

# EVALUATION OF BRAIDED STIFFENER CONCEPTS FOR TRANSPORT AIRCRAFT WING STRUCTURE APPLICATIONS

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## INTRODUCTION

Braided composite materials have potential for application in aircraft structures. Stiffeners, wing spars, floor beams, and fuselage frames are examples where braided composites could find application if cost effective processing and damage requirements are met. Braiding is an automated process for obtaining near-net shape preforms for fabrication of components for structural applications. Previous test results on braided composite materials obtained at NASA Langley indicate that damage tolerance requirements can be met for some applications. In addition, the braiding industry is taking steps to increase the material through-put to be more competitive with other preform fabrication processes.

Data are presented on the compressive behavior of three braided stiffener preform fabric constructions as determined from individual stiffener crippling test and three stiffener wide panel tests. Stiffener and panel fabrication are described and compression data presented for specimens tested with and without impact damage. In addition, data are also presented on the compressive behavior of the stitched stiffener preform construction currently being used by McDonnell Douglas Aerospace in the NASA ACT wing development program.

## OBJECTIVE AND APPROACH

Figure 1 outlines the objective and approach used to characterize the braided stiffener concepts for application to transport aircraft wing structure reported herein. Two braided T-stiffener architectures were selected for evaluation; a braided/woven configuration of  $[\pm 45^\circ/0^\circ]$  and a 100% braid configuration of  $[\pm 53^\circ/0^\circ]$ . These architectures were selected as they compare closely with the stitched Saerbeck warp knit material configuration currently being evaluated by McDonnell Douglas Aerospace in their stitched wing concept under the NASA Advanced Composites Technology Program. The materials selected, preform and panel fabrication, and compression property characterizations are discussed in more detail.

## OBJECTIVE AND APPROACH

### **Objective:**

**Assess potential of braided stiffeners for stitched/resin transfer molded aircraft wing structures**

### **Approach:**

- **Braided stiffener selection**
  - **Architectures**
  - **Fiber**
  - **Resin**
- **Fabrication of panels**
- **Evaluation of panel compression properties**

Figure 1. Objective and approach.

## COST COMPARISON OF BRAIDED VS STITCHED SAERBECK STIFFENERS

The impetus for this study is the potential cost saving by going to the braided stiffener concept compared to the stitched Saerbeck warp knit material as shown in figure 2. The figure indicates a cost savings of about 15 percent for straight braided stiffeners can be obtained if this concept can meet the design requirements. The data shown assumes a production run but no capital equipment for producing either type of stiffeners. Curved braided stiffeners will cost more than straight braided stiffeners but they can be braided to fit wing curvature whereas the stitched Saerbeck warp knit material concept may not conform to wing curvature without buckling. The remainder of this paper will address the materials, preform and panel fabrication, and compression properties of braided stiffener panels.

## COST COMPARISON OF BRAIDED VS STITCHED SAERBECK STIFFENERS

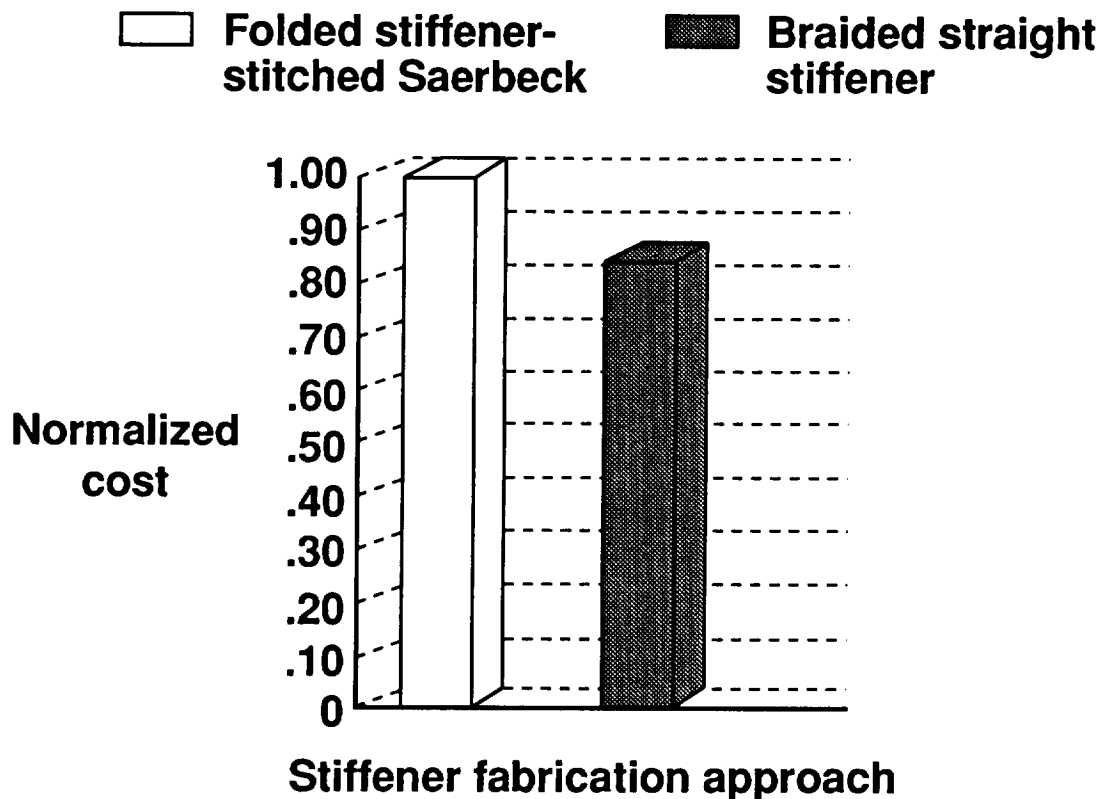


Figure 2. Cost comparison of braided vs stitched Saerbeck stiffeners.

## BRAIDED T-STIFFENER CROSS SECTION

Figure 3 shows the desired cross section of the braided T-stiffeners after resin film infusion (RFI) processing into panels. The dimensions shown are nominal values for processed stitched Saerbeck warp knit stiffeners which the braided stiffeners could replace. Braided stiffeners of these dimensions would allow use of existing tooling for processing into compression panels for property evaluation.

## BRAIDED T-STIFFENER CROSS SECTION

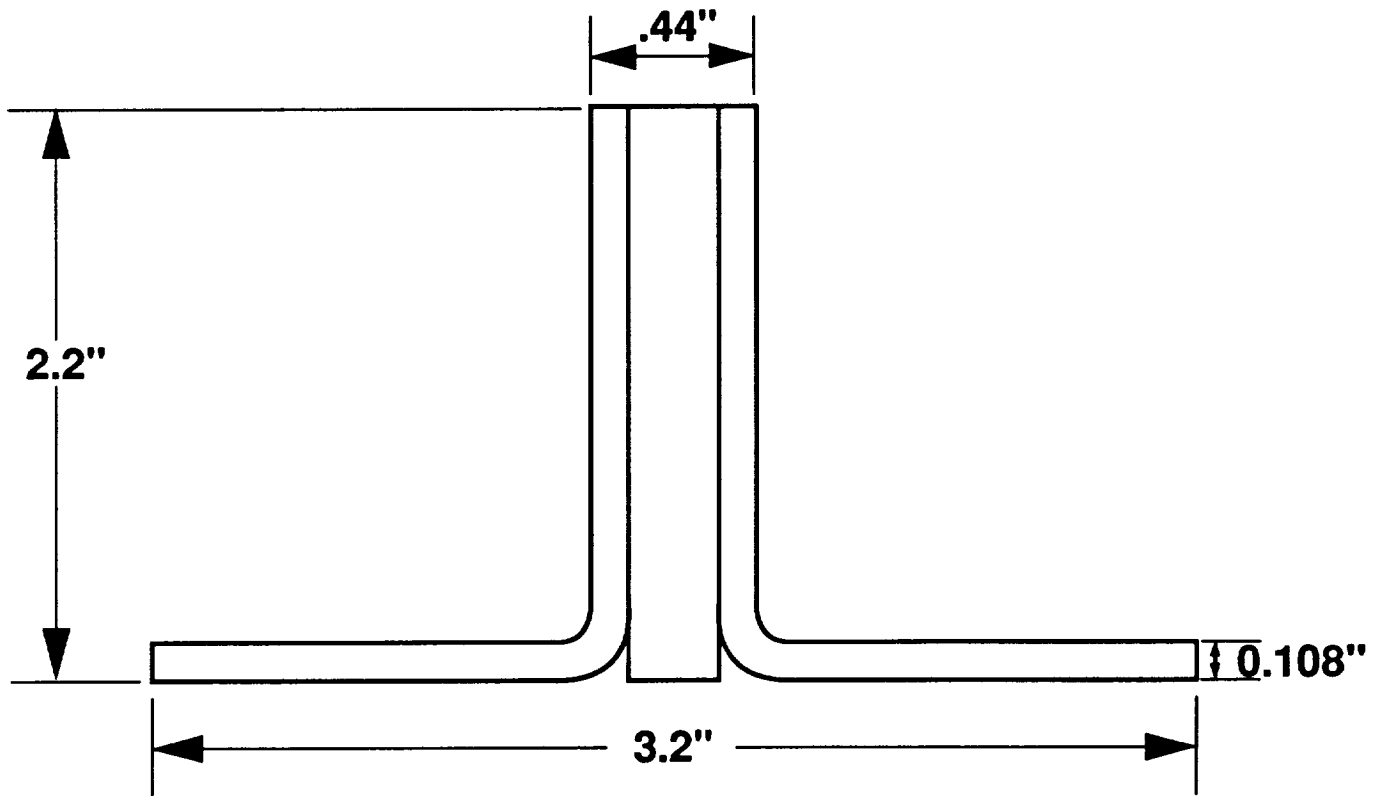


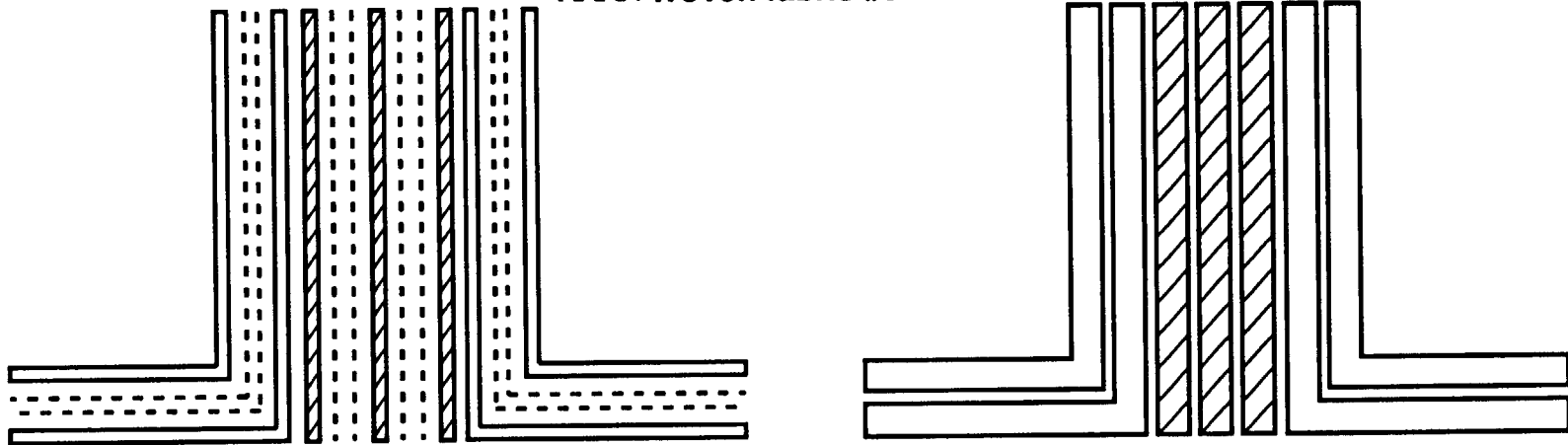
Figure 3. Braided T-stiffener cross section.

