015B
B-5	2.83	.012	-	-	0.22/	2460	43,600	Both @ 10	FW	.0011B
B-6	2.83	.016/	-	-	0.28/	1520	26,800	Bot @ 10	FW	.0019B
B-7	2.83	.015/	-	-	0.24/	1820	32,000	Bot @ 10	CS	.0047B
B-8	2.83	.010/	-	-	0.2/	2000	36,600	Both @ 10	FW	.0014B
B-9	2.83	.031/	-	-	0.25/	1220	27,000	Both @ 10	CS	.0041T
B-10	2.83	-	0	2.25	0.43/0.45	1130	30,100	Both @ 10	FW	.0013B

SKIN: .010/.012 ALUMINUM
CORE: .001A/.002 ALUMINUM

* Retest
CS - Core shear
FW - Face wrinkling

(L₁ = .1)

Table 3
TEST RESULTS - PANELS C & D

SPEC. NO.	WIDTH	TOP		BOTTOM		LOAD IN POUNDS	PSI	FAILURE		A ₀	
		A _T	λ ₁	λ ₂	A _T			λ ₁	λ ₂		LOCATION
C-2	2.82	0	-	-	.003	0.45	2820	50,000	Bot @	FW	.0008
C-3	2.82	0	-	-	.002	0.45	2970	52,700	End	-	.0006
C-4	2.82	.004	-	Low Corner	0	-	3250	57,300	End	-	-
C-5	2.82	0	-	-	.004	0.47	Not Recorded	-	Bot @	FW	.0011
C-6	2.82	.010/	-	0.55/	0	-	1190	21,200	Top @	FW	.0006
C-7	2.82	0	-	-	0	-	3630	64,700	End	-	-
C-8	2.82	0	-	-	.0035	0.55	2820	46,600	Bot @	FW	.0008
C-9	2.82	0	-	-	.0025	0.42	2900	51,700	End	-	.0008
C-10	2.82	0	-	-	0	-	3450	61,300	End	-	-
D-2	2.76	0	-	-	.0035	0.45	2415	48,100	Bot @	CS	.0010
D-3	2.76	0	-	-	.002	0.35	3130	56,700	Bot @	CS	.0007
D-4	2.76	0	-	-	0	-	3365	60,800	End	-	-
D-5	2.76	0	-	-	.004	0.55	2575	46,500	Bot @	CS	.0009
D-6	2.76	0	-	-	.002	Side	2715	48,000	End	-	-
D-7	2.76	0	-	-	0	-	3405	61,800	End	-	-
D-8	2.76	0	-	-	.0035	0.3b	1724	31,200	Bot @	CS	.0012
D-9	2.76	0	-	-	.0022	0.4	3070	55,500	End	-	.0006
D-10	2.76	0	-	-	0	-	3135	56,700	End	-	-

SKIN: .010 / 07-176 ALUMINUM
 CORE: .200 IA 3052 ALUMINUM
 CS - Core Shear
 FW - Face Wrinkling
 (λ₁ = .125)

Table 4
TEST RESULTS - PANELS E & F

SPEC. NO.	WIDTH	TOP		LOAD IN POUNDS	PSI	FAILURE		Ao
		λ_1	λ_2			LOCATION	TYPE	
E-2	2.75	.018/.013	1.9	0.30/0.48				
E-3	2.75	.020/	-	0.6/	46,800	Top @ Ao	FW	.0027
E-4	2.75	.015/	-	0.40/	61,000	Both @ Ao	FW	.0014
E-5	2.75	0	-	0.45/0.35	49,500	Both @ Ao	FW	.0016
E-6	2.75	.005/	-	0.40/	47,500	Both ends	FW	-
E-7	2.75	.006/	-	0.35/	51,200	Bot @ Ao	FW	.0010
E-8	2.75	.006/	-	0.40/	56,300	Top @ Ao	FW	.0007
E-9	2.75	.006/	-	0.40/	60,000	Bot @ Ao*	FW	.0007
E-10	2.75	.006/	-	0.35/	60,000	Top @ Ao*	FW	.0009 Bot .0008 Top
F-2	2.77	.028/	-	0.35/	51,000	Top @ Ao*	FW	.0036
F-3	2.87	.008/	-	0.5/	57,200	Bot @ Ao	FW	Cramped .0027 Bot
F-4	2.87	.003/.007	-	0.20/	67,500	Top @ Ao	FW	.0025 Top
F-5	2.87	.003/	-	0.20/	111,000	Both Ao	FW	.0007
F-6	2.87	.007/	-	0.30/	59,500	Top Ao	FW	.0010 Top
F-7	2.87	.045/	-	0.28/	62,500	Top Ao	FW	.0071 Top
F-8	2.87	.008/	-	0.15/	72,300	Top Ao	FW	.008*
F-9	2.87	.0015 Side	0.4	-	91,200	Poss. Void	FW*	.0006

