Boron Aluminum Crippling Strength Shows Improvement

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Results are presented from an experimental program directed toward improving boron aluminum crippling strength. Laminate changes evaluated were larger filament diameter, improved processing, shape changes, adding steel-aluminum cross plies, reduced filament volume in corners, adding boron aluminum angle plies, and using titanium interleaves. Filament diameter and steel-aluminum cross plies have little effect on crippling. It is shown that better processing combined with appropriate shape changes improved crippling over 50% at both room temperature and 600°F. Tests also show that crippling improvements ranging from 20 to 40% are achieved using angle plies and titanium interleaves.

Introduction

IN July 1970, McDonnell Douglas Astronautics Company—East began a contractual program with NASA MSFC for the development of boron aluminum structure fabricated by the low pressure eutectic bonding process. As part of this program, a 5 ft long by 4 ft wide boron aluminum compression panel was designed, fabricated, and tested. Based on tests of this panel and related element tests, it was apparent that further work to improve crippling strength of boron aluminum was needed. Our next program with NASA MSFC, which began in July 1971, also involved the design, fabrication, and test of a compression panel. Loading of this panel was more complex and severe than for the first panel. Consequently, a major effort was directed toward improvement of boron aluminum crippling strength. Seven variations of the original compression element design were evaluated experimentally. Results of this investigation show that boron aluminum compression members can now be designed which have crippling strengths nearly 100% higher than those of early compression members.

Background

Structural arrangement of the boron aluminum skin-stringer panel fabricated during our first program with NASA MSFC is shown in Fig. 1. The panel is 48 in. wide and 61.5 in. long. Eleven zee-shaped unidirectional stringers spaced at 4.29 in. were mechanically joined to an eight-ply symmetric, ±45° laminate skin. Steel frames for supporting the stringers, divided the panel into two 20-in.-long center bays and two 10.75-in.-long load introduction bays. The panel was designed to withstand an ultimate compressive load of 6500 lb/in. (305,000 lb) combined with an ultimate shear flow of 1000 lb/in. at a temperature of 500°F. When tested under these combined loads, the panel failed prematurely. Based on a failure analysis, the primary failure was attributed to a poor design detail, which led to locally high shear flows in the corners of the panel. However, stringer compressive strength was also questionable; therefore, an extensive program was begun to improve strength of members loaded in compression.

Numerous crippling tests were conducted during the first program at both room temperature and 500°F.[1] Results of room temperature tests are shown in Fig. 2. They will be used as a basis for comparison with results from the current program. Unidirectional specimens with thicknesses ranging from 4 plies to 17 plies were tested. The one-edge-free strength was obtained from tests of equal leg angle sections. The no-edge-free strength was obtained from tests of zee sections. Load carried by the no-edge-free element is the total load carried by zee section less the load carried by the one-edge-free elements.

The specimens were designed with a slenderness ratio (L'/ρ) ranging from about 12 for hat sections to 20 for angle sections. Ends of specimens were ground to ensure flatness, squareness, and parallelism. It was not necessary to pot the ends of specimens because the crippling stress levels were not sufficiently high to cause brooming. Limited post buckling strength was present in these specimens. Initial buckling of one-edge-free elements in zee and hat-shaped members was usually followed by longitudinal splitting and complete failure of member.

Our current program with NASA MSFC is for the design, development, manufacture, and evaluation of structural components using boron aluminum. This program, which began

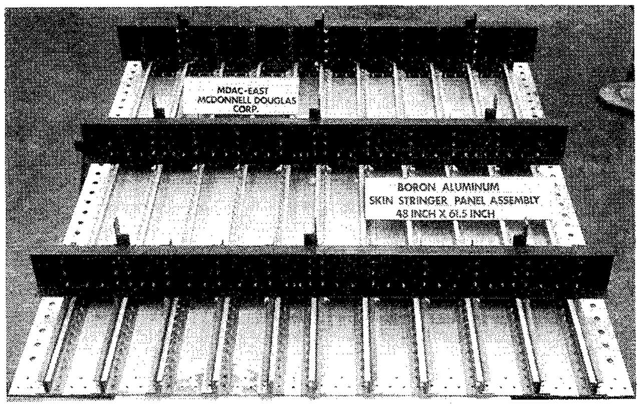

Fig. 1 Panel fabricated during previous program.