## BRAIDED T-STIFFENER PREFORM ARCHITECTURES

Two different architectures are shown in figure 4 employing braids to produce stiffeners equivalent to the stitched Saerbeck warp knit stiffener concept currently being proposed as baseline under the NASA ACT wing development program with McDonnell Douglas Aerospace. The braided/woven configuration shown on the left consists of triaxially braided tubes and woven fabric which are stitched together in the blade area of the T-stiffener. The triaxially braided tubes were fabricated from AS4 6K graphite fiber in the  $\pm 45^\circ$  direction and either AS4 12K or IM7 12K/2E graphite fiber in the  $0^\circ$  direction. The AS4 axial fiber is used in stiffeners for the compression cover of the wing whereas the IM7 fiber is used in stiffeners for the tension cover. The plain weave fabric was woven with AS4 6K graphite fiber and had the same yarn count in the warp and fill directions. The tubes were braided on mandrels whose circumferences equaled the height of the blade plus the flange, for tube #1, and the height of the blade, for tube #2. Similarly, the fabrics were woven to widths equal to the height of the stiffener blade plus the flange width and a width equal to the blade height. Thus, there are no loose fibers in this configuration, except at the cut ends of the stiffeners where the fill yarns of the woven fabrics may unravel. However, since the woven fabric is sandwiched between the braided components and the blade of the T-stiffener is stitched, unraveling should not be a problem. The configuration shown on the right consists of just braided tubes which were braided on mandrels similar to that just described for the braided/woven configuration. These triaxially braided tubes were fabricated from AS4 6K graphite fiber in the  $\pm 53^\circ$  direction and either AS4 18K or IM7 12K/3E graphite fiber in the  $0^\circ$  direction. Again, the AS4 fiber is used in stiffeners for the compression cover of the wing and the IM7 fiber is used in stiffeners for the tension cover. Both of these configurations were evaluated in combination with the stitched Saerbeck warp knit skin material.

# BRAIDED T-STIFFENER PREFORM ARCHITECTURES

- ▭ Triaxially braided tube #1
- ▨ Triaxially braided tube #2
- ⋯ Woven fabric #3



## Braided/woven

- Bias fiber - AS4 6K
- Axial fiber - AS4 12K  
- IM7 12K/2E
- Braid angle  $\pm 45^\circ/0^\circ$
- Fabric - AS4 6K, 10.5/in. warp and fill

## 100% braided

- Bias fiber - AS4 6K
- Axial fiber - AS4 18K  
- IM7 12K/3E
- Braid angle  $\pm 53^\circ/0^\circ$

Figure 4. Braided T-stiffener preform architectures.

## SCHEMATIC OF SAERBECK/LIBA MULTIAXIAL WARP KNITTING MACHINE

Saerbeck produces multiaxial warp knit fabrics on a machine developed by Liba, a German-owned company. Figure 5 shows a schematic of the machine which can produce fabric with up to 8 plies, each of which can be oriented  $0^\circ$  or  $\pm 30^\circ$  through  $90^\circ$ . Fabrics can be produced up to 100 inches wide at 50 lineal yards per hour. Yarn carriers with multiple tows traverse the width of the fabric and place tows around pins that are attached to a moving belt. The tow size and the number of tows per inch determine the ply areal weight. Different tow sizes can be used in each direction if desired. Figure 5 illustrates  $90^\circ$  and  $\pm 45^\circ$  tows being laid down by the yarn carriers moving along fixed guides. The  $0^\circ$  tows are laid down off a beam just prior to the knitting head, which can use either a chain of tricot stitch to knit these 4 plies into a stack. This type of machine was used to produce 7-ply material ( $+45^\circ$ ,  $-45^\circ$ ,  $0^\circ$ ,  $90^\circ$ ) for fabricating stitched tension and compression skins to attach the braided stiffeners to assess their CAI performance. Tow sizes and knitting parameters were varied to obtain nominal percentages of fibers in the  $0^\circ$ ,  $\pm 45^\circ$ , and  $90^\circ$  directions of 44/44/12, respectively. The  $0^\circ$  direction contains 12K fiber tows. The  $\pm 45^\circ$  directions each contain 6K fiber tows and the  $90^\circ$  direction contains 3K fiber tows. The compression skin material uses all AS4 graphite fiber and the tension skin material uses AS4 fibers in the  $\pm 45^\circ$  and  $90^\circ$  directions and IM7 fiber in the  $0^\circ$  direction.

# **SCHEMATIC OF SAERBECK/LIBA MULTIAXIAL WARP KNITTING MACHINE**

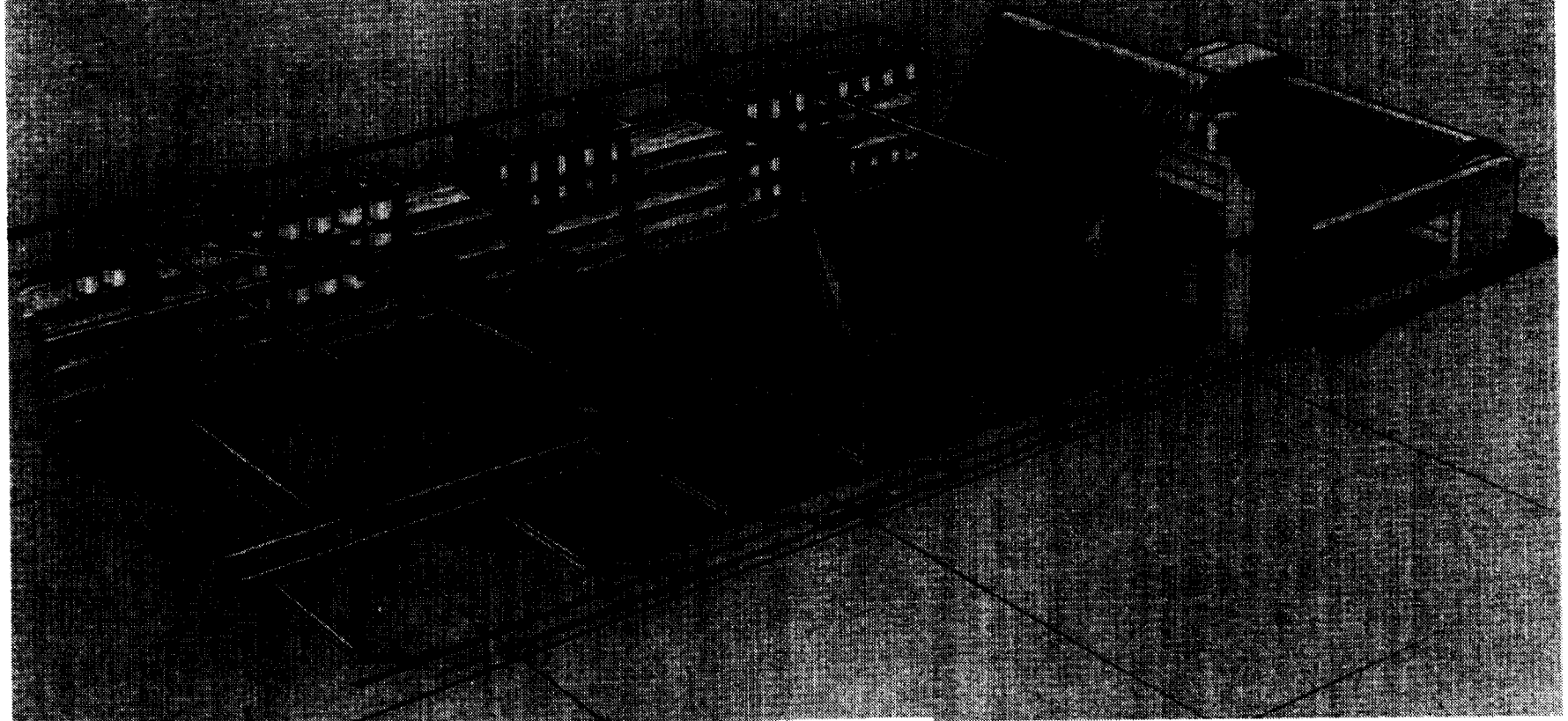


Figure 5. Schematic of Saerbeck/Liba multi-axial warp knitting machine.



## COMPUTER CONTROLLED SINGLE-NEEDLE STITCHING MACHINE

Figure 6 shows the computer controlled single-needle stitching machine installed in the Advanced Composites Section, Fabrication Division, NASA- Langley. The machine is capable of stitching dry high-performance textile materials over an area of 4 ft by 6 ft and thicknesses greater than 1.5 inches. The machine uses a lock stitch and can be programmed to stitch in any direction (including curves) within the 4 ft by 6 ft area. Stitch pitch can be varied from 4 to 14 per inch and stitching speed can be varied from 40 to 200 stitches per minute. Both stitch pitch and stitching speed can be changed within a stitching program by a key stroke on the control keyboard. The machine is capable of stitching with a wide variety of needle and bobbin threads, such as, polyester, nylon Kevlar, and carbon. Also, different thread sizes can be used in combination for the needle and bobbin. The machine was used to stitch the tension and compression skins and the attachment of the braided stiffeners to produce 3-stiffener wide preforms for this investigation.

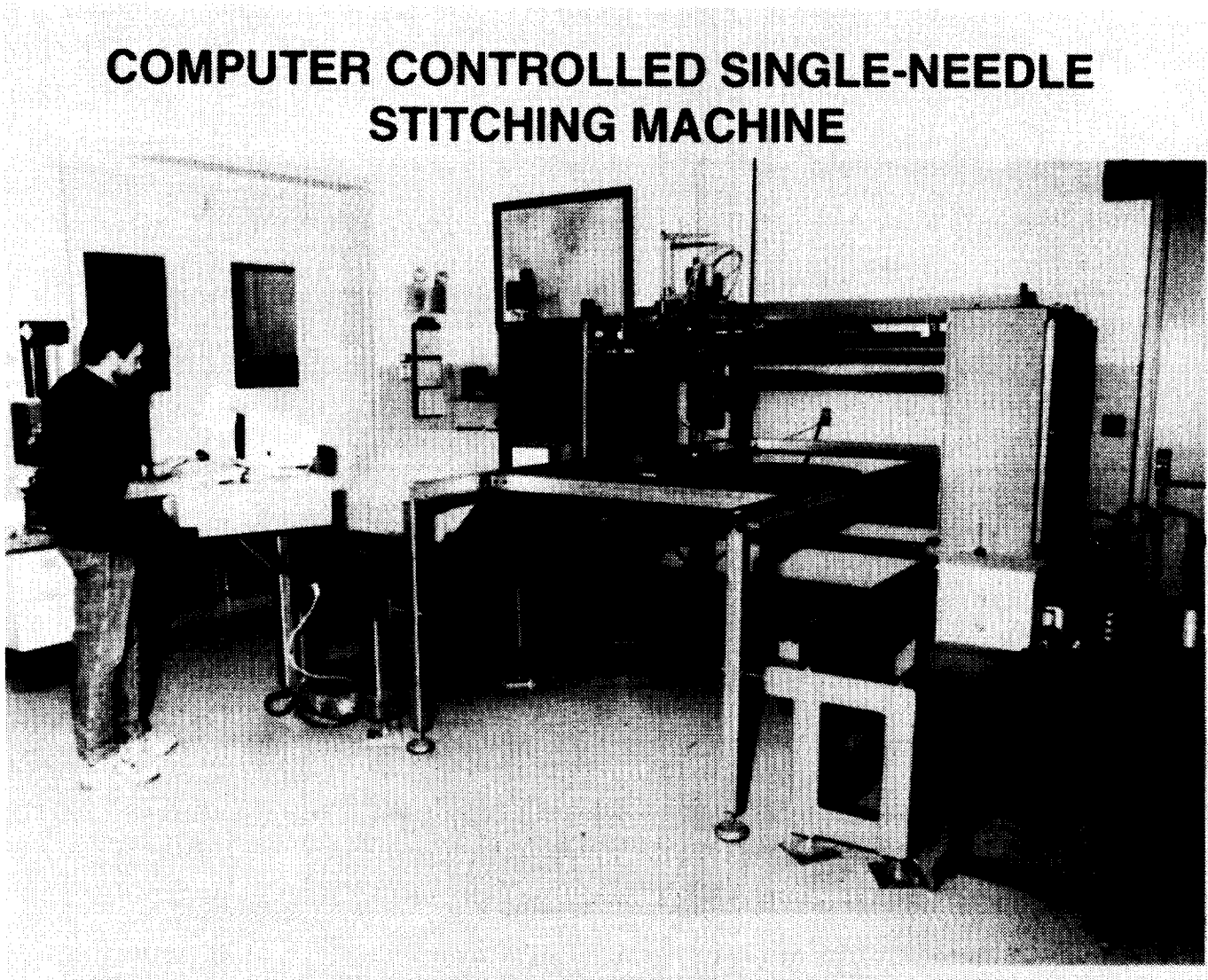


Figure 6. Computer controlled single-needle stitching machine.