SKIN: .008 17-7 PH (WH 1050) STEEL
CORE: .500 IA 50/2 ALUMINUM
($\lambda_1 = .178$)

* Retest
CS - Core Snear
FW - Face Wrinkling

Table 4
TEST RESULTS - PANELS E & P

SPEC. NO.	WIDTH	TOP		λ_T	λ_2	λ_T	BOTTOM		LOAD IN POUNDS	PSI	FAILURE		AO
		λ_1	λ_2				λ_1	λ_2			LOCATION	TYPE	
E-2	2.75	.018/.013	1.9	0.30/0.48	.009/	-	0.55/	Not Tested	46,800	Top @ Ao	FW	.0027	
E-3	2.75	.020/	-	0.6./	.0071	-	0.4/	2060	61,000	Both @ Ao	FW	.0014	
E-4	2.75	.015/	-	0.40/	.014/.014	1.4	0.45/0.35	2680	49,500	Both @ Ao	FW	.0016	
E-5	2.75	0	-	-	0	-	-	216.	47,500	Both ends	FW	-	
E-6	2.75	.005/	-	0.40/	.0131	-	0.60	2240	51,200	Bot @ Ao	FW	.0010	
E-7	2.75	.006/	-	0.35/	0	0	-	2470	56,300	Top @ Ao	FW	.0007	
E-8	2.75	.006/	-	0.40/	.005/	-	0.22/	2650	60,000	Bot @ Ao*	FW	.0007	
E-9	2.75	.006/	-	0.35/	.003	.6	-	2630	60,000	Top @ Ao*	FW	.0009 Bot .0008 Top	
E-10	2.75	.006/	-	0.35/	.028/	-	0.90/	2270	51,000	Top @ Ao*	FW	.0036 Cramped	
P-2	2.87	.008/	-	0.35/	.011/	-	0.18/	2530	57,200	Bot @ Ao	FW	.0027 Bot	
P-3	2.87	.008/	-	0.35/	.004/.004	1.7	0.35/0.35	2990	67,500	Top @ Ao	FW	.0025 Top	
P-4	2.87	.003/.007	-	0.20/	.003/	-	0.20/	4990	111,000	Both Ao	FW	.0007	
P-5	2.87	.003/	-	0.20/	Not Tested	-	-	-	-	-	-	-	
P-6	2.87	.007/	-	0.30/	.003	-	0.50/	2630	59,500	Top Ao	FW	.0010 Top	
P-7	2.87	.045/	-	0.28/	.060/	-	1.50/	2770	62,500	Top Ao	FW	.0071 Top	
P-8	2.87	.008/	-	0.15/	.0025	0.2	-	3200	72,300	Top Ao	FW	.008*	
P-9	2.87	.0015 Side	0.4	-	0	-	-	4180	91,200	Poss.Void	FW*	.0006	