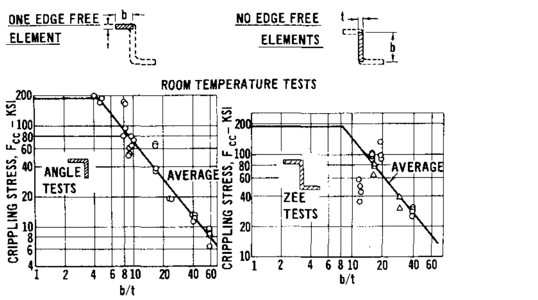

Fig. 2 Average crippling strength obtained during previous program.

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in July 1971, consists of five phases: 1) materials evaluation, 2) design studies, 3) process technology development, 4) fabrication and assembly, and 5) test and evaluation. The compression panel shown in Fig. 3 was designed in Phase 2 and fabricated in Phase 4. The panel will be tested by NASA MSFC during Phase 5, which is scheduled for the spring of 1974. The panel is designed for a concentrated load of 350,000 lb applied at one end reacted by a uniformly distributed load at the opposite end while at a temperature of 600°F. It was designed so that load peaking at the distributed end did not exceed a uniform load by more than 30%. Both the stringers and skin are tapered in thickness because the loads vary over the length of the panel.[2]

In Phase 1, mechanical property and design data were obtained for verification of compression panel design and analysis. Limited crippling test results obtained during this phase are compared, in Fig. 4, to results from many tests obtained in previous program. A significant improvement is shown for both "one-edge-free" and "no-edge-free" elements. For example, at a b/t of 25, the trend curve for a no-edge-free-element shows a 90% improvement over previous program and 40% increase over titanium. It should be noted that curves labeled "current trend" are based on limited results because the objective was to verify crippling strength of the selected stringer design and not to develop general "one-edge-free" and "no-edge-free" data.

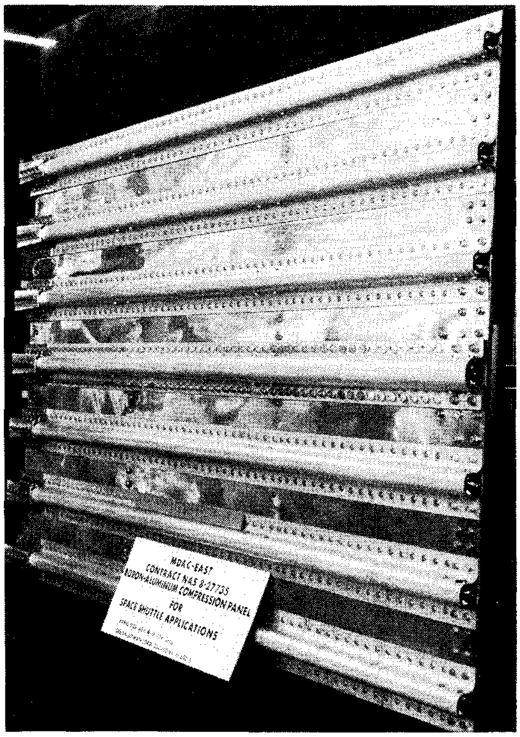


Fig. 3 Boron aluminum compression panel delivered to NASA MSFC for test.

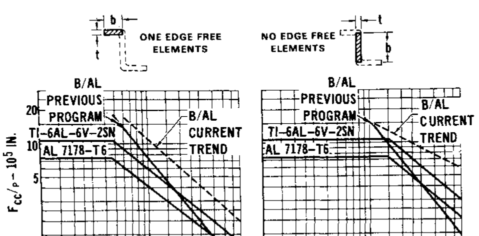


Fig. 4 Recent results have shown significant improvement in crippling efficiency.

