NASA Technical Memorandum 89088
USA AVSCOM Technical Memorandum 87-B-4

A Method of Predicting the Energy-Absorption Capability of Composite Subfloor Beams

(NASA-TM-89088) A METHOD OF PREDICTING THE ENERGY-ABSORPTION CAPABILITY OF COMPOSITE SUBFLOOR BEAMS (NASA) 22 p CSCL 11D
N87-19450
Unclas
G3/24 43667

Gary L. Farley

March 1987

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

A METHOD OF PREDICTING THE ENERGY-ABSORPTION CAPABILITY OF COMPOSITE SUBFLOOR BEAMS

By

Gary L. Farley

Aerostructures Directorate
U.S. Army Aviation Research and Technology Activity - AVSCOM
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2866

ABSTRACT

A simple method of predicting the energy-absorption capability of composite subfloor beam structure has been developed. The method is based upon the weighted sum of the energy-absorption capability of constitutent elements of a subfloor beam. An empirical data base of energy absorption results from circular and square cross section tube specimens were used in the prediction capability. The procedure is applicable to a wide range of subfloor beam structure. The procedure was demonstrated on three subfloor beam concepts. Agreement between test and prediction was within seven percent for all three cases.

INTRODUCTION

The efficient design of crashworthy helicopters has evolved into a systems design approach, references 1 and 2. In a systems design approach the requirements and limitations of the total vehicle are considered in the development of an optimal design. Previous non-systems-based crashworthy design procedures typically resulted in heavier designs than designs based upon a systems design procedure. These systems design methods are analogous with those found in structural optimization. The most efficient structural designs are those where the objective function is maximized or minimized subject to the simultaneous satisfaction of all constraint conditions.

Unfortunately, in the present crashworthy systems-design procedure the designer must select the energy absorbing structural concept from a very limited test data base. A test data base approach is employed because no other method exists for predicting the energy-absorption capability of a structural concept. These structural concepts are point designs and limited guidance has been developed with respect to the effect of changes in material and test specimen architecture. The inflexible requirement of a test data base in selecting a structural concept typically results in a heavier than necessary design. Ideally, the designer would conduct "trade" studies to investigate the effects of changing material and specimen architecture to achieve an optimal design.

In this paper, a procedure for predicting the energy-absorption capability of structures fabricated from composite materials is presented. The procedure is based upon the energy-absorption capability of the characteristic elements that compose the structure. The associated assumptions and limitations pertaining to the prediction procedure are discussed. Examples are given for energy absorbing composite sine wave and integrally stiffened subfloor beam structure to verify the prediction procedure.

BACKGROUND

Energy absorbed in a helicopter during a crash is primarily accomplished by controlled stroking of the landing gear and subsequent crushing of the subfloor beam structure. In this paper, the subfloor beam structure will be used to describe and verify the method of predicting the energy-absorption capability of structural elements.

The subfloor beam structure of a helicopter, as depicted in figure 1, is composed of a "grillwork" of longitudinal and transverse beams. Noncrash loads carried by the beam structure typically consist of reaction loads from the fuselage skin, frames, bulkheads and seats. The geometry of the individual beams is representative of the design philosophy and experience of the helicopter manufacturer. These beam configurations typically consist of integrally stiffened, honeycomb sandwich, unstiffened or sine-wave beams. Examination of these beam geometries shows that they consist of an assemblage of straight and curved elements, as shown in figure 2. Based upon observation of previously tested energy absorbing composite beam structure, reference 3, the crushing modes of the straight and curved parts of composite beams were similar to those of square and circular cross section tubes, respectively.

Figure 3 shows the characteristic crushing modes of circular and rectangular cross section tube stiffened beams fabricated from graphite/epoxy (Gr/E) and Kevlar/epoxy (K/E). The K/E beams exhibit the local folding crushing mode similar to the modes observed in tubular specimens. The Gr/E beams exhibit a brittle fracturing mode in the circular cross section tubular stiffener. However, a lamina bending crushing mode is exhibited by the straight portions of the beam. This lamina bending mode is similarly exhibited by Gr/E square cross-section tube specimens. Sine-wave beams (figure 4) fabricated with Gr/E typically exhibit the brittle fracturing crushing mode while beams fabricated with K/E exhibit a local folding mode. The brittle fracturing and local folding modes are similar to crushing modes exhibited by circular tube specimens fabricated from comparable materials.

Upon observing this similarity of crushing modes, a hypothesis was formulated for predicting the energy absorption of structural elements. The hypothesis is as follows: the crash energy-absorption capability of a structural element is the sum of the weighted average of the energy-absorption capability of its characteristic elements. Mathematically, in terms of the specific sustained crushing stress (σ/ρ), where σ is the sustained crushing stress and ρ is the density of the material, the energy-absorption capability can be expressed as:

$$(\sigma/\rho)_{S.E.} = \sum_{i=1}^{N} \frac{A_{i_{C.E}}}{A_{S.E.}} *(\sigma/\rho)_{i_{C.E.}} \qquad (1)$$

The terms $A_{i_{C.E.}}$ and $A_{S.E.}$ are the cross-sectional areas of the ith characteristic element (C.E.) and the structural element (S.E.) respectively. The $(\sigma/\rho)_{i_{C.E.}}$ and $(\sigma/\rho)_{S.E}$ are the specific sustained crushing stress of the ith characteristic element and the structural element, respectively.

This hypothesis assumes that the structure will progressively crush prior to catastrophic failure. Structures incorrectly designed can exhibit an instability-induced failure prior to the initiation of the crushing process. Other requirements pertain to the commonality of architecture between test specimens and structural element and commonality of material. The tube specimens must have the same diameter-to-thickness or width-to-thickness ratio as the characteristic element of the beam, the same ply orientation and stacking sequence, and have the same material form.

It has been observed, reference 3, that sine-wave beams composed of half-tangent circles (included angle of 180 degrees) have the same energy-absorption capability as comparable circular cross-section tube specimens. However, based upon unpublished test results of sine-wave beams having included angles of less than 180 degrees the energy-absorption capability of the beams are substantially less than that of a comparable tube specimen. These results suggest that if the included angle of the curved section of the beam is less than 180 degrees circular cross-section tubular crushing test data may not be totally applicable. Furthermore, beams that have characteristic elements with unsupported edges can exhibit catastropic failure modes and not crush. Using empirical tube data to predict the energy-absorption capability of unsupported characteristic elements will result in predicted values higher than obtained from experiments.

EXAMPLE PROBLEM

Detail examples of the application of the prediction procedure will be made using Gr/E sine-wave beam, K/E circular cross section tube stiffened beam, and a Gr/E rectangular cross section tube stiffened beam. Table 1 contains a summary of these results. Circular and square cross section tube data from references 4 and 5, respectively, are used in these examples. For completeness, these data are shown in figures 5-8.