SKIN: .008 1/-7 PH (TH 1050) STEEL ($\lambda_1 = .178$)
CORE: .500 IA 50.2 ALUMINUM

* Retest

CS - Core Snear
FW - Face Wrinkling

Table 2
TEST RESULTS - PANELS G & H

SPEC. NO.	WIDTH	TOP		BOTTOM		LOAD IN POUNDS	PSI	FAILURE		Ao
		AT	λ_1	λ_2	AT			λ_1	λ_2	
0-2	2.81	.002 Side	0.7	-	-	3455	76,600	End		
0-3	2.81	0	-	-	2.0	2280	50,700	End		
0-4	2.81	0	-	-	.025 Side	3930	87,100	End		
0-5	2.81	.0015 Side	0.7	-	-	3150	69,800	End		
0-6		Not Tested								
0-7	2.81	.030 Side	2.0	-	-	1915	42,800	End		
0-8	2.81	0	-	-	.5	4450	99,100	End		
0-9	2.81	0	-	-	.001 Dents	3565	79,500	End		
0-10	2.81	0	-	-	.25 Dia	2535	56,600	End		
H-2	2.71	0	-	-	0.3	4265	98,200	End	*	.0008
H-3	2.71	.001	0.4	-	Corner	1100	25,200	End		
H-4	2.71	0	-	-	Bump	1290	29,900	End		
H-5	2.71	.0015	0.35	-	-	1665		Possible Bond		
H-6	2.71	.012 Dents (long)		-	2.0	3270	75,000	Bot Ao	*CS	.0005
H-7	2.71	0	-	-	-	4040	93,400	End	*	
H-8	2.71	.016	.1	-	0.4	3340	72,200	Top @ Ao	CS	
H-9	2.71	.035/.035	1.3	0.35/0.30	-	1250	29,000	Top @ Ao	*CS	.0043
H-10	2.71	.020 Low	0.5 Dia	-	-	4740	109,000	End	*	

NOTE: Only Panels H-8 and -9 are represented on Figure 8--these are the only two failure panels.