Simultaneously with Phase 1 activities, an extensive IRAD program directed toward the improvement of boron aluminum crippling strength was initiated. Many crippling tests discussed in the following section support the trend that significant improvements in crippling strengths have been achieved.

Experimental Evaluation of Crippling

Experience from the first program indicated that boron aluminum compression members possessed limited post buckling capability. Initial buckling of elements comprising the member was usually followed almost immediately by longitudinal splitting in the corners and total failure of the member, as shown in Fig. 5. Consequently, to investigate differences in crippling strengths from the two programs and to evaluate techniques for improving crippling, seven changes shown in Fig. 6 were considered. It was reasoned that larger filament diameters may improve microbuckling strength and reduce support foundation requirements of the matrix. Improved processing of both monolayer material and of the eutectic bonding process should increase the strength and uniformity of the composite. In addition, changing from flat to curved elements should increase buckling and, therefore, crippling strength. Finally, adding stainless steel-aluminum plies, angle plies, or titanium interleaves and reducing filament volume in corners should increase transverse ductility, reduce longitudinal splitting, and thereby increase crippling strength.

The specimens were designed to the same slenderness ratios and ends were ground to the same tolerances as used in the first program. However, it was necessary to pot the ends of thick wall specimens for prevention of brooming because of the much higher crippling stress levels obtained. Specimens tested at room temperature were potted in Epon 828 resin containing aluminum oxide filler, and specimens for 600°F tests were potted in glassrock castable ceramic. In the following

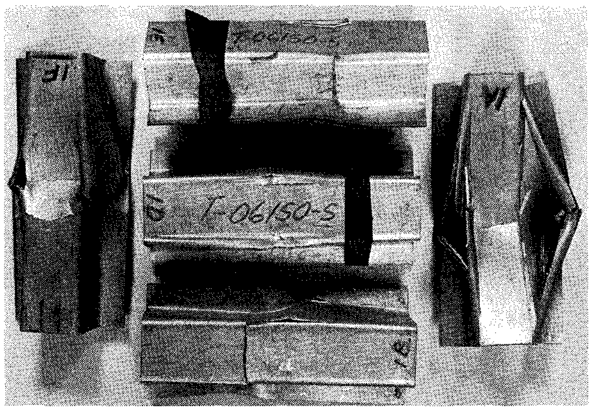


Fig. 5 Longitudinal splitting evident in early crippling specimen.

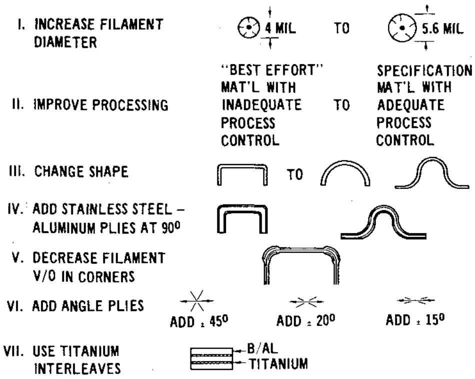


Fig. 6 Changes considered to improve boron aluminum crippling.

paragraphs, each of the seven items are discussed and their apparent effect on crippling strength is indicated.

Material Processing

Monolayer material used in the two programs are compared in Fig. 7. In the first program, material was purchased on a "best effort" basis. The monolayer contained four mil diameter boron filaments with a filament volume fraction (V/o) of about 40%. The maximum transverse tensile strain was about 1500 μin./in. and showed considerable scatter. Monolayer material containing 5.6 mil diameter filaments used in the current programs was purchased using material specifications to control quality and properties. Transverse tensile strain capability has more than doubled.

Many changes and improvements were also made in the eutectic bonding process which has greatly improved properties and uniformity of fabricated parts. Two of the more important changes involved accurate control of the copper coating used to form the eutectic bond and careful control of temperature during the bonding cycle. As a result of improved materials and processing, crippling strength has been improved as shown in Fig. 8. The lower dashed curve is predicted using average crippling allowables from the first program. The upper solid curve is drawn through the average of tests obtained in current program. Crippling improvement ranging from 20 to 35% is due to improved processing because the same specimen dimensions and corner radius were used.