Gr/E Sine-Wave Beam

The first example is a Gr/E sine-wave beam as depicted in figure 9. A sine-wave beam where all the waves have the same geometry consists of a single characteristic element repeated N times. To predict the energy-absorption capability of this beam requires information about only one characteristic element. If a sine-wave beam had waves of different geometries, multiple characteristic elements would be required to predict its energy-absorption capability. In the example, described herein the sine-wave beam is a geometrically uniform design, as depicted in figure 9, having only one characteristic element. The sine waves are tangent half tubes, that have an included angle of 180 degrees, with a radius of 3.81 cm. Ply layup was $[\pm 45]_{12}$ and beam wall thickness was 0.35 cm. The resulting diameter to thickness ratio (D/t) is 21.8. In this example $A_{S.E.} = N * A_{i_{C.E.}}$ where N is the number of characteristic elements and $(\sigma/\rho)_{S.E.} = (\sigma/\rho)_{C.E.}$ Based upon test results in figure 5 a Gr/E tube having the same ply layup, internal diameter, and wall thickness as the previously described sine-wave beam had an energy-absorption capability of 56 N-m/g. The energy-absorption capability of the sine-wave beam, based upon test results, is 54 N-m/g which is approximately four percent greater than the predicted value.

K/E Circular Cross-Section Tube Stiffened Beam

Figure 10 depicts a four stiffener K/E circular cross section tube integrally stiffened beam. Web width (W) between tube stiffeners is 3.81 cm and web thickness is 0.20 cm, resulting in a width-to-thickness ratio (W/t) of 19.1. The cross-sectional area of each web is 0.76 cm^2. The web extends beyond the stiffeners 1.27 cm on each side of the beam. The W/t ratio of this section is 6.4 and the cross-sectional area is 0.25 cm^2. The composite layup is $[\pm 45]_{3S}$ in the web region. The stiffener is a circular tube stiffener with an inside diameter of 2.54 cm and a wall thickness of 0.09 cm, resulting in a D/t ratio of 28.2. The layup of the tube is $[\pm 45]_3$ and the cross-sectional area is 0.78 cm^2. Using equation 1 to compute the energy-absorption capability of the beam and the appropriate circular and square cross-section tube data from figures 6 and 8 results in

$$(\sigma/\rho)_{S.E.} = [4*A_{Tube}*(\sigma/\rho)_{Tube} + 3*A_{Web}*(\sigma/\rho)_{Web}$$

$$+ 2*A_{\text{End of Web}}*(\sigma/\rho)_{\text{End of Web}}]/A_{S.E.},$$

$$(\sigma/\rho)_{S.E.} = [4*0.78*27.0 + 3*0.76*32.0 + 2*0.25*45.0]/5.9$$

$$(\sigma/\rho)_{S.E.} = 30 \text{ N-m/g}$$

The energy-absorption capability of the beam was experimentally determined to be 28 N-m/g. The difference in the predicted and measured behavior is approximately seven percent.

Gr/E Rectangular Cross-Section Tube Stiffened Beam

The third example is of a four stiffener rectangular cross-section tube stiffened Gr/E beam depicted in figure 11. The beam is uniform in design. The web width and thickness was 3.55 cm and 0.19 cm, respectively, and a W/t ratio of 18.7. The web extends beyond the stiffeners 1.65 cm on each side of the beam. The W/t ratio of this section is 8.7 and the cross-sectional area is 0.32 cm^2. The layup of the web is $[\pm 45]_{3S}$. Each rectangular stiffener is composed of two unique elements, the side and end elements. Each stiffener has two of each type of element. The side element of the stiffener has a width of 5.08 cm, a thickness of 0.09 cm, a W/t ratio of 56.4 and a cross-sectional area of 0.46 cm^2. The end stiffener element has a width of 2.54 cm, a thickness of 0.09 cm, a W/t ratio of 28.2 and a cross-sectional area of 0.23 cm^2. The layup of the stiffener is $[\pm 45]_3$. Using equation 1 and the tube data in figures 5 and 7 the energy-absorption capability of the beam is:

$$(\sigma/\rho)_{S.E.} = [8*A_{\substack{Stiffener\\End}}*(\sigma/\rho)_{\substack{Stiffener\\End}} + 8*A_{\substack{Stiffener\\Side}}*$$

$$(\sigma/\rho)_{\substack{Stiffener\\Side}} + 3*A_{Web}*(\sigma/\rho)_{Web} + 2*A_{\substack{End\\of\\Web}}*(\sigma/\rho)_{\substack{End\\of\\Web}}]/A_{S.E.},$$

$$(\sigma/\rho)_{S.E.} = [8*0.23*46.0 + 8*0.46*31.0 + 3*0.67*52.0 + 2*0.31*57.0]/8.2$$

$$(\sigma/\rho)_{S.E.} = 41 \text{ N-m/g}.$$

The experimentally-determined energy-absorption capability is 42 N-m/g which is within 3 percent of the predicted value.

DISCUSSION

Equation 1 has been shown to accurately predict the energy-absorption capability of sine wave and integrally stiffened subfloor beam structure. The equation is applicable to a broad range of structural concepts that can include significant variation in geometry and material form. The limitations associated with the application of equation 1 are not excessively restrictive. At present the only limitation of any consequence is the use of tube data to determine the energy-absorption capability of the characteristic elements and the similarity in crushing mode between the tube response and the characteristic elements of the beam. To date, no analytical capability exists that accurately predicts the energy-absorption capability of composite tubes. Therefore, an experimental data base must be developed. Even if an analytical procedure was available to predict the energy-absorption capability of composite tubes it would be necessary to conduct a limited experimental screening study to verify crushing trends and modes.

CONCLUDING REMARKS

A simple method of predicting the energy absorption capability of subfloor beam structure of composite materials has been presented. The prediction procedure is based upon the energy-absorption capability of the beam constituent elements. The beam constituent elements can be either straight or curved sections. Circular and square cross-section tube specimens are used to determine the energy-absorption capability of the beams characteristic elements. Agreement between test and prediction was within seven percent. The procedure is general and is applicable to a large range of energy-absorbing structures. The crushing modes of the beam characteristic elements must be similar to the modes exhibited by the tube specimens. Until an analytical capability is developed to predict the energy-absorption capability of tube specimens, the application of the beam prediction procedure will require an empirically developed tube data base.

REFERENCES

1. Cronkhite, J. D., "Design of Aircraft Structures for Crash Impact", Proceedings of the National Specialist's Meeting on Crashworthy Design of Rotorcraft, (April 1986).