SKIN: .003 17-7 FH (TH 1050) STEEL ($\lambda_1 = .149$)
CORE: .250 5052 ALUMINUM

* Retest

CS - Core Shear
FW - Face Wrinkling

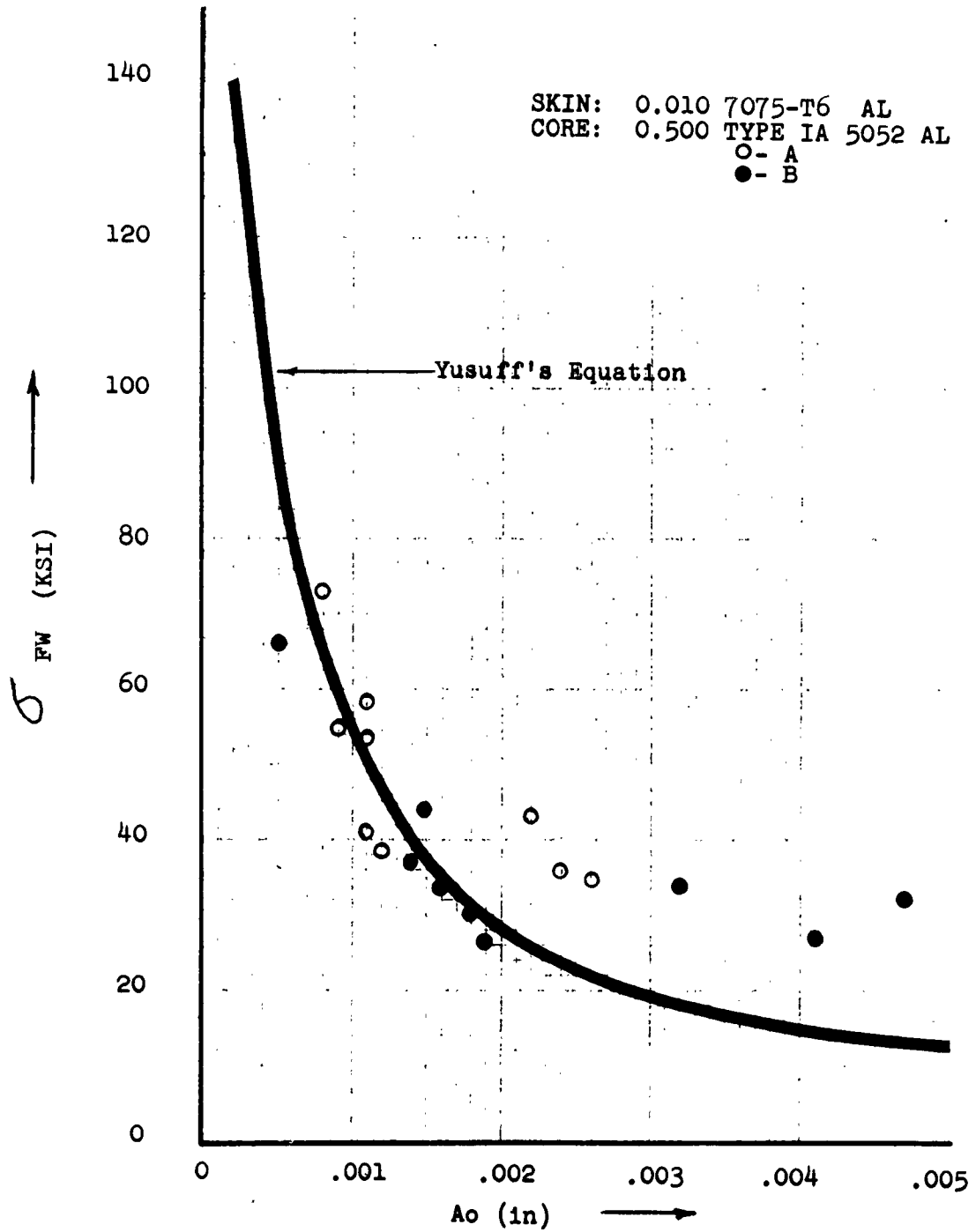


Figure 5 CRITICAL FACE-WRINKLING STRESS
 VS
 SURFACE WAVINESS, A & B

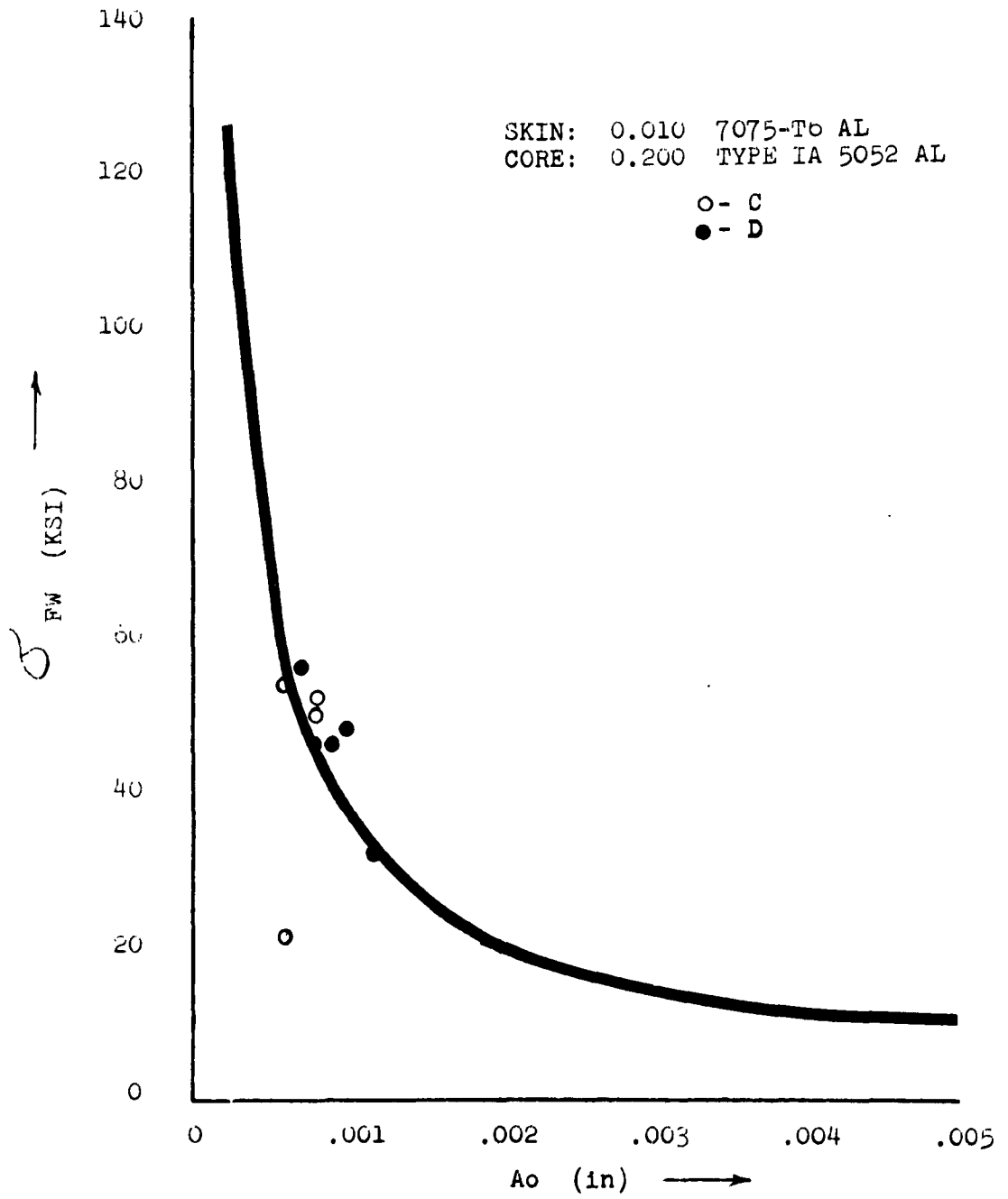


Figure 6 CRITICAL FACE-WRINKLING STRESS
 VS
 SURFACE WAVINESS, C & D

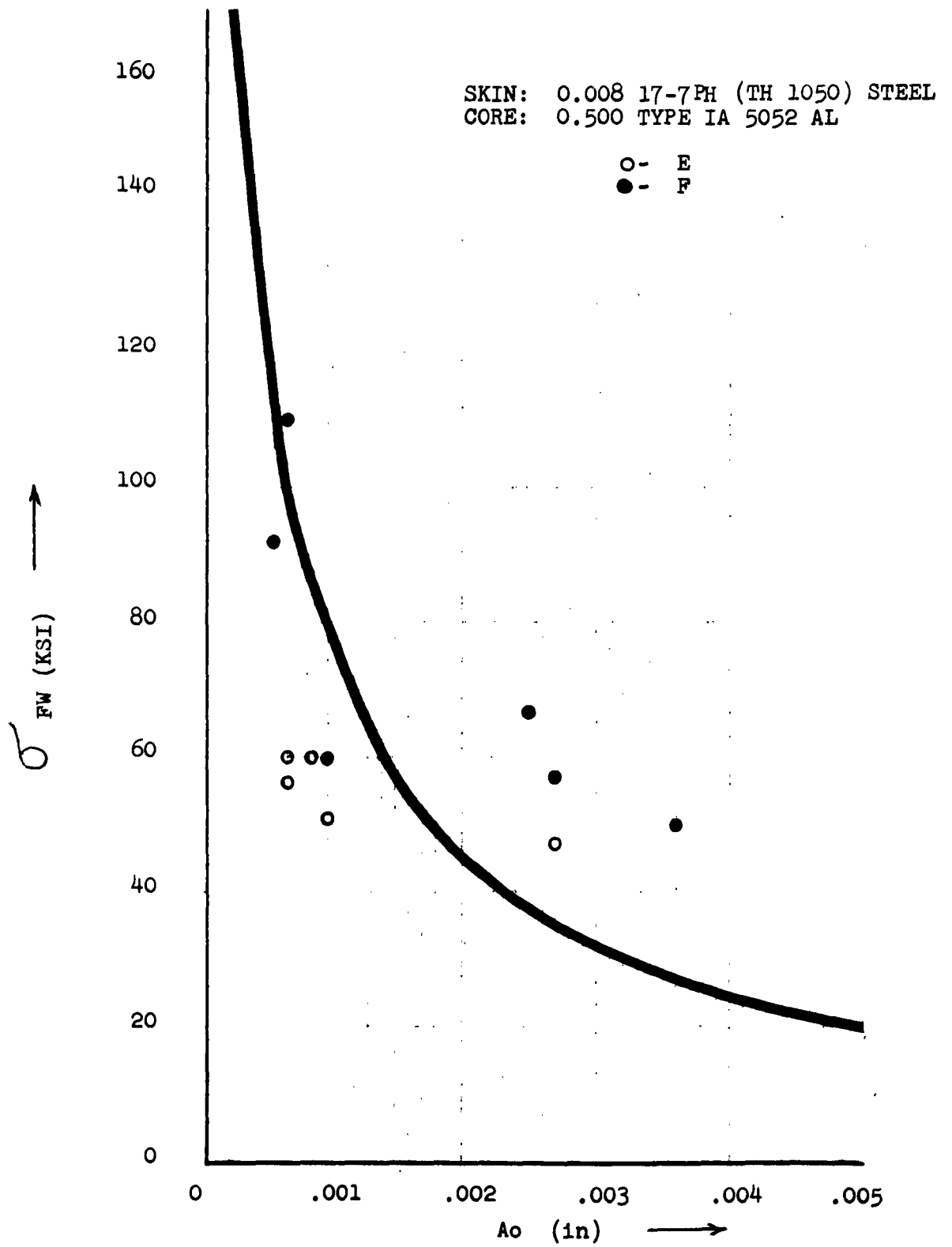


Figure 7 CRITICAL FACE-WRINKLING STRESS
 VS
 SURFACE WAVINESS, E & F

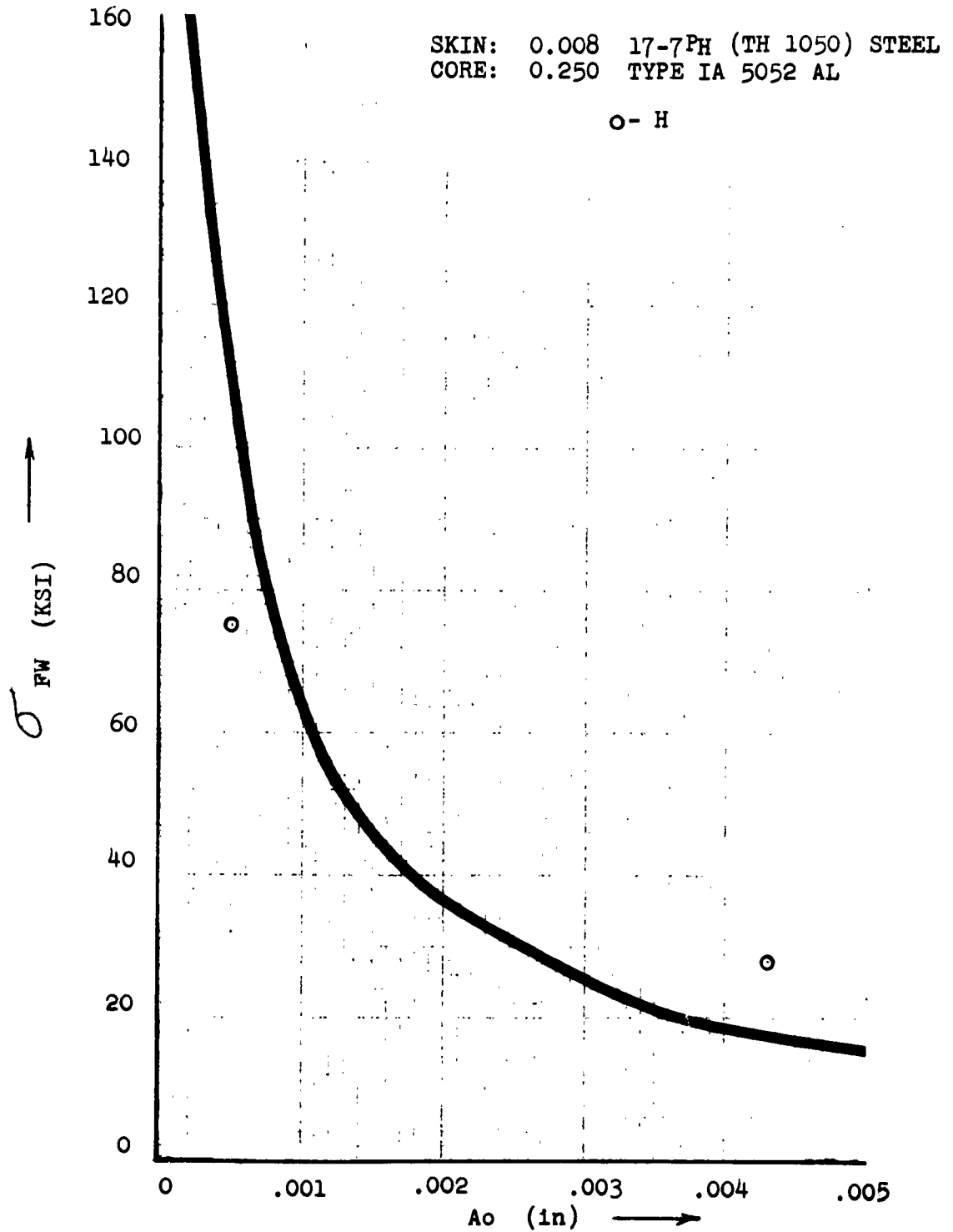


Figure 8 CRITICAL FACE-WRINKLING STRESS
 VS
 SURFACE WAVINESS, H

TYPES OF FAILURE

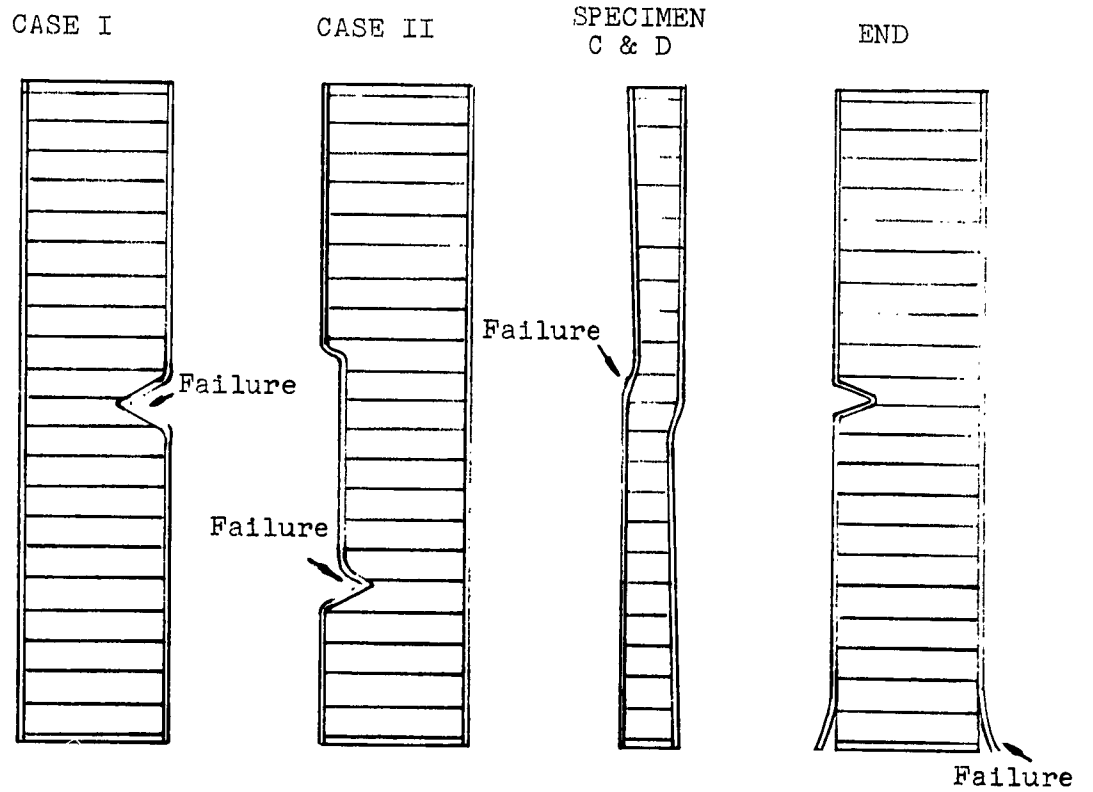