## STITCHED MULTIAXIAL WARP KNITTED TENSION SKIN

A completed stitched tension skin is shown in figure 7. The skin consists of 6 stacks of the 7-layer Saerbeck material with the IM7 fiber in the  $0^\circ$  direction previously described stitched together using a stitch pitch of 8 and a row spacing of 0.5 inch. The stitch area was 2 ft wide and 4 ft long. The needle thread was 1600 denier Kevlar (400/1x4) with a low-melt nylon coating and the bobbin thread was 400 denier Kevlar (200/1x2).

## STITCHED MULTIAXIAL WARP KNITTED TENSION SKIN

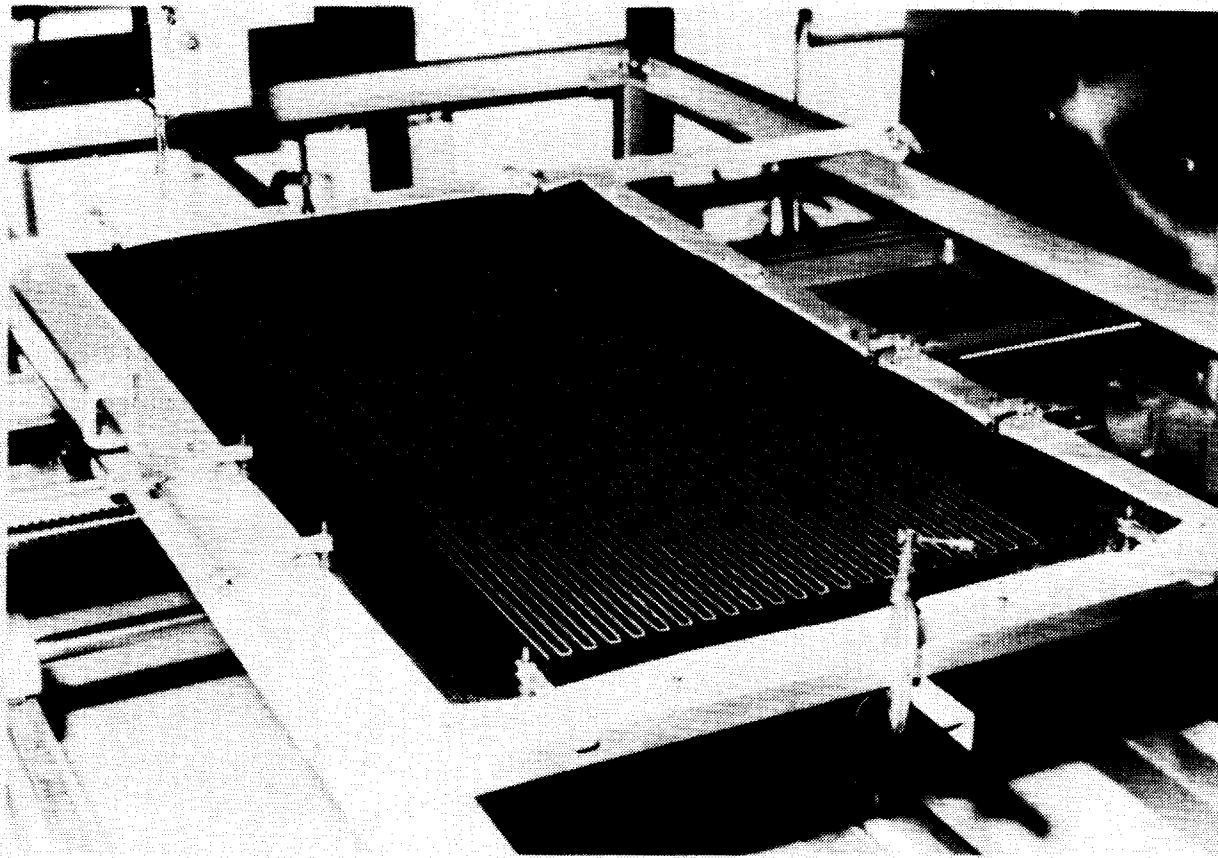


Figure 7. Stitched multiaxial warp knitted tension skin.

## STITCHED MULTIAXIAL WARP KNITTED COMPRESSION SKIN

Figure 8 shows a completed stitched compression skin. It consists of 6 stacks of the 7-layer all AS4 Saerbeck warp knit material. The stitching parameters were; stitch pitch of 8, and a row spacing of 0.2 inch. The needle and bobbin threads are the same size as used for the tension skin, 1600 denier for the needle thread and 400 denier for the bobbin thread. The overall stitch area was also 2 ft by 4 ft, however, the skin is not stitched in the area where the stiffener flanges are to be stitched to the skin. Also shown in figure 8 is a 4 foot length of braided T-stiffener along with the stiffener locating tool which aids in stitching the stiffener to the skin.

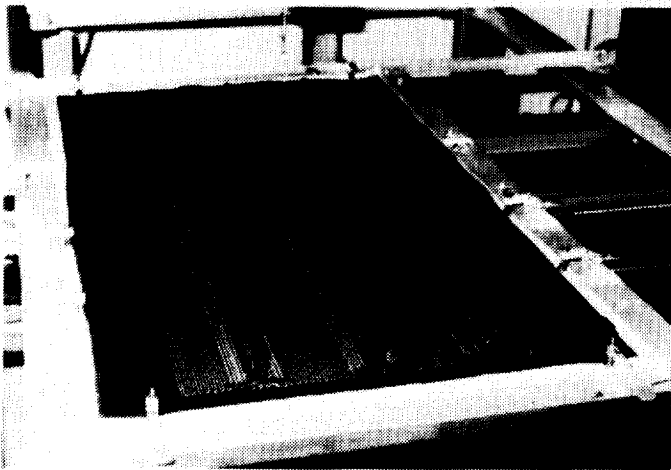


Figure 8. Stitched multi-axial warp knitted compression skin.

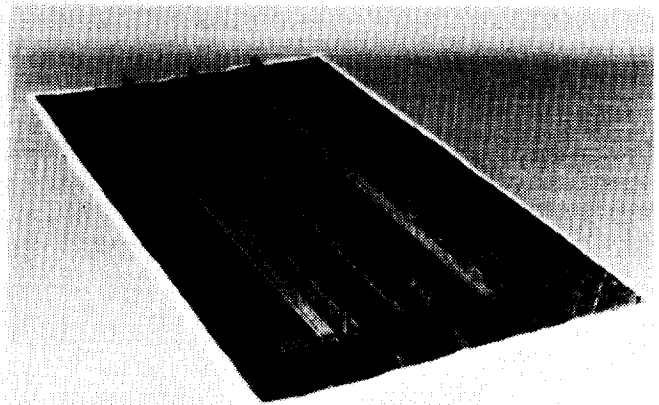
## STITCHED MULTIAXIAL WARP KNITTED PREFORMS WITH BRAIDED/WOVEN STIFFENERS

Completed compression and tension skin preforms with stiffeners attached are shown in figure 9. The overall sizes are the same and both preforms have a 7-inch stiffener spacing. The basic differences in the two preforms is the stitching parameters used to assemble the skins and the use of the IM7 graphite fiber in the 0° direction of both the skin material and stiffener in the tension preform. The blade of the stiffener was inserted into the T-stiffener locating tool shown in figure 8 and placed over locating pins at each end of the stitching frame and one flange was stitched to the skin using the same stitching parameters for fabricating the compression skin preform. After one stiffener flange was stitched to the skin, the tool was removed and turned, end for end, and placed over the stiffener blade and the other flange was stitched to the skin.

## STITCHED MULTIAXIAL WARP KNITTED PREFORMS WITH BRAIDED/WOVEN STIFFENERS



**Compression skin**



**Tension skin**

Figure 9. Stitched multiaxial warp knitted preforms with braided/woven stiffeners.

## **TOOLING FOR RESIN INFUSION OF SAERBECK SKIN/BRAIDED 3-STIFFENER PREFORM**

McDonnell Douglas Aerospace uses the tooling method shown in figure 10 to mold 3-stiffener panels in an autoclave using Hercules 3501-6 resin. This approach uses hard mandrels to support the stiffener blades. Air and resin vent holes are at the top of each stiffener. The edges of the assembly are sealed with tape to prevent resin leakage while the preform debulks and resin flows. The accurately located stiffeners in conjunction with the aluminum mandrels and silicone pressure pads give uniform compaction and the desired dimensions upon cure. As with flat panels, the resin film infusion (RFI) flow path is through the thickness of the skin. However, the flow becomes two-dimensional at the base of the stiffeners, then becomes in-plane with respect to the fibers in the stiffener blade. Research conducted by Virginia Polytechnic Institute and the College of William and Mary using a computer model and dielectric sensors arrived at an autoclave cure cycle that resulted in full infusion for panels fabricated for this investigation, as determined from ultrasonic C-scans. Panel sizes were 24 inches long and 22 inches wide for the RFI processing. Four panels of this size for each braided stiffener architecture were processed by McDonnell Douglas Aerospace for this joint program with NASA-Langley.

# TOOLING FOR RESIN INFUSION OF SAERBECK SKIN/ BRAIDED 3-STIFFENER PREFORM

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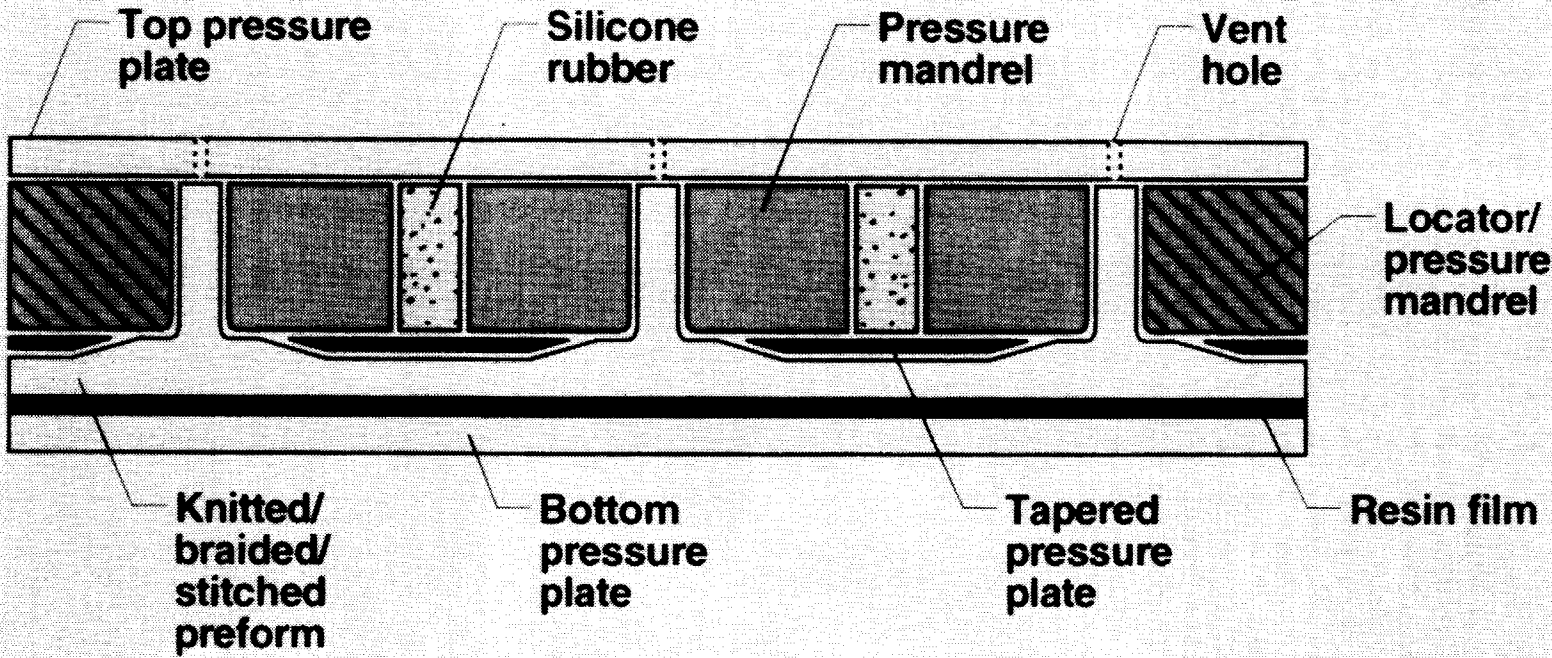


Figure 10. Tooling for resin film infusion of Saerbeck skin/braided 3-stiffener preform.