2. Sen, J. K., "Survivability and Crashworthiness Design Criteria", Proceedings of the National Specialist's Meeting on Crashworthy Design of Rotorcraft, (April 1986).

3. Farley, G. L., "Crash Energy Absorbing Composite Sub-Floor Structure", Presented at the 27th SDM Conference 1986 and submitted to AHS Journal for publication.

4. Farley, G. L., "Effect of Specimen Geometry on the Energy Absorption Capability of Composite Materials", Journal of Composite Materials, Vol. 20 (July 1986).

5. Farley, G. L., "Energy Absorption Capability and Scalability of Square Cross-Section Composite Tube Specimens," NASA TM-89087, USA AVSCOM TM-87-B-3, 1987.

Table 1. Summary of Energy Absorption results

SPECIMEN DESCRIPTION	ENERGY-ABSORPTION CAPABILITY	
	PREDICTED (N-M/g)	EXPERIMENTAL (N-M/g)
Gr/E Sine-Wave Beam	56	54
K/E Circular Cross-Section Tube Stiffened Beam	30	28
Gr/E Rectangular Cross-Section Tube Stiffened Beam	41	42

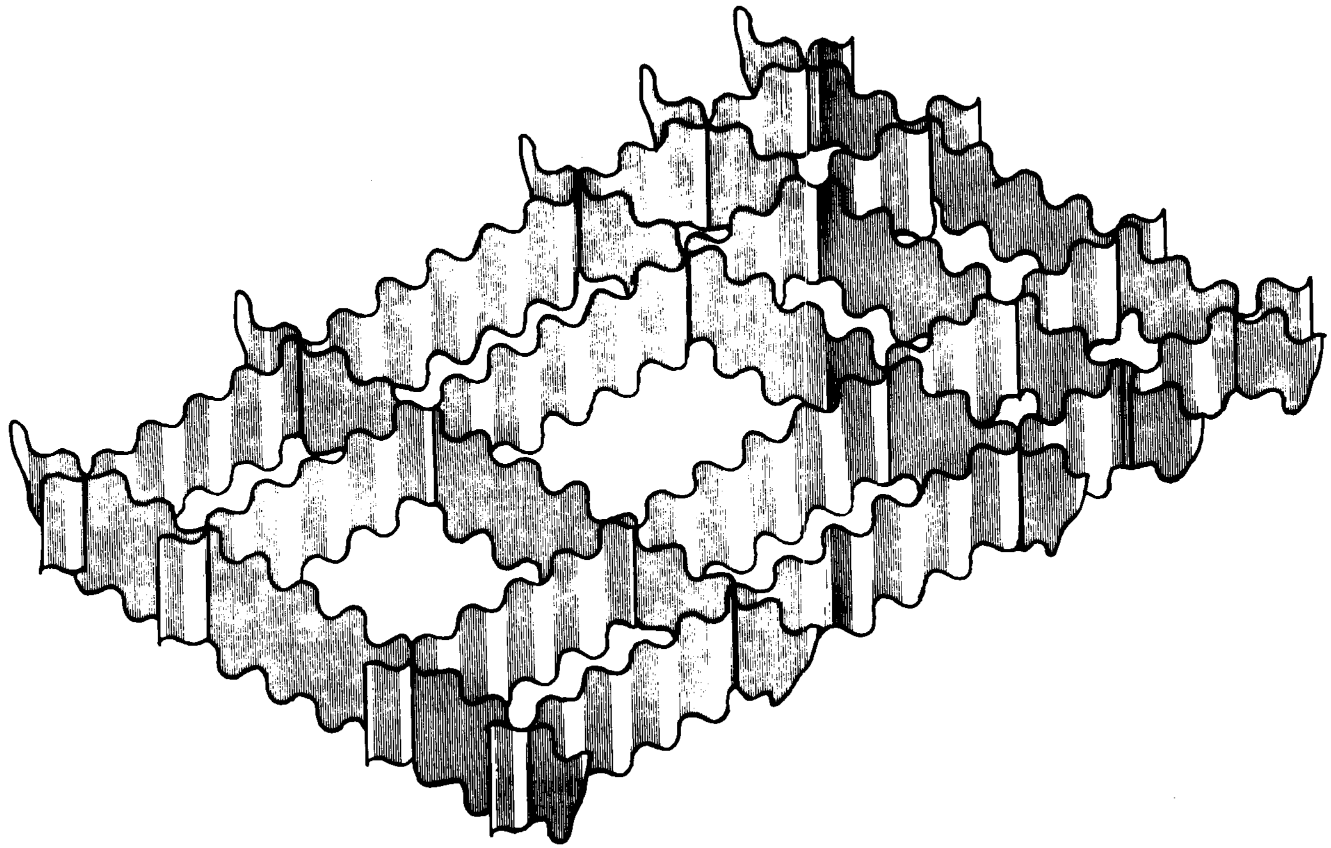


Figure 1. Typical subfloor beam structure of a helicopter.