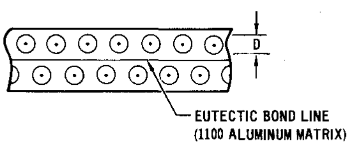
Filament Diameter and Corner Radii

To evaluate the effects of filament diameter on crippling strength, semicircular specimens fabricated from 4 and 5.6 mil diameter material were tested. Results presented in Fig. 9 show that filament diameter has little effect on crippling. Quality of monolayer material used to fabricate the two groups of specimens was judged to be equivalent and the same process control was exercised during the eutectic bonding operation.

Large corner radii can increase crippling strength of composite sections because curved sections have high initial buckling strength and the b/t of the adjacent flat sections is reduced. An indication of the improvement to be obtained by using large corner radii is shown in Fig. 10. Crippling strength of semicircular specimens of 0.5 in. inside radius is compared to channel sections with 0.25-in. corner radius on an equivalent area basis. Material containing 5.6 mil diameter filaments was used to fabricate both types of specimens and the same eutectic bonding process control was employed. Although it is difficult to obtain an accurate evaluation of corner radii using these specimen, the trend for improved crippling strength is clearly shown.

Stringer Crippling Strength

When both improved processing and large corner radii are used, a significant improvement in crippling strength is obtained, as shown in Fig. 11. Crippling tests at both room temperature and 600°F were conducted on hat sections where both flat and curved elements were used. Results are shown by the circles. Also shown is the predicted crippling curve based on allowables from the previous program. Nearly a 90% improvement is shown for six-ply specimens tested at room temperature and approximately 80% improvement when tested at 600°F. For thicker specimens, the improvement is less as expected because initial buckling prior to failure would not occur and the failure mode changed to block compression, Crippling strength of these specimens at 600°F is about 55% of the room temperature strength. This reduction is attributed to the



	SUPPLIER	BORON FILAMENT DIAMETER	BORON FILAMENT V/O	ϵ_{T}^{tu} μIN/IN
PREVIOUS PROGRAM (NAS 8-26295)	NO. 1	4 MIL	40	~1500
CURRENT PROGRAM (NAS 8-27735)	NO. 2	5.6 MIL	40–45	~3500

Fig. 7 Material differences between two programs.

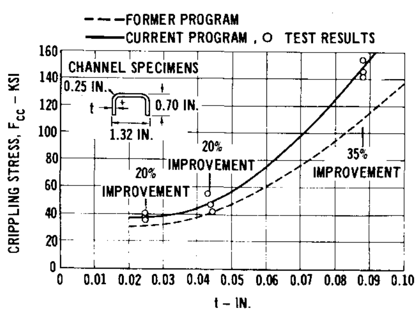


Fig. 8 Improved manufacturing processing has increased crippling strength.

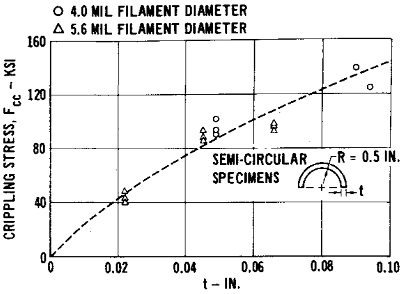


Fig. 9 Filament diameter has no apparent effect on crippling strength.

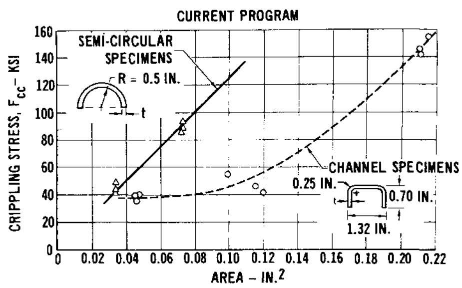
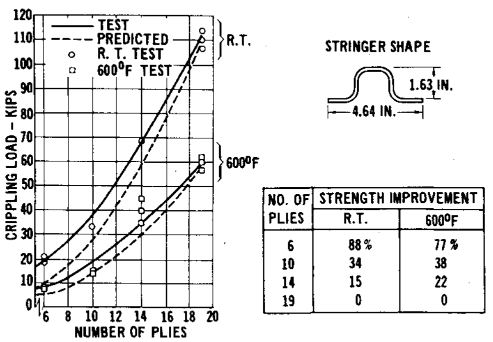


Fig. 10 Larger corner radii can improve crippling strength.