## IMPACTING OF 3-BRAIDED STIFFENER PANELS

Figure 11 illustrates how the 3-stiffener panels were supported for the impact event. Panels were supported by hardwood blocks at each end and C-clamped at each stiffener location. A drop weight impactor having a diameter of one inch was used to apply a 100 ft-lb impact on the skin side mid-bay between two stiffeners or at the flange edge of the center stiffener as illustrated on the sketch. After the panels were impacted C-scans were used to determine the amount of damage. One 3-stiffener panel from each group of four was designated for single-stiffener crippling tests. This panel was also impacted but at different locations. The panel was impacted (100 ft-lb) on the skin side directly behind the center stiffener at the quarter-length from each end. One of the other stiffeners also received a 20 ft-lb impact at the quarter-length from each end on the side-of-blade. All 3-stiffener panels were returned to Langley for trimming, machining, measurements, end potting, instrumentation, and testing.



# IMPACTING OF 3-BRAIDED STIFFENER PANELS

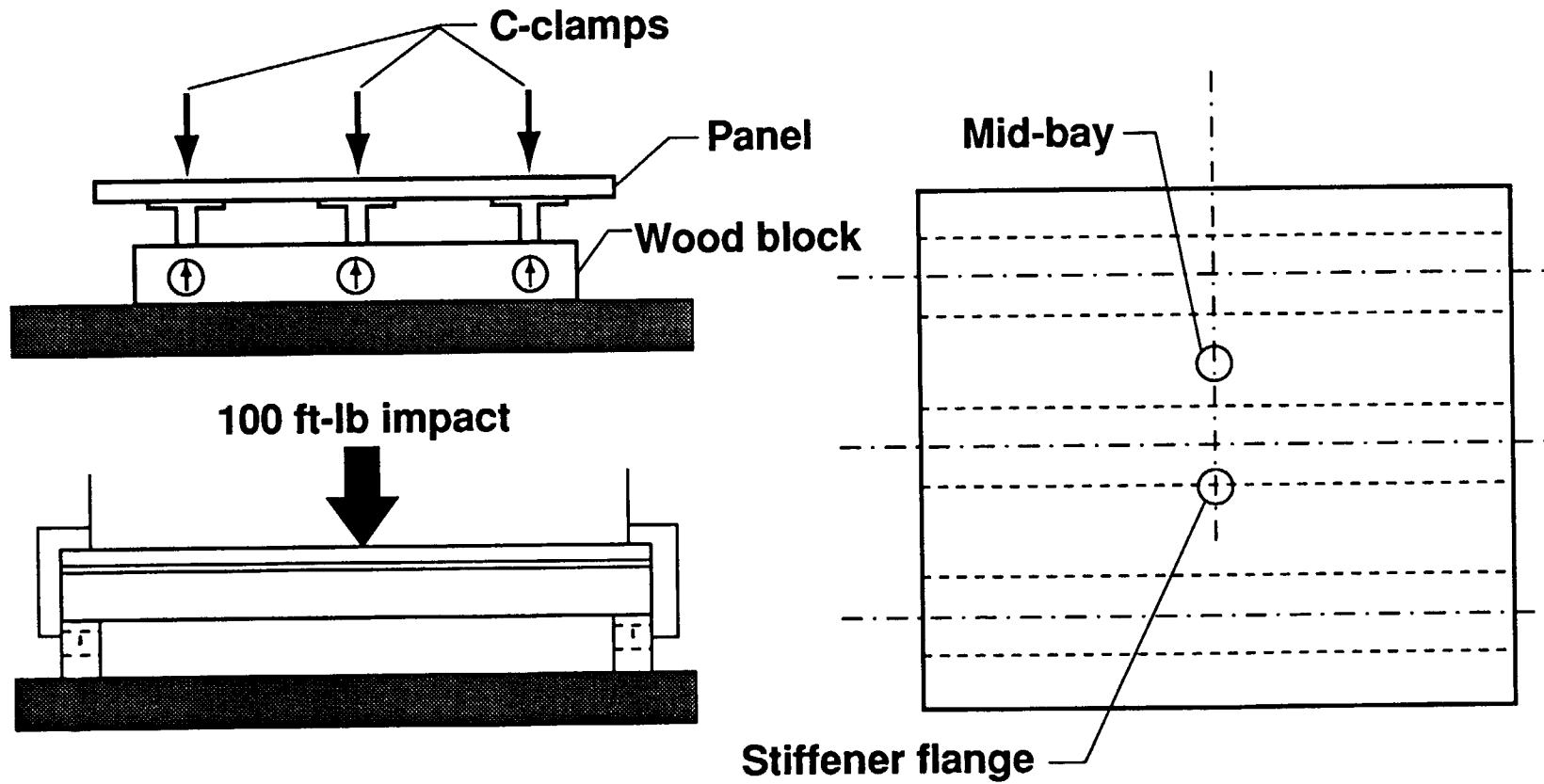


Figure 11. Impacting of 3-braided stiffener panels.

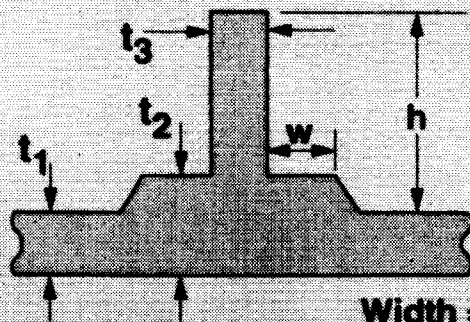
## DESCRIPTION OF 3-BRAIDED STIFFENER COMPRESSION PANELS

The 3-braided stiffener compression panels were measured as indicated in figure 12 after the panels were trimmed to a width of 21.0 inches and a length of 22.0 inches. Five thickness measurements, stiffener flange width, and stiffener height were obtained, along the length, for each panel segment or stiffener and the average values are given in the figure. The skin and stiffener concept being evaluated and the associated panel number are also indicated in the figure along with the calculated cross-sectional area. In addition to the braided stiffener panels listed in figure 12, dimensions for a stitched skin and stitched stiffener panel (S7) are also shown. This panel was obtained from the trimmed ends of a large compression repair panel which was one of the test components from the McDonnell Douglas Aerospace ACT wing development program. After all measurements were obtained each panel end was potted and machined flat, square and parallel for uniform load introduction. Back-to-back strain gages were installed on the single-stiffener crippling and 3-braided stiffener compression panels. For the single-stiffener crippling panels, a minimum of six strain gages were mounted at the mid-length on the skin and side-of-blade of the stiffener. Back-to-back strain gages were also mounted at the mid-length for the 3-braided stiffener compression panels, on the top of each stiffener and on the skin between each stiffener. Strain gages for impacted panels were also mounted approximately 1-inch above and below and on both sides of the impact site.

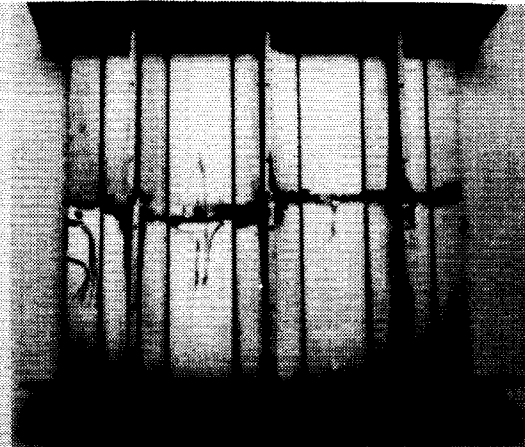
# DESCRIPTION OF 3-BRAIDED STIFFENER COMPRESSION PANELS

Figure 12. Description of 3-braided stiffener compression panels.

Typical Stiffener



Width = 21.0 in.  
Length = 22.0 in.  
Stiffener spacing = 7.0 in.



(a) Panel numbers 1 through 8.

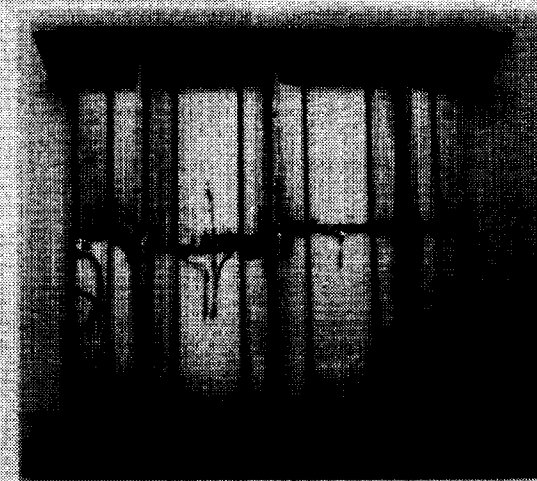
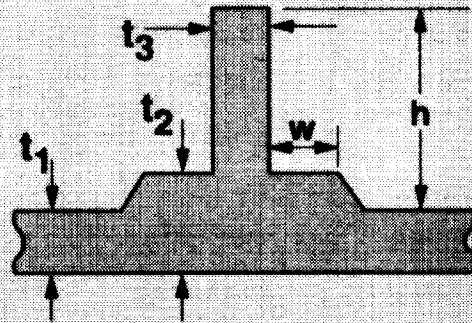
Nominal Dimensions

Panel No.	Skin	Stiffener	$t_1$ , in.	$t_2$ , in.	$t_3$ , in.	$w$ , in.	$h$ , in.	Cross-sectional area, in. <sup>2</sup>
1	Saerbeck	Braided/woven	0.359	0.464	0.427	1.58	2.14	11.52
2	AS4 fiber	AS4 fiber	0.346	0.450	0.429	1.51	2.14	11.11
3*	(44% 0°, 44%	(±45/0°)	0.340	0.444	0.427	1.51	2.14	—
4	±45°, 12% 90°)		0.336	0.440	0.424	1.58	2.14	10.90
5	Saerbeck	100% Braided	0.340	0.448	0.422	1.51	2.14	10.99
6	AS4/M7 fiber	AS4 fiber	0.335	0.443	0.422	1.51	2.13	10.87
7	(44% 0°, 44%	(±53/0°)	0.332	0.436	0.424	1.50	2.14	10.85
8*	±45°, 12% 90°)		0.323	0.427	0.423	1.50	2.14	—

\*Single stiffener specimens machined from panel after impacting

# DESCRIPTION OF 3-BRAIDED STIFFENER COMPRESSION PANELS

Typical Stiffener



Width = 21.0 in.  
Length = 22.0 in.  
Stiffener spacing = 7.0 in.

\*Width = 15.0 in.  
Length = 9.9 in.  
Stiffener spacing = 8.0 in.