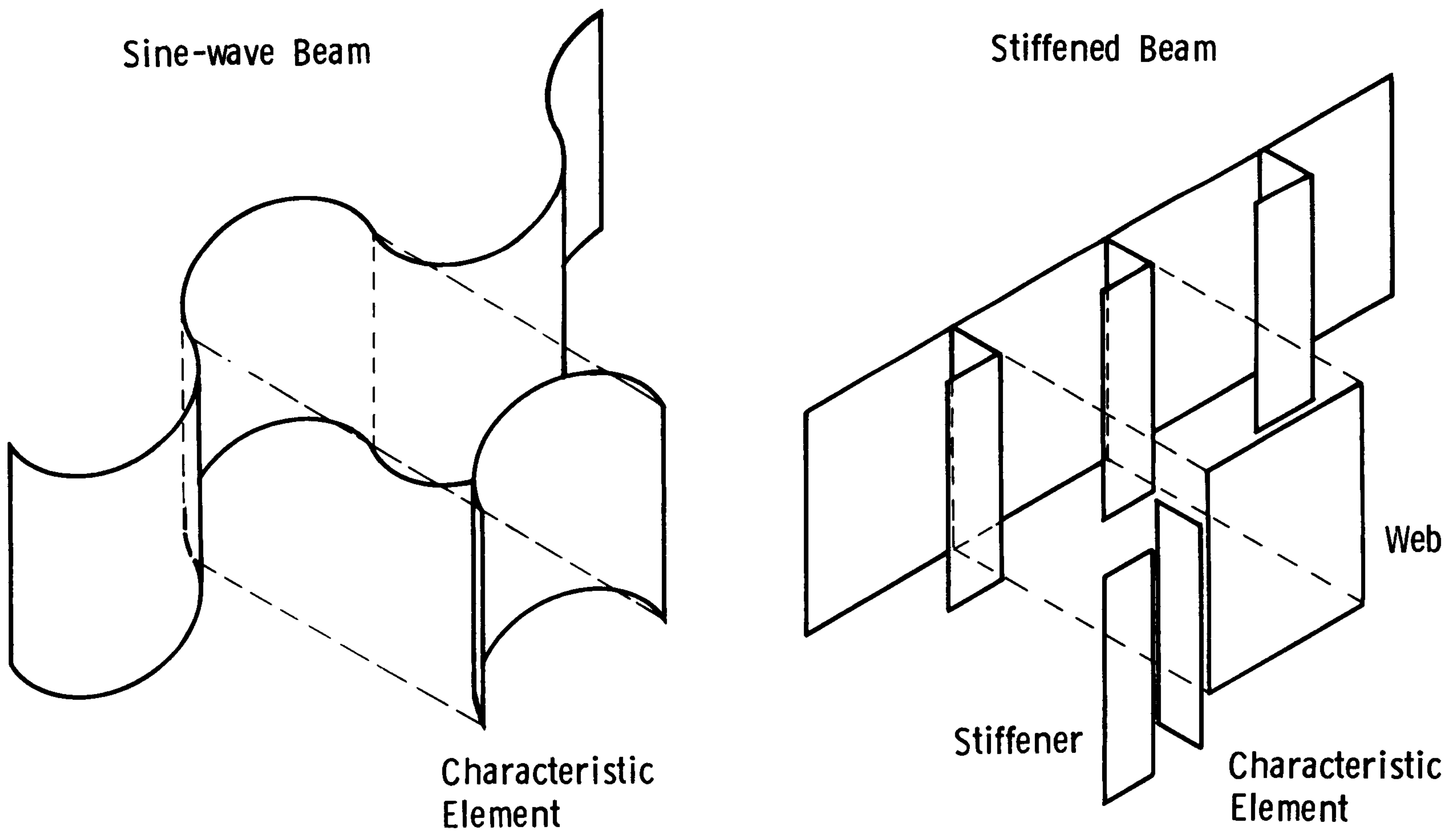


Figure 2. Elements of sine-wave and stiffened subfloor beam structure.

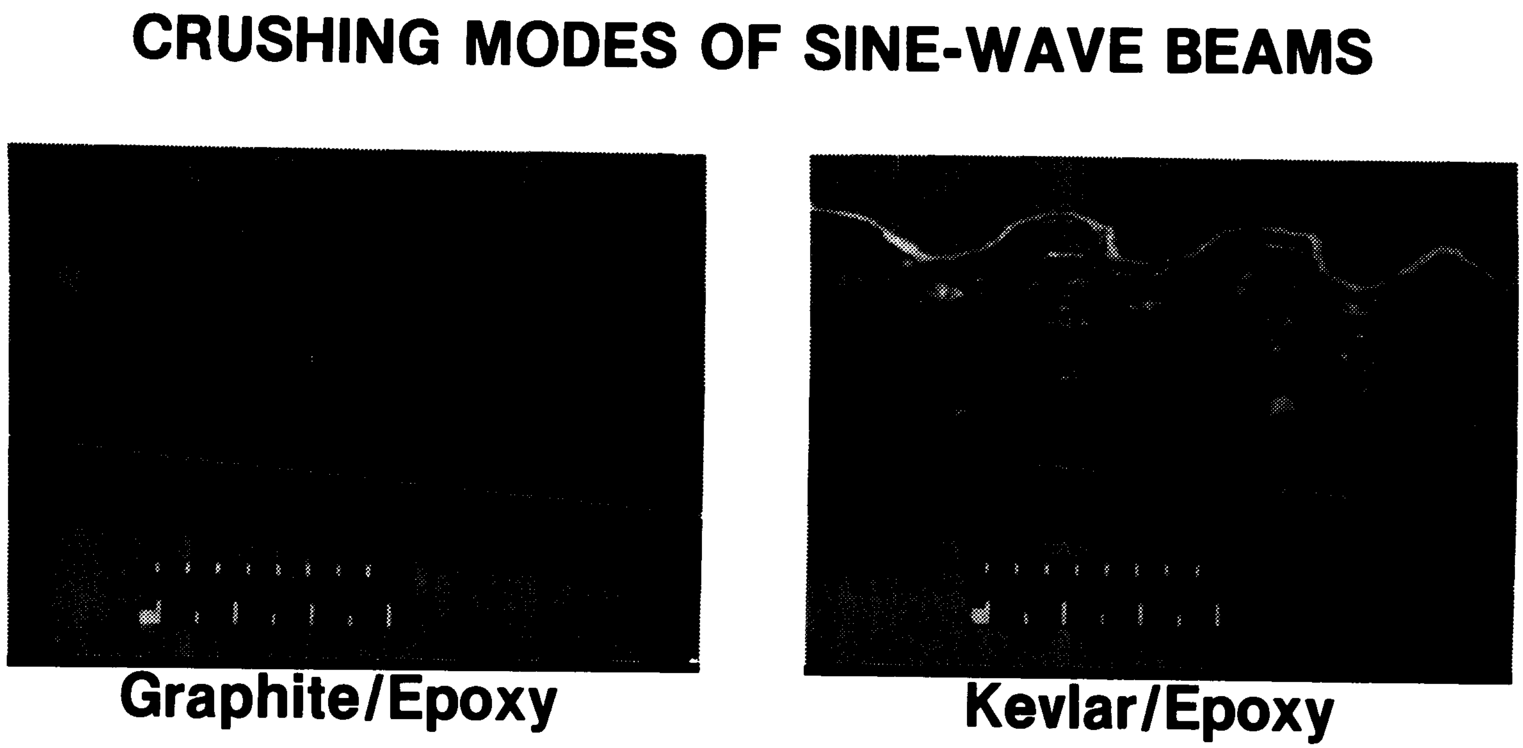
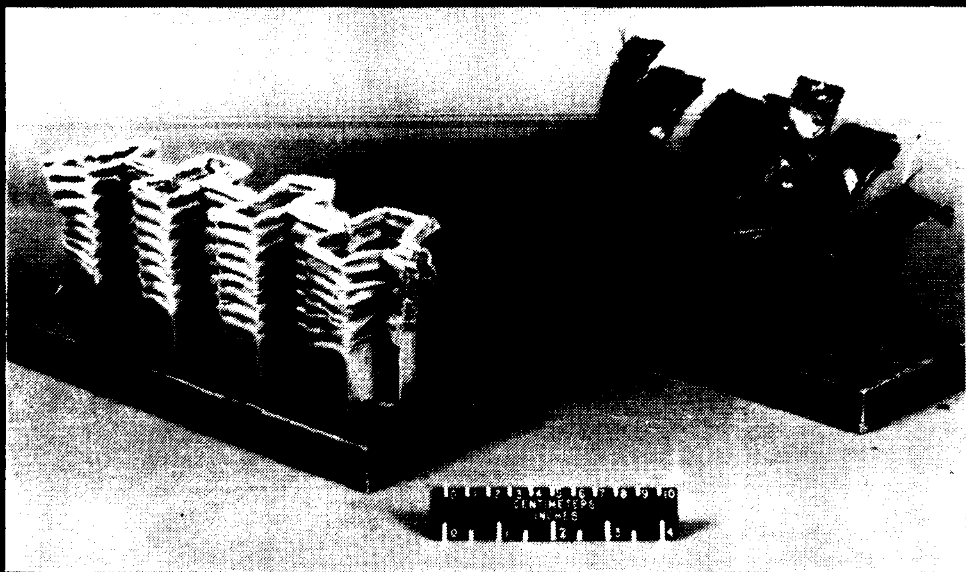
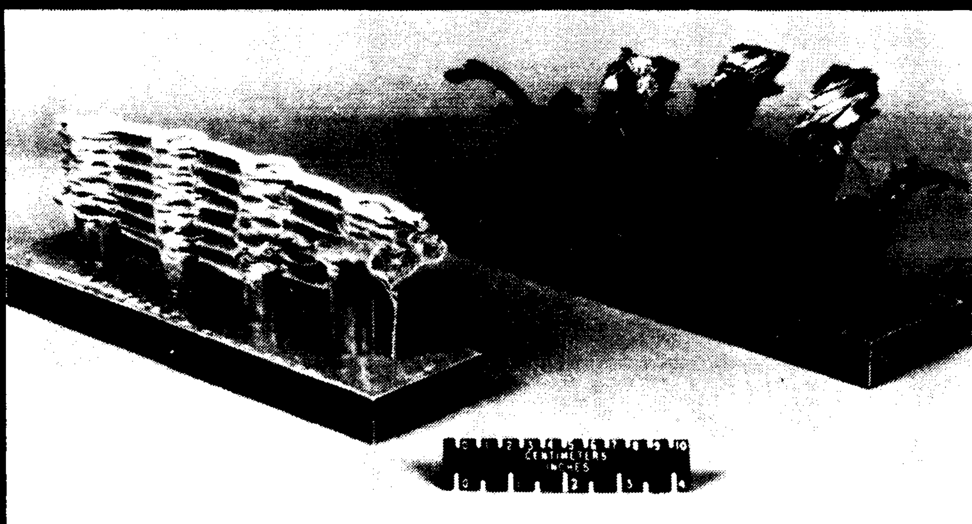