NO. OF PLIES	STRENGTH IMPROVEMENT R.T.	STRENGTH IMPROVEMENT 600°F
6	88%	77%
10	34	38
14	15	22
19	0	0

Fig. 11 Process control and large corner radii improve stringer crippling strength.

low shear and transverse properties of the aluminum matrix at 600°F.

A six-ply (0.046 in.) unidirectional boron aluminum stringer containing several strain gages was tested at room temperature. The free flange was observed to buckle at 8600 lbs, which agrees well with divergence of data from back-to-back strain gages 1 and 2 shown in Fig. 12. These two gages also show that no additional load is carried by that portion of flange after free flange buckling occurs. Gages 3 and 4 indicate that the corner radii region has not buckled and continues to accept additional load until crippling occurs. The average strain at which crippling occurs (~2750 μ in./in.) agrees well with failure strain associated with crippling stress of equal thickness semicircular specimens.

Stainless Steel-Aluminum Cross Plies

Cross plies consisting of stainless steel filaments in an aluminum matrix were used to replace the outer ply of unidirectional boron aluminum specimens. The steel-aluminum ply was 0.0054 in. thick and had a steel filament volume content of 26%. Average density of the steel-aluminum plies was 0.15 lb/in.^{3} These cross plies were expected to improve transverse strength, reduce longitudinal splitting, and thereby, increase crippling strength. Both channel sections and hat sections having large corner radii were tested at room temperature. Results are shown in Fig. 13. Specimens with steel-aluminum cross plies showed crippling strength reductions ranging from 13 to 21% less than the six-ply unidirectional specimen. For this specimen thickness, crippling strength was reduced because the improvement in transverse strength and strain was more than overcome by the reduction in longitudinal strength.

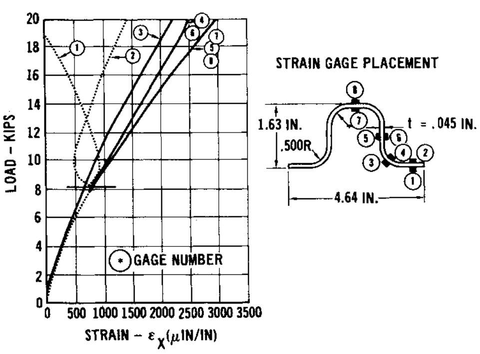


Fig. 12 Stringer hat section possesses good postbuckling strength.

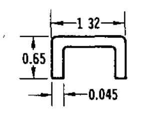
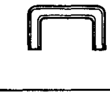
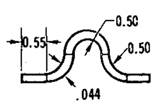
CONFIGURATION	LAY-UP	F_{cc}/ρ – IN. (10^5)	% CHANGE COMPARED TO ALL U.D.
	6 PLY UNIDIRECTIONAL B/AL	4.96	
	2 SURFACE PLIES 90° STAINLESS STEEL WIRE/ ALUMINUM, 4 INTERNAL PLIES 0° B/AL	4.30	-13
	6 PLY UNIDIRECTIONAL B/AL	6.35	
	2 SURFACE PLIES 90° STAINLESS STEEL WIRE/ ALUMINUM, 4 INTERNAL PLIES 0° B/AL	5.02	-21

Fig. 13 Stainless steel wire cross plies do not improve crippling strength.