Nominal Dimensions

Panel No.	Skin	Stiffener	$t_1$ , in.	$t_2$ , in.	$t_3$ , in.	$w$ , in.	$h$ , in.	Cross-sectional area, in. <sup>2</sup>
1c	Saerbeck	Braided/woven	0.344	0.449	0.425	1.50	2.14	11.01
2c	AS4/IM7 fiber	AS4/IM7 fiber	0.350	0.455	0.427	1.50	2.14	11.17
3c	(44% 0°, 44% ±45°, 12% 90°)	(±45/0°)	0.346	0.451	0.427	1.50	2.14	11.09
S7*	Stitched Saerbeck AS4 fiber (44% 0°, 44% ±45°, 12% 90°)	Stitched Saerbeck AS4 fiber (44% 0°, 44% ±45°, 12% 90°)	0.341	0.554	0.438	1.15	2.09	8.14

Figure 12. Concluded.

(b) Panel numbers 1c through 3c and S7.

## STRESS-STRAIN RESPONSE OF SINGLE-BRAIDED STIFFENER PANELS

Figure 13 shows the stress-strain response of the single braided stiffener panels which were machined from panels RFI processed as 3-stiffener panels. The data shown are for specimens tested in compression without impact damage. The first digit of the panel number shown above the stress-strain plots refers to the 3-stiffener panel given in figure 12 from which the single-stiffener crippling specimen was obtained and the second digit is the specimen number for record keeping. The data are the average of all six strain gage readings since the output of all six gages were virtually identical up until just prior to failure. The data indicate that the 100% braided AS4 stiffener stitched to the Saerbeck warp knit material with the IM7 graphite fiber in the 0° direction has about 7% higher compression strength compared to the braided/woven all AS4 stiffener stitched to the all AS4 Saerbeck warp knit material. However, the stitched Saerbeck stiffener and Saerbeck skin concept has about 25% higher compression strength than the best braided stiffener concept. The 0° and ±45° direction tows in the stitched Saerbeck stiffener are straighter than the 0° and bias tows in the braided stiffener concepts and can better support compression loads.

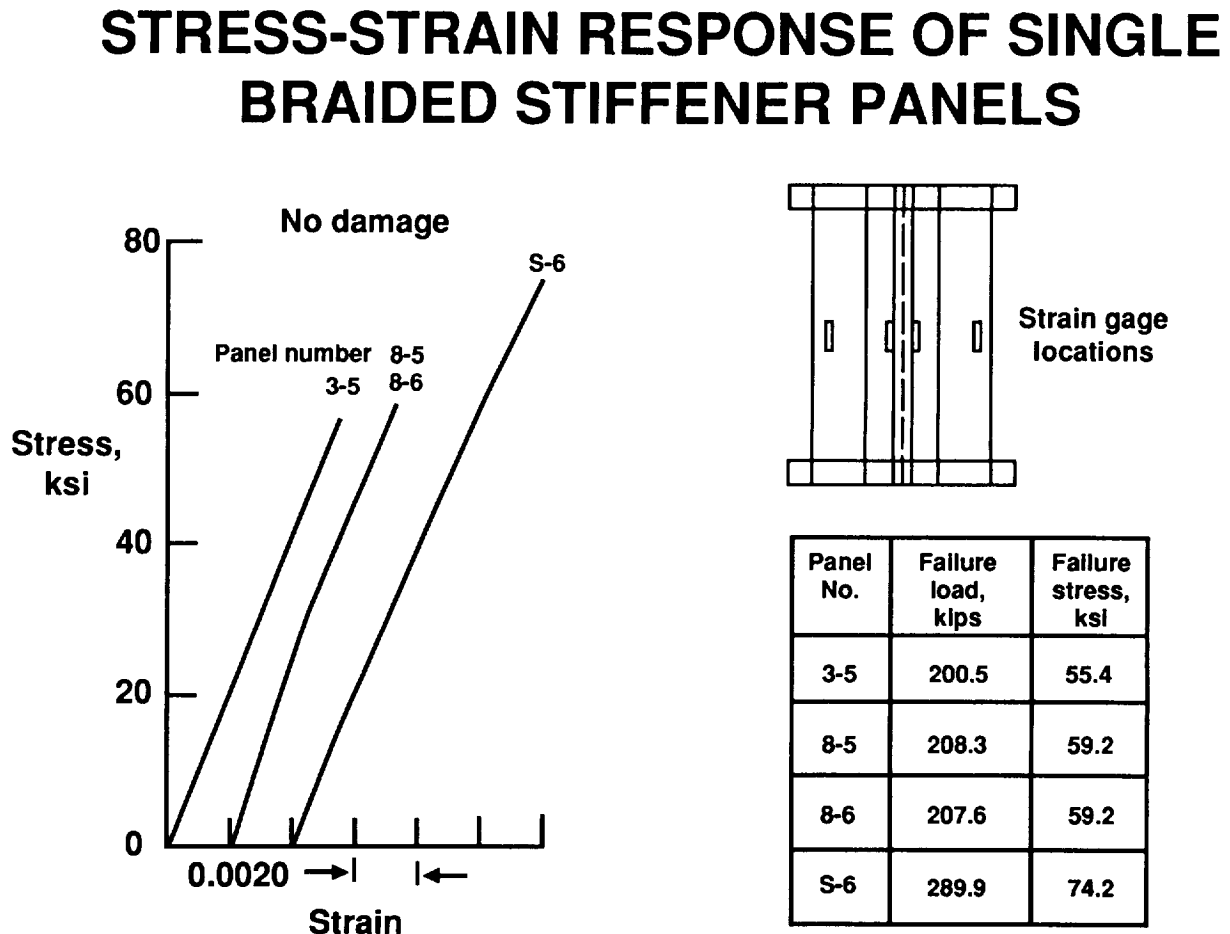


Figure 13. Stress-strain response of single-braided stiffener panels.

## STRESS-STRAIN RESPONSE OF SINGLE BRAIDED STIFFENER PANELS IMPACTED AT MID-STRINGER

Data are shown in figure 14 for the six single-stiffener crippling specimens which were impacted on the skin side directly beneath the blade of the stiffener as indicated on the figure. Again, the first digit of the panel number relates to the panel number given in figure 12 from which the single-stiffener specimens were obtained. The data shown are the average from all six strain gages and is representative for both specimens evaluated. Both braided stiffener concepts (panels 3 and 8) had about the same compression after impact (CAI) strength as the specimens tested which were not impacted (see figure 13). The stitched stiffener concept also did not show any loss in compression strength due to the 100 ft-lb impact and, again, had about 25% higher compression strength than the two braided stiffener concepts.

## STRESS-STRAIN RESPONSE OF SINGLE BRAIDED STIFFENER PANELS IMPACTED AT MID-STRINGER

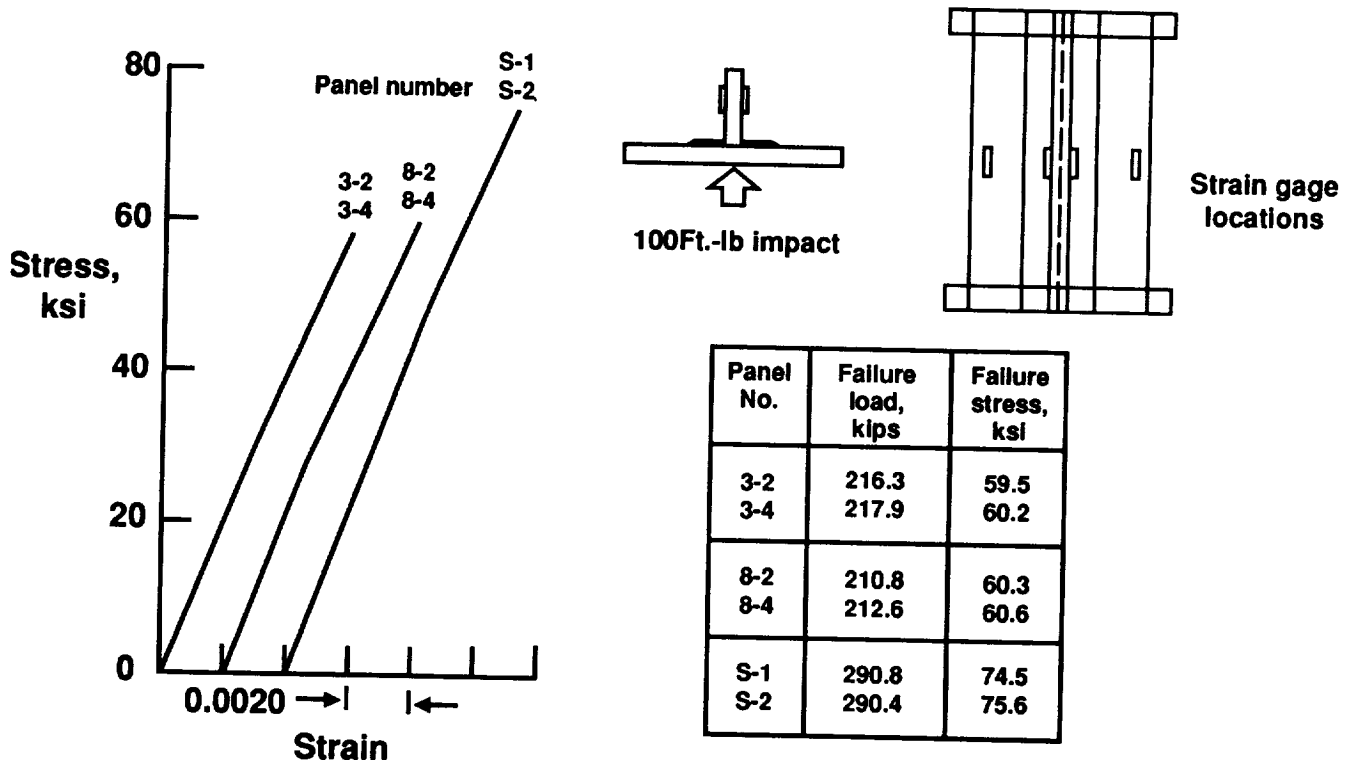


Figure 14. Stress-strain response of single-braided stiffener panels impacted at mid-stringer.

## STRESS-STRAIN RESPONSE OF SINGLE BRAIDED STIFFENER PANELS IMPACTED ON SIDE OF STRINGER

Figure 15 shows the results for the single-stiffener specimens which were impacted on the side-of-blade as indicated on the figure. The data shown are the average from all strain gages and is representative for each specimen. The data shown indicate that the AS4 braided/woven stiffener and the 100% braided AS4 stiffener concepts had about the same compression after blade impact strength which is about the same as for the specimens which were not impacted (see figure 13). The stitched Saerbeck stiffener concept specimen has more than 25% higher compression strength after side of blade impact than the two braided stiffener concepts evaluated under this condition.