Figure 3. Typical crushing modes of stiffened subfloor beams.

TYPICAL CRUSHING MODES OF STIFFENED COMPOSITE BEAMS



Rectangular cross-section tube stiffened beam



Circular cross-section tube stiffened beam

Figure 4. Typical crushing modes of sine-wave beams.

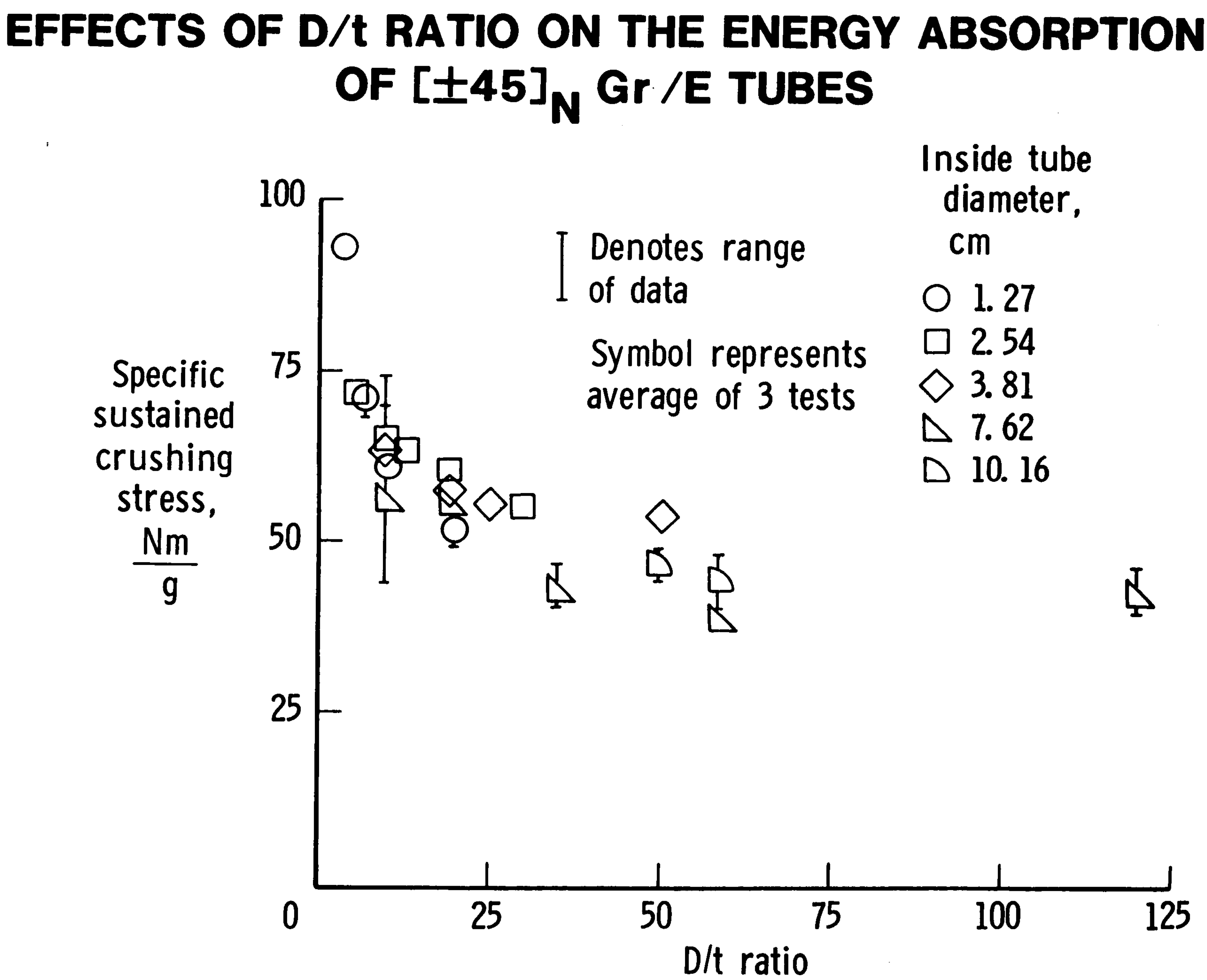


Figure 5. Energy-absorption capability of $[\pm 45]_N$ circular graphite/epoxy tubes (ref. 4).