Filament Volume in Corners

The effect of reduced filament volume in corners of crippling specimen was evaluated from tests of six-ply unidirectional sections, as shown in Fig. 14. Filament volume in corners was reduced from 45% to 34% by placing a two mil aluminum foil between each boron aluminum ply. Filament volume in remaining portion of specimen was approximately 45%. The reduced filament volume in corners increased transverse ductility and reduced longitudinal splitting in the region of the specimen where bending occurs during buckling. As shown in Fig. 14, this approach increases crippling strength about 30%. Transverse tensile tests of 34 volume % coupons indicated that ultimate transverse strain is increased nearly 50% compared to 45 volume % coupons. Results from these experiments show that improved transverse strain capability in the corners increases crippling strength. However, as evidenced by tests of specimens with stainless steel cross plies (Fig. 13), this improved strain can not be achieved at the expense of reduced longitudinal strength.

Boron Aluminum Angle Plies

Another approach for improving transverse properties of unidirectional boron aluminum is to add small-angle cross plies near the outer surface. Resulting improvements in crip-

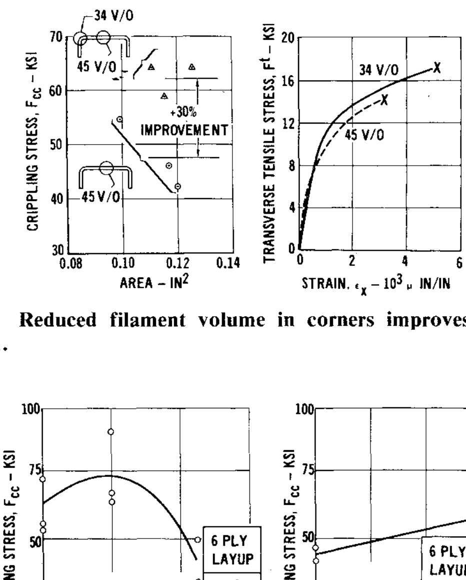


Fig. 14 Reduced filament volume in corners improves crippling strength.

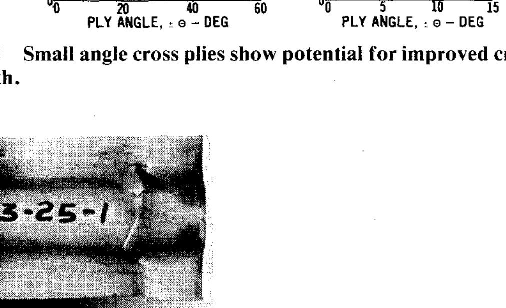


Fig. 15 Small angle cross plies show potential for improved crippling strength.

Fig. 16 Hat sections with ±20° angle plies after test.

pling strength were determined by room temperature tests of channel and hat section specimens, as shown in Fig. 15. All specimens were six ply, having two center plies at 0° orientation and the outer four plies at $\pm\theta$ orientation. For the hat section with outer plies oriented at $\pm 20°$, a 20% improvement in crippling strength was observed compared to specimens with all unidirectional material. No evidence of longitudinal splitting was present in these specimens, as shown in Fig. 16. For the channel section with outer plies at $\pm 15°$ orientation, a 40% improvement was noted. Ply angles greater than $\pm 30°$ have a detrimental effect on crippling strength. This is to be expected, considering the significant reduction in longitudinal strength for large-angle cross plies located near the surface.

Titanium Interleaves

Titanium interleaves are used to increase inplane shear strength of unidirectional boron aluminum and to improve mechanical joint bearing strength of boron aluminum laminates. They can be used effectively to achieve minimum weight tailoring of stringers subjected to a variable axial load, as shown in Fig. 17. In this example, the stringer is loaded by a shear flow (q) which peaks 10 in. from the end. At that location, five titanium interleaves combined with eleven unidirectional boron aluminum plies provide the required shear and axial strength. As the number of boron aluminum plies increases to sustain the axial load, fewer titanium interleaves are required to carry the shear load.

To evaluate the effect of titanium interleaves on crippling strength, hat sections composed of unidirectional boron aluminum and titanium interleaves at two different locations in the cross section were tested at room temperature and 600°F. Results are compared to crippling strength of unidirectional specimens in Fig. 18. A five ply and a 17 ply crippling specimen with a center ply of 8 mil thick, 6AL-4V titanium were tested at room temperature. Results show that the midplane titanium ply had little effect on crippling.