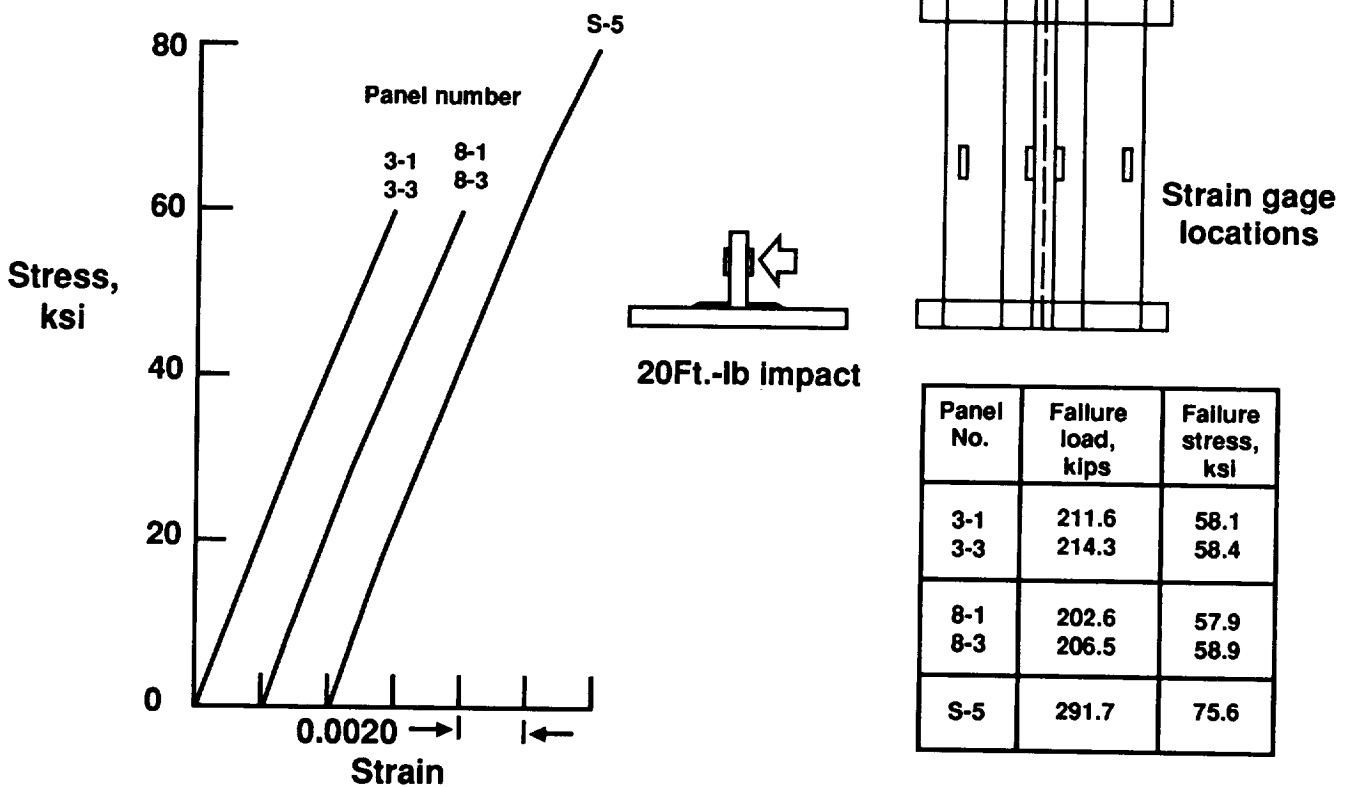


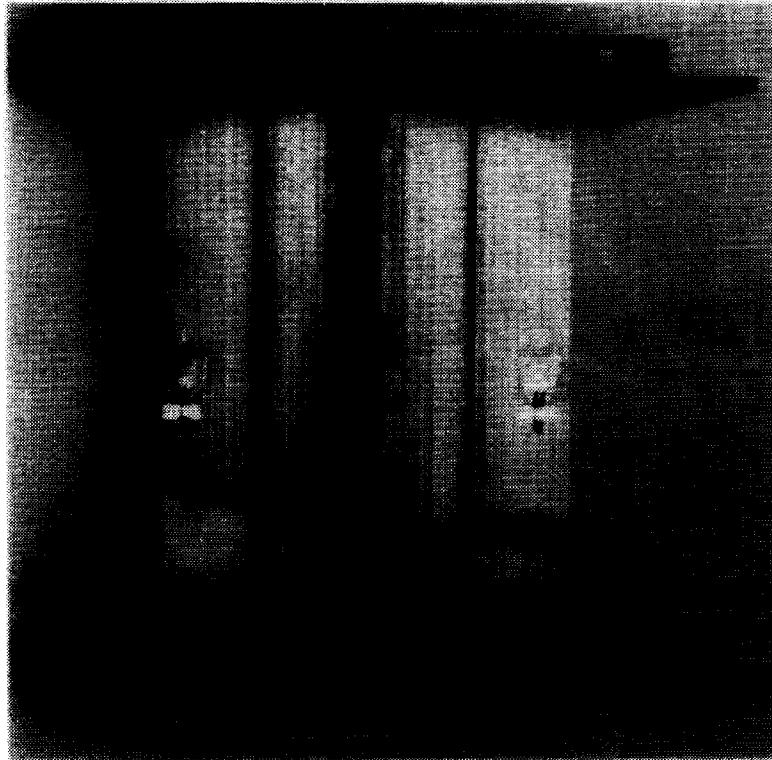
Figure 15. Stress-strain response of single-braided stiffener panels impacted on side of stringer.

## **SINGLE BRAIDED STIFFENER WING PANEL COMPRESSION FAILURE**

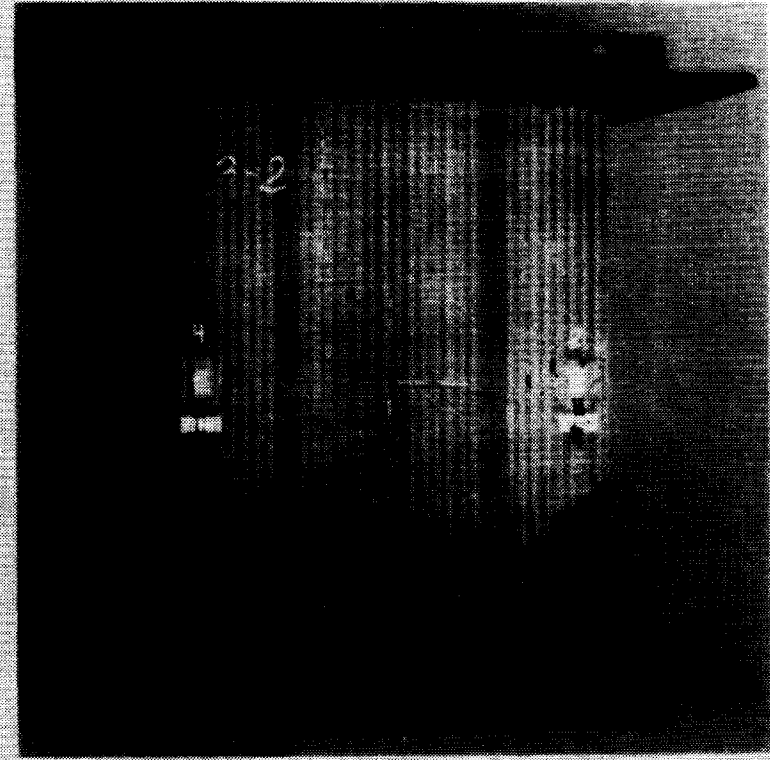
Failure photographs for the AS4 braided/woven stiffener stitched to the AS4 Saerbeck warp knit wing lay-up material which was impacted (100 ft-lb) on the skin side are shown in figure 16. The type of failure shown is typical for all single-stiffener specimens tested, all failed at about the quarter-length away from the impact site. Note that there is no separation of skin and stiffener indicated which is also typical for all single-stiffener specimens tested in this investigation.



# SINGLE BRAIDED STIFFENER WING PANEL COMPRESSION FAILURE



**Stiffener side**



**Skin side**

Figure 16. Single-braided stiffener wing panel compression failure.

## COMPRESSION STRENGTH OF SINGLE STRINGER STIFFENED PANELS FOR DOUGLAS WING

Figure 17 summarizes the single-stiffener compression results presented in figures 13-15. The open bars represent the average failure stress of the single-stiffener specimens tested without impact damage and the hatched bars represent the average failure stress of the specimens which were impacted as indicated by the key at the top of the figure. The skin and stiffener configurations are indicated along the abscissa, beneath the respective data bars. It is clear that the braided/woven stiffener and the 100% braided stiffener concepts have about the same compression properties which is about 25% less than the stitched Saerbeck stiffener concept. Although the two braided stiffener concepts were out performed in compression by the stitched Saerbeck stiffener concept their average failure stress is still about 50% greater than the 40 ksi (CAI) design goal indicated on the figure by the dashed line.

An additional stitched Saerbeck stiffener was used to obtain data on the effect of a 100 ft-lb stiffener flange impact and the results are indicated by the cross-hatched bar on the far right of the figure. The failure stress of this specimen was only about 67% of the undamaged strength and the specimen failed through the impact site. A similar reduction in strength applied to a stiffener flange impact for the two braided stiffener concepts would fall just under the CAI design goal. However, data obtained from the 3-stiffener panels to be presented indicate that a stiffener flange impact is not the critical impact location.

# COMPRESSION STRENGTH OF SINGLE STRINGER STIFFENED PANELS FOR DOUGLAS WING

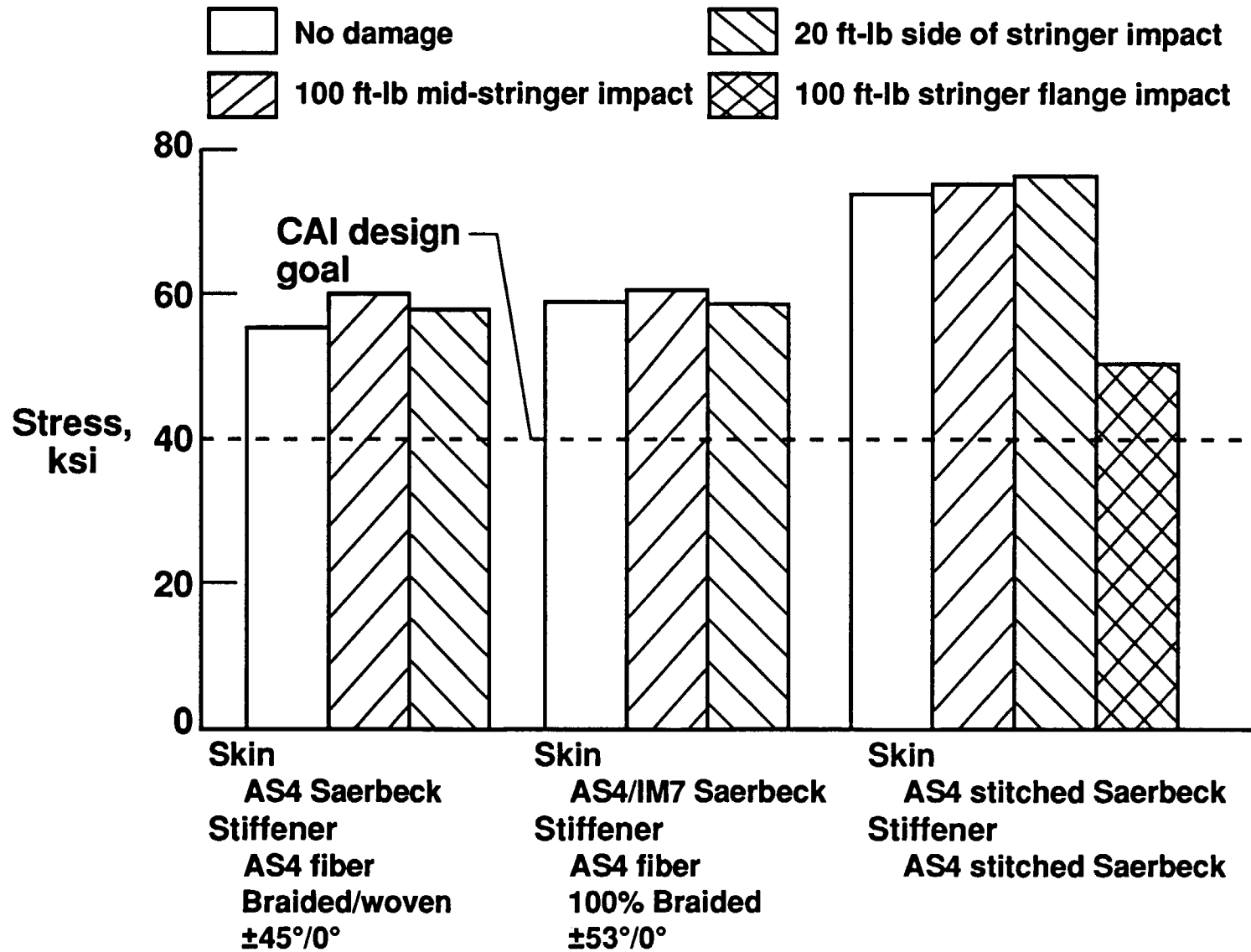


Figure 17. Compression strength of single stringer stiffened panels for Douglas wing.