EFFECTS OF D/t RATIO ON THE ENERGY ABSORPTION OF $[\pm 45]_N$ K/E TUBES

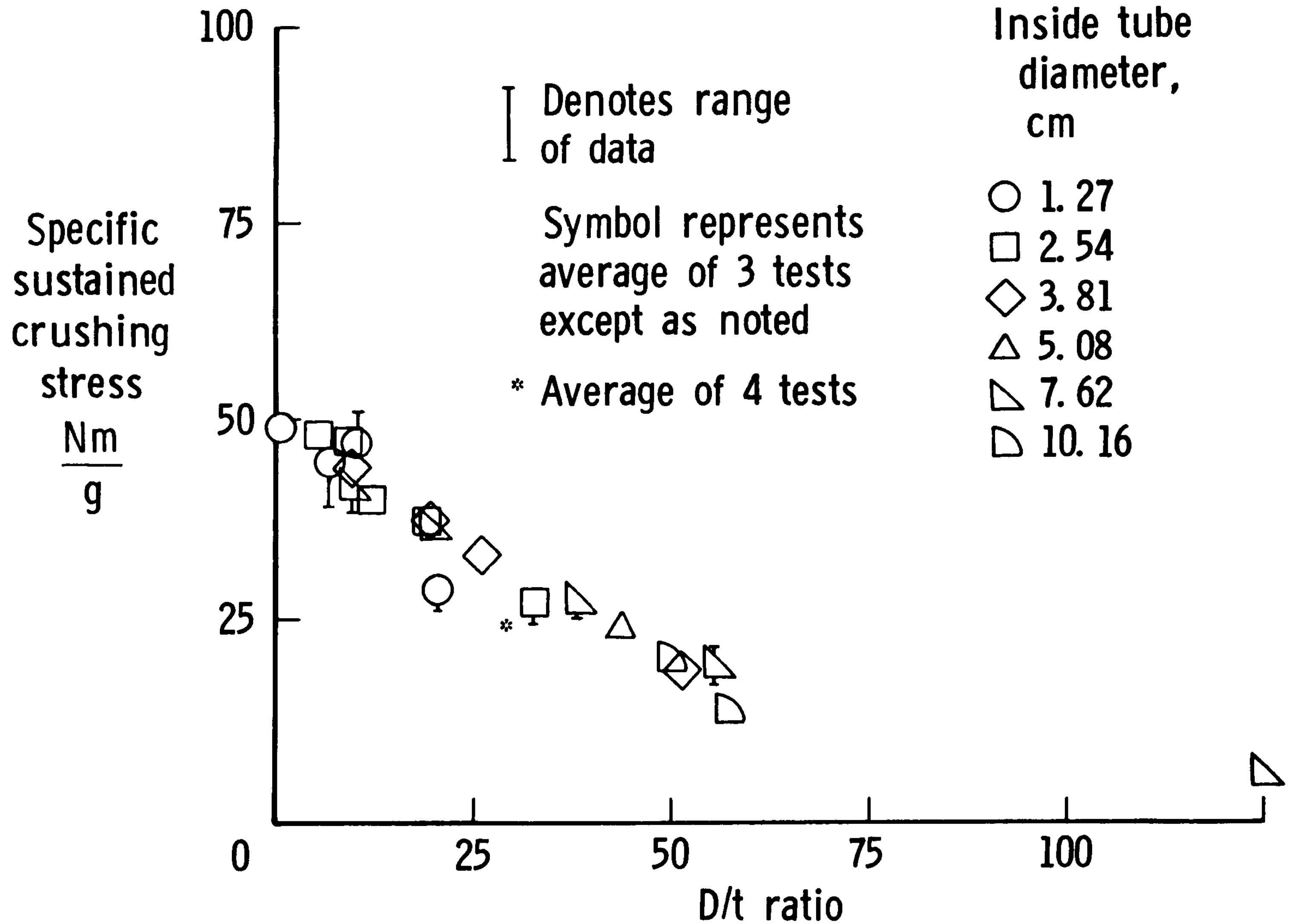


Figure 6. Energy-absorption capability of $[\underline{+}45]_N$ circular Kevlar/epoxy tubes tubes (ref.4).