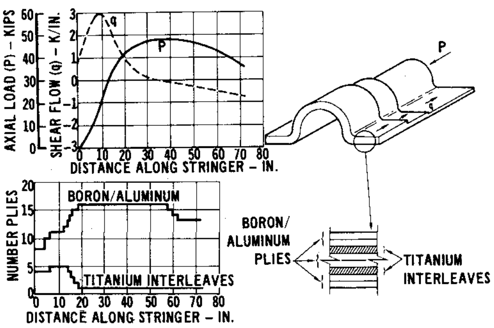


Fig. 17 Titanium interleaves and ply terminations permit minimum weight tailoring of stringer subjected to varying loading.

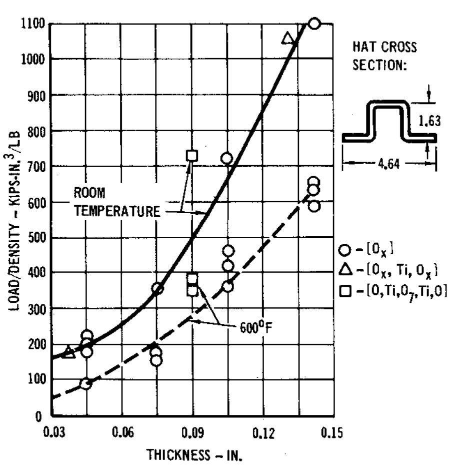


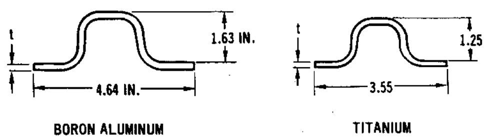
Fig. 18 Titanium interleaves near outer surface improves crippling.

Eleven-ply specimens containing nine unidirectional boron aluminum plies and two titanium plies, one each located near the inner and outer surface of the specimen, were tested at room temperature and 600°F. As shown in Fig. 18, this configuration is approximately 45% stronger at room temperature and 35% stronger at 600°F than unidirectional boron aluminum specimens. Analysis of load-deflection data for the specimens containing titanium interleaves showed that some element buckling occurred at approximately 50% of the failing load.

The significant improvements obtained by adding approximately 25% by volume of titanium interleaves represents a major advancement in boron aluminum crippling strength technology. Further analytical and experimental work is needed to study stacking sequence, titanium volume percentage, and interleaf thickness.

Comparison of Boron Aluminum and Titanium Columns

The column strength of boron aluminum is superior to titanium, as shown in Fig. 19. Boron aluminum crippling strength determined by test is compared to predicted strength of titanium specimens. The titanium specimens selected are equal in weight and (b/t) to the boron aluminum specimens. Crippling strength of boron aluminum at room temperature is about 37% better than titanium; however, at 600°F, boron aluminum is 10-30% less efficient. For a 24-in.-long simply supported column, boron aluminum is best at both room temperature and 600°F. Boron aluminum is more efficient as a column because its stiffness is twice that of titanium and the boron aluminum section has a greater moment of inertia.



TEMPERATURE	THICKNESS – IN. (EQUAL WEIGHT) (EQUAL b/t)		CRIPPLING STRENGTH			COLUMN STRENGTH
			P_{cc} – LB		P_{cc} (B/AL) / P_{cc} (Ti)	P_c (B/AL) / P_c (Ti)
	B/AL	Ti	B/AL*	Ti		
ROOM	0.046 0.143	0.035 0.110	19,000 112,000	13,800 81,100	1.37 1.38	1.95 3.32
600°F	0.046 0.143	0.035 0.110	8,600 60,000	12,000 65,000	0.68 0.92	1.08 2.26

* TEST RESULTS

Fig. 19 Column strength of boron aluminum is superior to titanium.