## STRESS-STRAIN RESPONSE OF 3-BRAIDED STIFFENER PANELS

The stress-strain response of the 3-braided stiffener panels tested in compression without impact damage is shown in figure 18. The panel number shown at the top of the stress-strain curves refer to the panel number given in figure 12 which identifies the fabrication of the panel for which stress-strain data are presented. The data shown are the average of the mid-bay back-to-back strain gage output. Results indicate that the braided/woven stiffener with the IM7 tows in the 0° direction stitched to the Saerbeck warp knit wing lay-up material also with the IM7 tows in the 0° direction (panel 2C) gives the best compression strength, about 9% greater than the braided/woven stiffener and skin fabricated from all AS4 materials (panel 4) but only about 4% greater than the panel with the same skin configuration but with the 100% braided stiffener using all AS4 fiber (panel 6). The maximum displacement values given in the figure were obtained from a linear variable differential transformer which measured end shorting of the test specimens. Global panel strain, defined as the measured end shorting at failure divided by the specimen length, was about the same for all three panel configurations evaluated.

## STRESS-STRAIN RESPONSE OF 3-BRAIDED STIFFENER PANELS

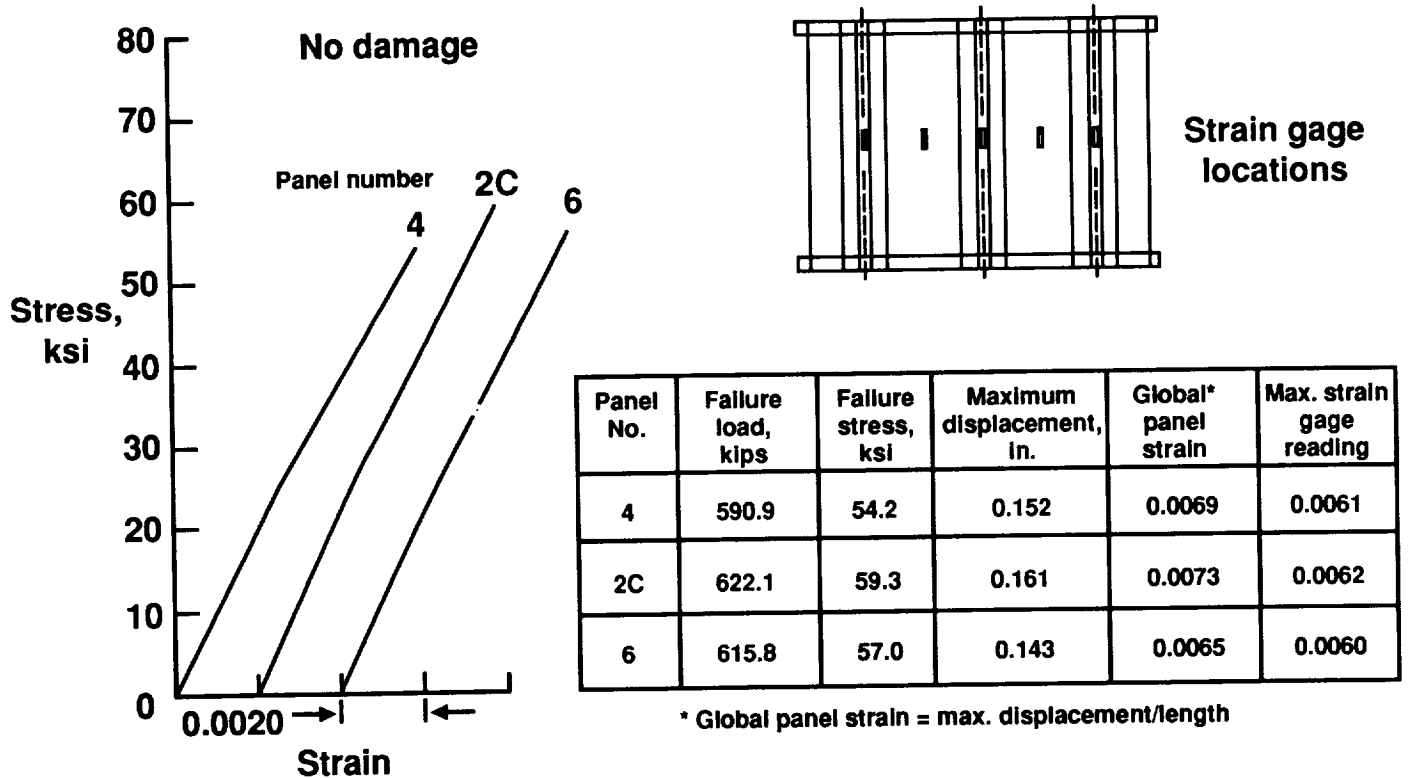


Figure 18. Stress-strain response of 3-braided stiffener panels.

## **STRESS-STRAIN RESPONSE OF 3-BRAIDED STIFFENER PANELS IMPACTED AT STIFFENER FLANGE**

Figure 19 shows the stress-strain response for the 3-stiffener panels impacted on the skin side back of the center stiffener flange previously described. Again, the panel number shown at the top of the stress-strain plots refer to the panel numbers given in figure 12 which identifies the panel fabrication configuration. Again, the data are the average of the mid-bay back-to-back strain gages located adjacent to the impact site. The braided/woven stiffeners with the IM7 tows in the  $0^\circ$  direction stitched to the Saerbeck warp knit wing lay-up material with IM7 tows in the  $0^\circ$  direction (panel 3C) gives the best CAI strength, 13% greater than the all AS4 braided/woven stiffeners stitched to the all AS4 Saerbeck wing lay-up material (panel 2) and about 5% greater than panel 5 which had the all AS4 100% braided stiffeners stitched to the Saerbeck skin material with the IM7 tows in the  $0^\circ$  direction. The global panel strains for the three panels are similar, slightly less than those of the panels tested without impact damage (see figure 18).

# STRESS-STRAIN RESPONSE OF 3-BRAIDED STIFFENER PANELS IMPACTED AT STIFFENER FLANGE

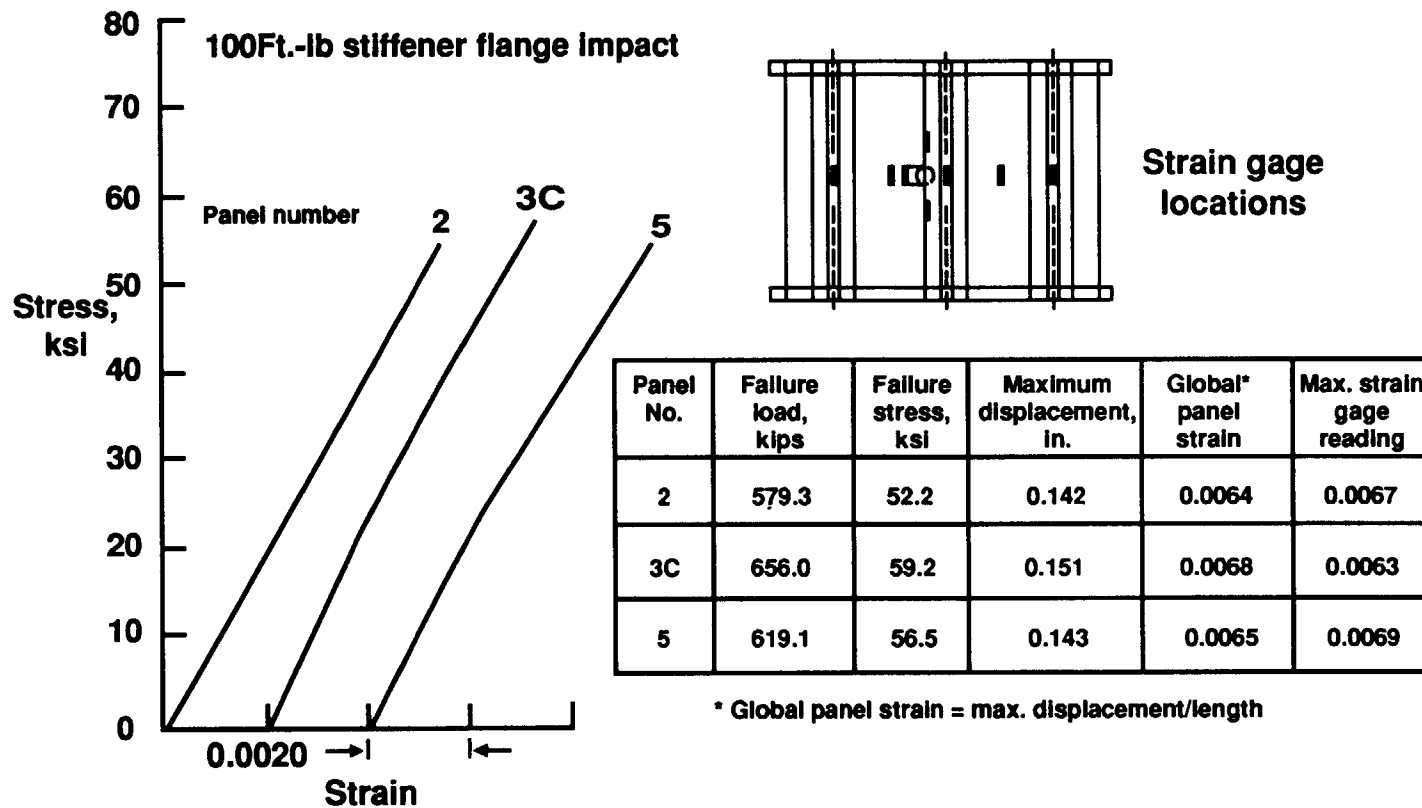


Figure 19. Stress-strain response of 3-braided stiffener panels impacted at stiffener flange.

## **STRESS-STRAIN RESPONSE OF 3-BRAIDED STIFFENER PANELS IMPACTED AT MID-BAY**

Data are shown in figure 20 for the 3-stiffener panels subjected to a mid-bay impact of 100 ft-lb on the skin side. The data are the average of the back-to-back strain gages located in the bay adjacent to the impact location. The all AS4 braided/woven stiffener stitched to the all AS4 Saerbeck wing lay-up material, panel 1 had the best CAI strength, about 7% higher than panel 1C and about 14% higher than panel 7. Note also the differences in the global panel strains. Also shown in figure 20 are the stress-strain results for the short stitched Saerbeck stiffener stitched on to the stitched Saerbeck warp knit wing lay-up material. This panel only had two stiffeners which were 8-inches apart. The CAI strength of this panel was about 12% higher than the CAI strength of the best braided stiffener specimen.