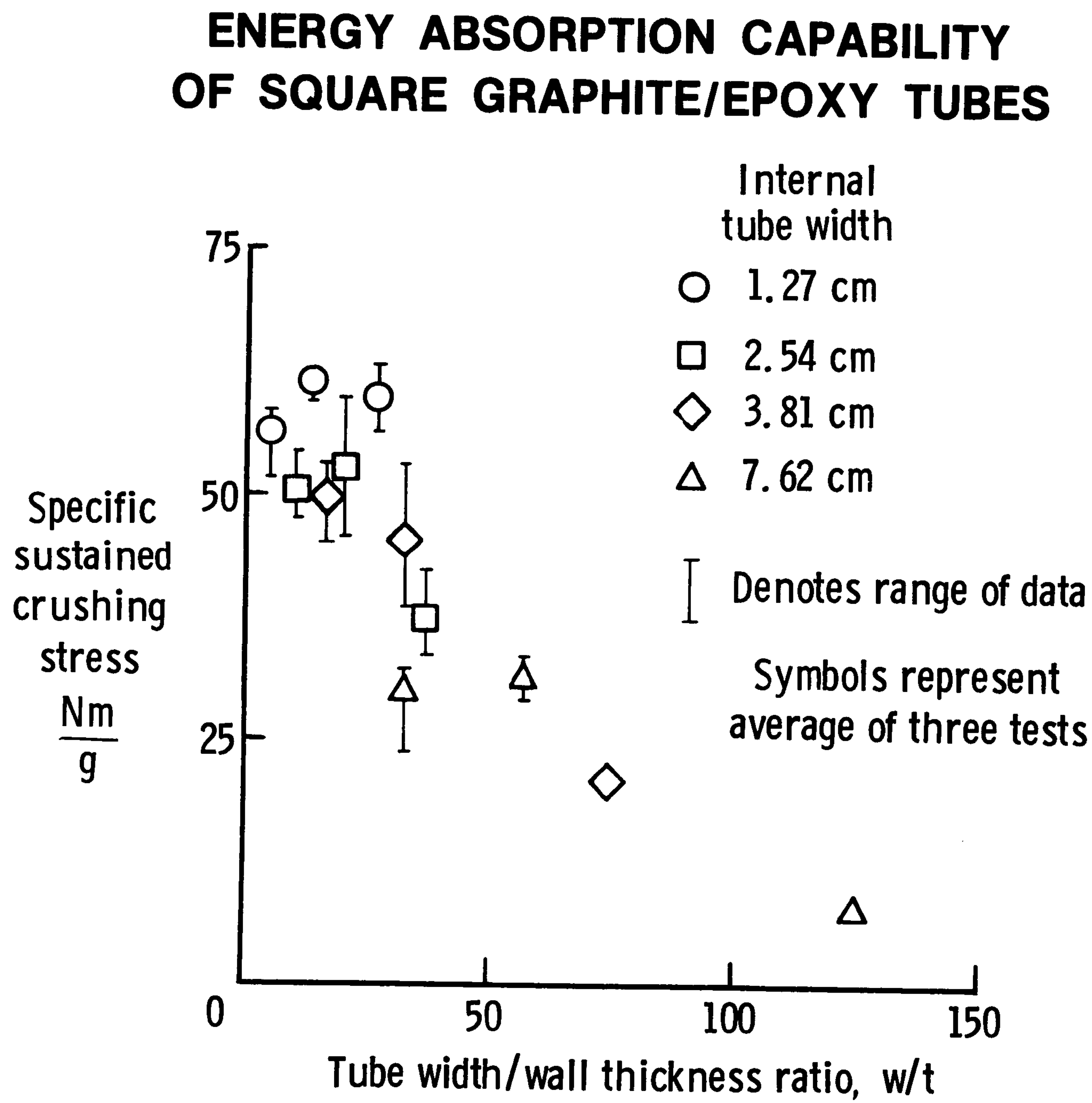


Figure 7. Energy-absorption capability of $[\pm 45]_N$ square graphite/epoxy tubes (ref. 5).

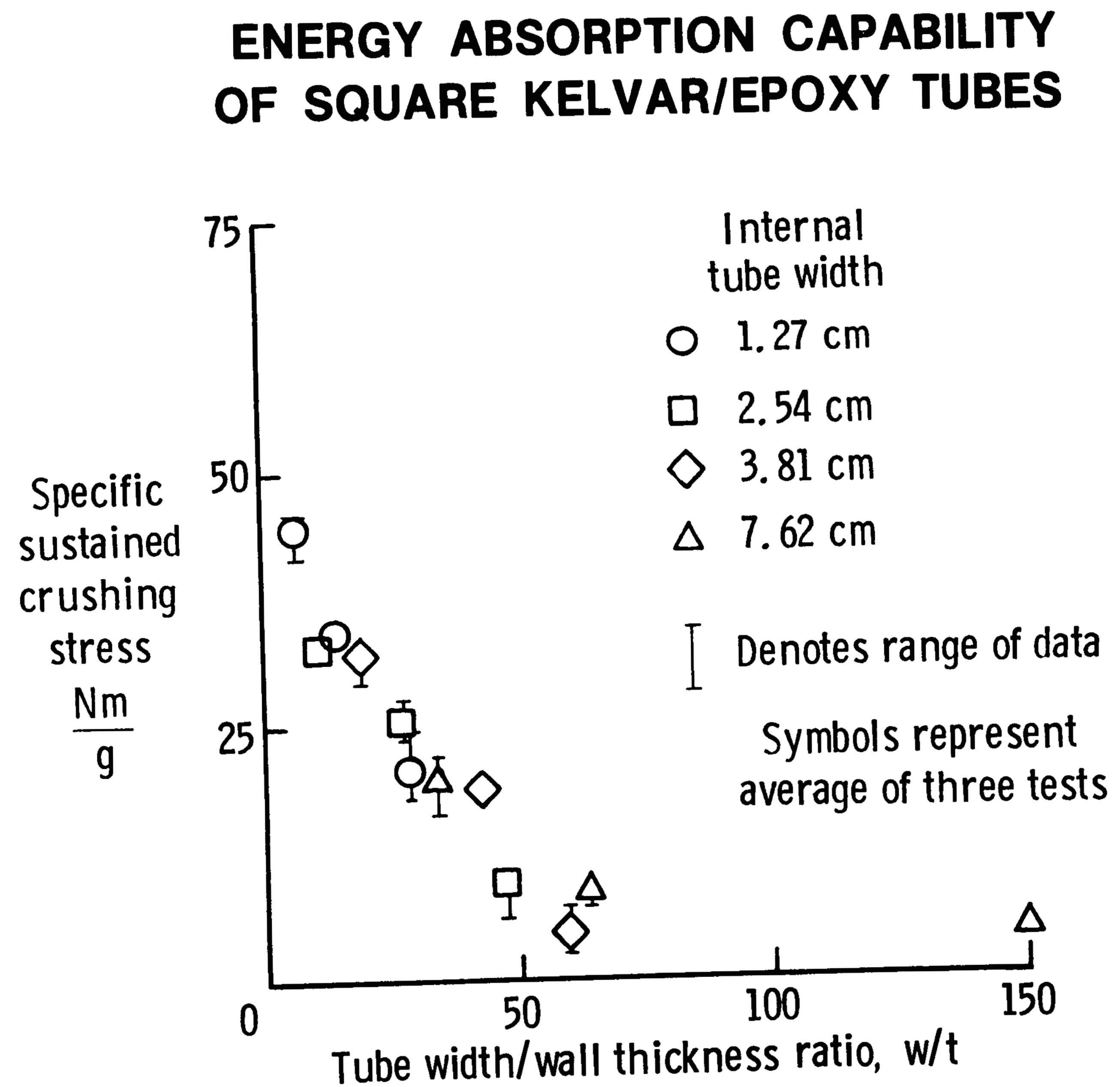


Figure 8. Energy-absorption capability of $[\underline{+}45]_N$ square Kevlar/epoxy tubes (ref. 5).