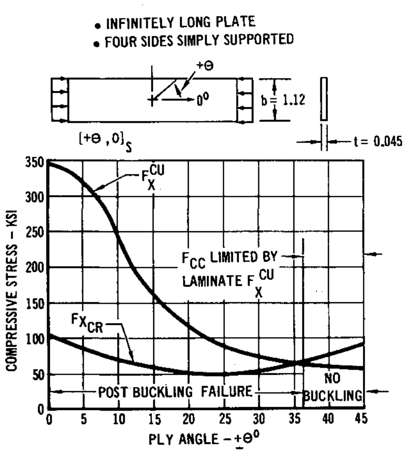


Fig. 20 High crippling strength requires post buckling capability.

Table 1 Factors contributing to improved crippling strength of boron aluminum components

Factor	Room temperature % improvement
Filament diameter (4mil vs 5.6 mil)	~0
Improved processing (eutectic	~ +25
and diffusion bonding)	+50
Large corner radii	~ +25
Add stainless steel wire-aluminum plies	~ −17
Reduced filament volume in corners	~ +30
67% angle plies, ±15°	~ +40
±20	~ +20
±45	~ −50
Titanium interleaf:	
midplane	~0
external surface (r.t.)	~ +45
(600°F)	+35

Analytical Studies of Crippling

A limited study was conducted to obtain a qualitative understanding of the apparent increase in crippling strength when small angle cross plies are added to unidirectional boron aluminum laminates. Because an accurate theoretical solution for predicting crippling is not available, the approach used was to compare predicted ultimate compressive strength (F_x^{cu}) with buckling strength ($F_{x_{cr}}$). A $[\pm\theta,0]_s$ laminate was analyzed and results are shown in Fig. 20. The ultimate compressive strength curve was obtained using the RD5 nonlinear composite analysis computer program and maximum strain failure criteria.[3] Ultimate strength of a unidirectional laminate, 344,000 psi, was obtained from tests of longitudinal sandwich beams. The reduction in compressive strength with increasing ply angles is due to transverse tensile failure in the 0° plies.

Angle plies possess high Poisson's ratios, which cause internal transverse stresses in the unidirectional plies. Failure occurs when the transverse strain of 0° plies is exceeded.

Buckling strength of the $[\pm\theta,0]_s$, 1.12-in.-wide laminate was obtained using the following equation applicable to an infinitely long plate simply supported on four sides:

$$F_{x_{cr}} = 2\pi^2/b^2t\,[(D_{11}D_{22})^{1/2} + D_{12} + 2D_{66}]$$

For a six-ply laminate, the stress-strain response is nonlinear. Therefore, plasticity was considered when determining the flexural stiffness terms (D_{ij}) in the buckling equation. Buckling strength of the $[\pm 45, 0]_s$ laminate is high relative to the other angle ply combinations because of the significant contribution of the shear stiffness term (D_{66}) in the buckling equation.

These two curves bracket the strength of elements comprising compression members. Failures occurring between these bounds are a result of combined failure modes. Crippling strength of unidirectional specimens containing small-angle cross plies of titanium interleaves near the surface are examples. Specimens of this type have improved transverse properties which provide significant post-buckling strength.

Conclusions

Many factors affecting crippling strength of boron aluminum have been investigated and are summarized in Table 1. Process improvements and use of larger corner radii in unidirectional specimens have increased crippling strength an average of 50%. Reducing filament volume in corners, adding small-angle cross plies, and adding titanium interleaves near the surface have increased crippling strength by 30, 40, and 45%, respectively.

Two of these approaches (small-angle cross plies and titanium interleaves near the surface) show considerable promise and deserve further experimental and analytical research. Variables investigated should include stacking sequence, ply orientation, titanium volume percentage, and interleaf thickness.

It is expected that improvements afforded by each factor can be added to some extent when they are combined. It has been shown that typical stringer shaped hat sections fabricated with improved process control and having larger corner radii can easily attain a 50% improvement over the level attained in previous MDAC-E programs. A similar hat section containing some angle plies or titanium interleaves should show an even greater improvement.

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