# STRESS-STRAIN RESPONSE OF 3-BRAIDED STIFFENER PANELS IMPACTED AT MID-BAY

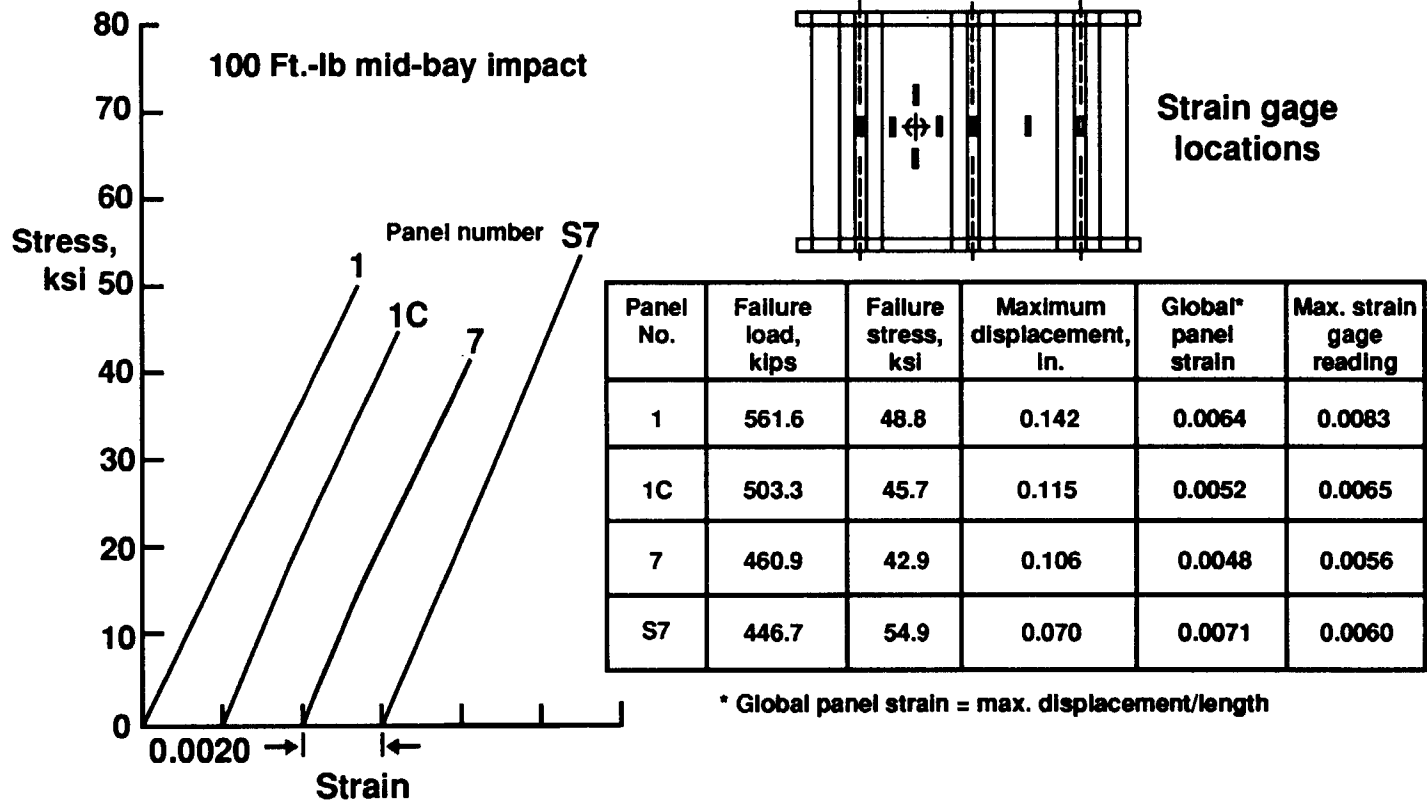


Figure 20. Stress-strain response of 3-braided stiffener panels impacted at mid-bay.



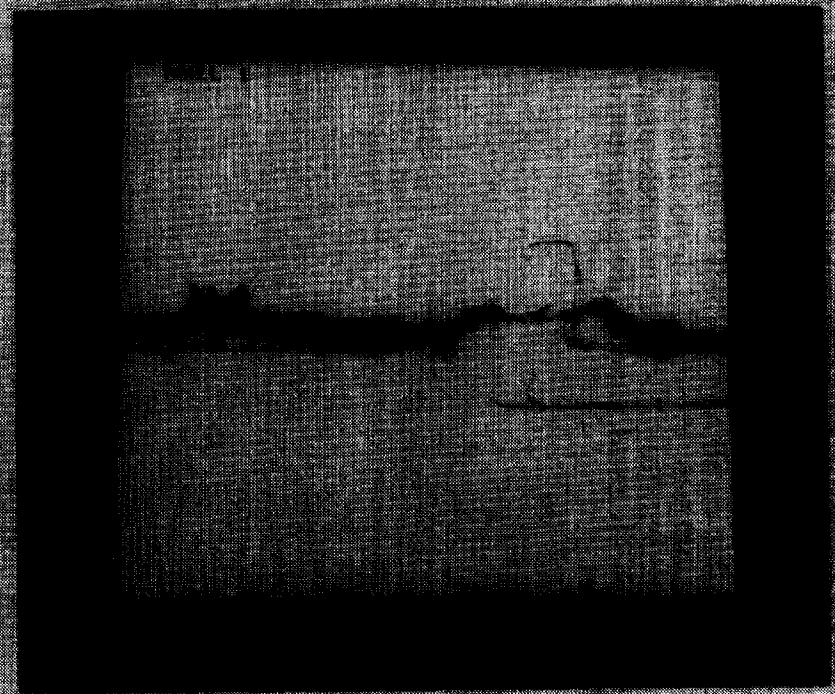
### **3-BRAIDED STIFFENER WING PANEL COMPRESSION FAILURE**

Figure 21 shows failure photographs of the 3-stiffener panel fabricated from all AS4 braided/woven stiffeners stitched to the all AS4 Saerbeck warp knit wing lay-up skin material which was impacted mid-bay at 100 ft-lb. As with the single-stiffener failures there was no skin stiffener separation for any of the 3-stiffener compression panels tested in this investigation. The failure shown is typical for all panels tested, although the panels tested without impact damage failed nearer the end of the panel.

## 3-BRAIDED STIFFENER WING PANEL COMPRESSION FAILURE



**Stiffener side**



**Skin side**

Figure 21. 3-braided stiffener wing panel compression failure.

## COMPRESSION STRENGTH OF 3-STRINGER STIFFENED PANELS FOR DOUGLAS WING

A summary of the 3-stiffener compression results presented in figures 18-20 are shown in figure 22. The open bars represent the failure stress of the 3-stiffener specimens tested without impact damage and the hatched bars represent the failure stress of the specimens which were impacted as indicated by the key at the top of the figure. The skin and stiffener configurations investigated are indicated along the abscissa. The braided/woven stiffener and skin material which had the IM7 tows in the 0° direction has the highest undamaged compression strength and the highest compression strength after a 100 ft-lb stiffener flange impact. However, the braided/woven stiffener and skin material which used all AS4 Tows had the highest compression strength of the 3-stringer panels subjected to a 100 ft-lb mid-bay impact. Also shown on the figure for comparison are the results of the 2-stringer panel tested during this investigation and the compression strength of a 3-stringer panel (ref. 1) which was fabricated using the stitched Saerbeck stiffener and stitched Saerbeck skin. Note that the compression strength of all 3-stiffener panels are not affected by the 100 ft-lb stiffener flange impact and the 100 ft-lb mid-bay impact is critical. All 3-stiffener panels employing braids in the stiffeners exceeded the CAI design goal of 40 ksi indicated on the figure by the dashed line.

# COMPRESSION STRENGTH OF 3-STRINGER STIFFENED PANELS FOR DOUGLAS WING

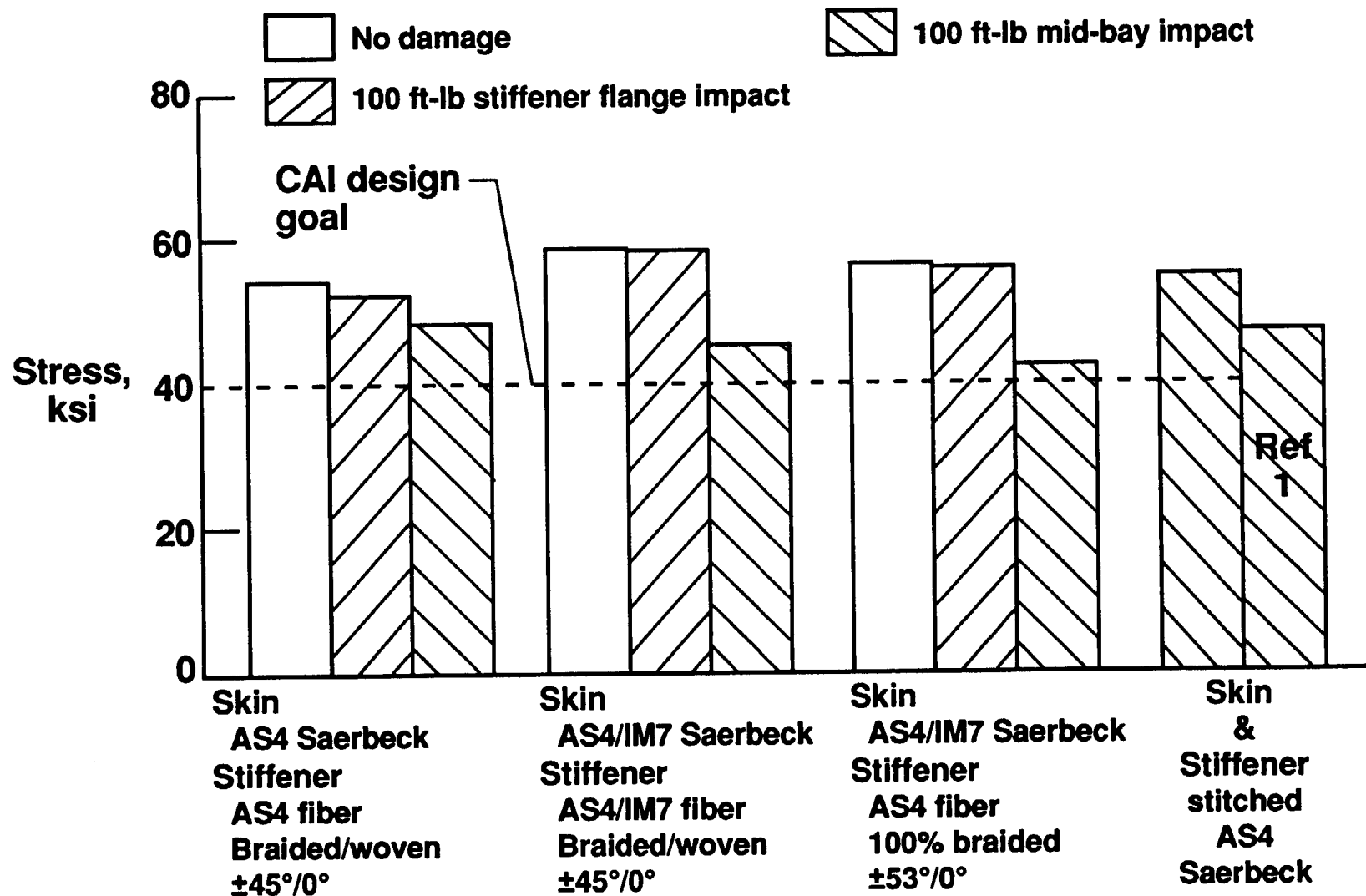


Figure 22. Compression strength of 3-stringer stiffened panels for Douglas wing.

## CONCLUDING REMARKS

Three different braided stiffener and stitched skin configurations resin film infused with 3501-6 resin have been evaluated to assess their potential for application to aircraft wing structure. The three concepts evaluated include: 1) all AS4 braided/woven stiffener ( $\pm 45^\circ/0^\circ$ ) stitched to all AS4 Saerbeck warp knit material with a wing lay-up (44%  $0^\circ$ , 44%  $\pm 45^\circ$ , 12%  $90^\circ$ ); 2) all AS4 100% braided stiffener ( $\pm 53^\circ/0^\circ$ ) stitched to AS4/IM7 Saerbeck warp knit wing lay-up (44%  $0^\circ$ , 44%  $\pm 45^\circ$ , 12%  $90^\circ$ ), IM7 tows in the  $0^\circ$  direction and AS4 tows in the  $\pm 45^\circ$  and  $90^\circ$  directions; and 3) AS4/IM7 braided/woven stiffener ( $\pm 45^\circ/0^\circ$ ), AS4 tows in the  $\pm 45^\circ$  direction and IM7 tows in the  $0^\circ$  direction, stitched to AS4/IM7 Saerbeck wing lay-up material as in (2). Single-stiffener and 3-stiffener wide panels were tested in compression with and without impact damage. The results of this investigation support the following observations.

1. All braided/woven and 100% braided stiffened panels exceeded the compression-after impact design goal of 40 ksi
2. CAI strength of single- stiffener specimens not affected by 100 ft-lb mid-stringer or 20 ft-lb side of stringer impacts
3. CAI strengths of 3-braided stiffener panels indicate that 100 ft-lb mid-bay impact is most critical
4. Preliminary cost studies indicate braided stiffener concepts are about 15% less than currently used stitched Saerbeck stiffeners
5. Based on CAI performance and cost estimates the braided stiffener concept is a viable alternative to the stitched Saerbeck stiffener concept

## REFERENCES

1. Dexter, H. Benson, Palmer, Raymond J., and Hasko, Gregory, H,: Mechanical Properties and Damage Tolerance of Multiaxial Warp Knit Structural Elements, Fourth NASA/DoD Advanced Composites Technology Conference, Salt Lake City, Utah, June 7-11, 1993, NASA CP- 3229, Part 2, pp 579-604.