Figure 9

3. CONCLUSIONS AND RECOMMENDATIONS

The results of this experiment support the solution to the face wrinkling problem as proposed by Yusuff. Although the theory would be expected to apply only to small magnitude of waviness, it yielded reasonable correlation with extremely large degrees of waviness.

The writer does not feel that the mode of failure described by Equation (5) is critical. However, the typical failure of the type C and D (thin core) specimens (see Figure 9) indicates this could be the critical relationship. Calculations using the denominator of Equation (5) in Equation (3) show that the resulting critical stresses are roughly the same. Additional analytical work should be done in this area.

Application of this theory to a practical design situation requires an approach similar to that of thin shell construction. Either some arbitrary imperfection must be assumed or an empirical constant found. More extensive testing is required to establish the full validity of this theory. Should this be accomplished, a designer could use this relationship to establish the manufacturing tolerances on surface waviness necessary to ensure an adequate face-wrinkling allowable.

4. REFERENCES

1. ANC-23 "Sandwich Construction for Aircraft", Part II (1955).
2. Kuenzi, E. W. and Jenkinson, P. M., Wrinkling of the Facings of Aluminum and Stainless Steel Sandwich Subjected to Edgewise Compression, No. 2171, Forest Products Laboratory, December 1959, p. 11.
3. Yusuff, S., "Face Wrinkling and Core Strength in Sandwich Construction", Journal of the Royal Aeronautical Society, Vol. 64, March 1960, p. 164.
4. Hetenyi, M., Beams on Elastic Foundation, University of Michigan, 1946, p. 142.
5. FZS-4-084, Structural Design Allowable Stresses, B-58 Airplane, General Dynamics/Fort Worth, April 1957, pp. 14-20.