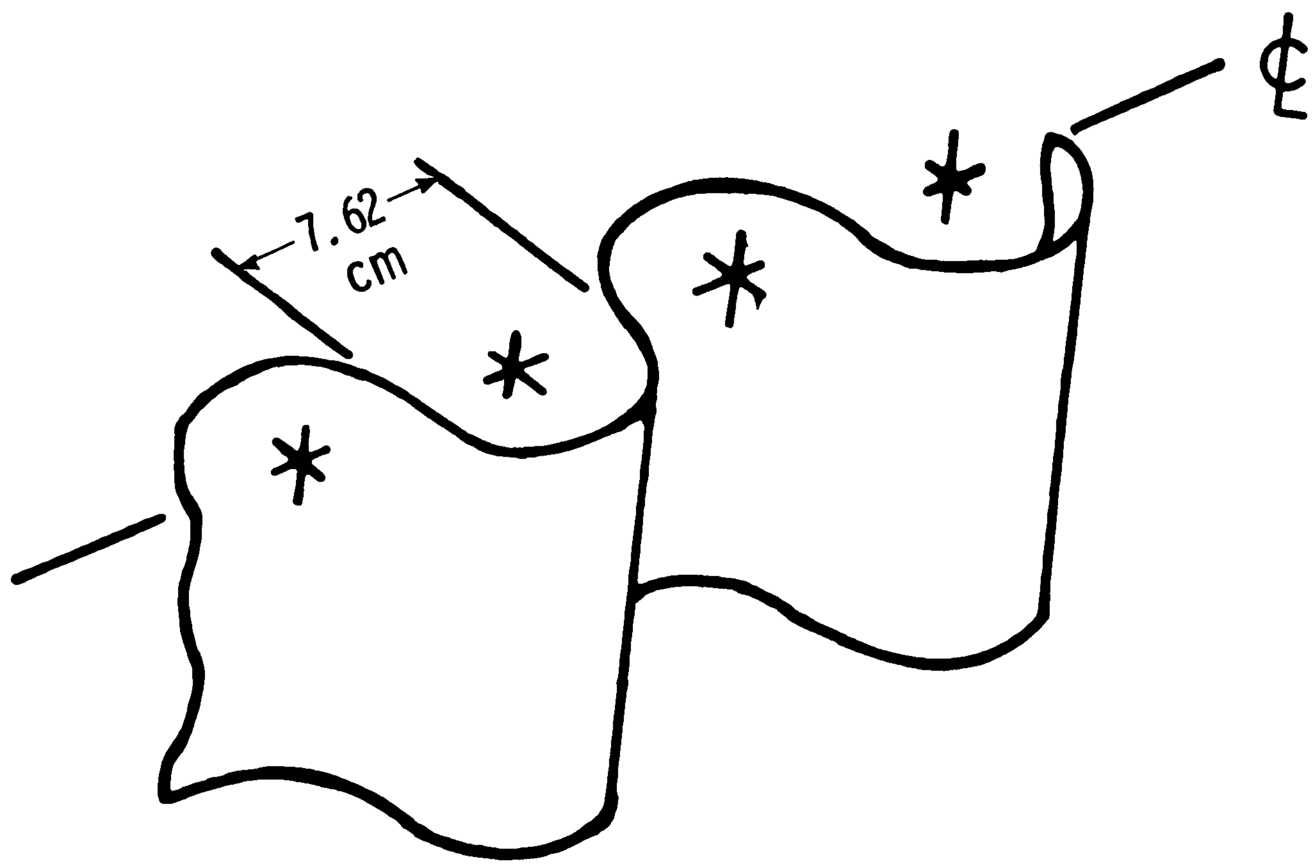


Figure 9. Sketch of sine-wave beam.

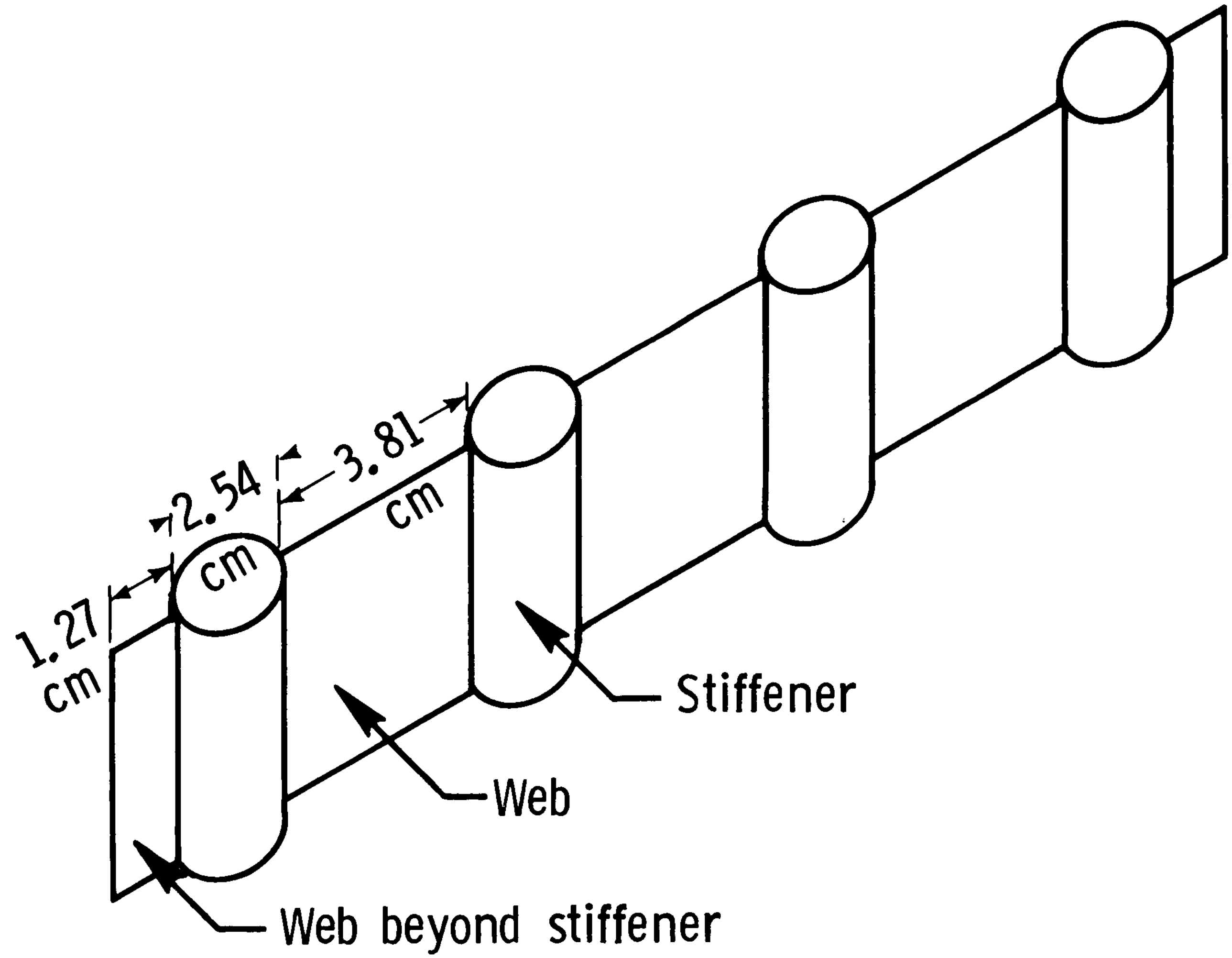


Figure 10. Sketch of four stiffener circular cross-section tube stiffened beam.

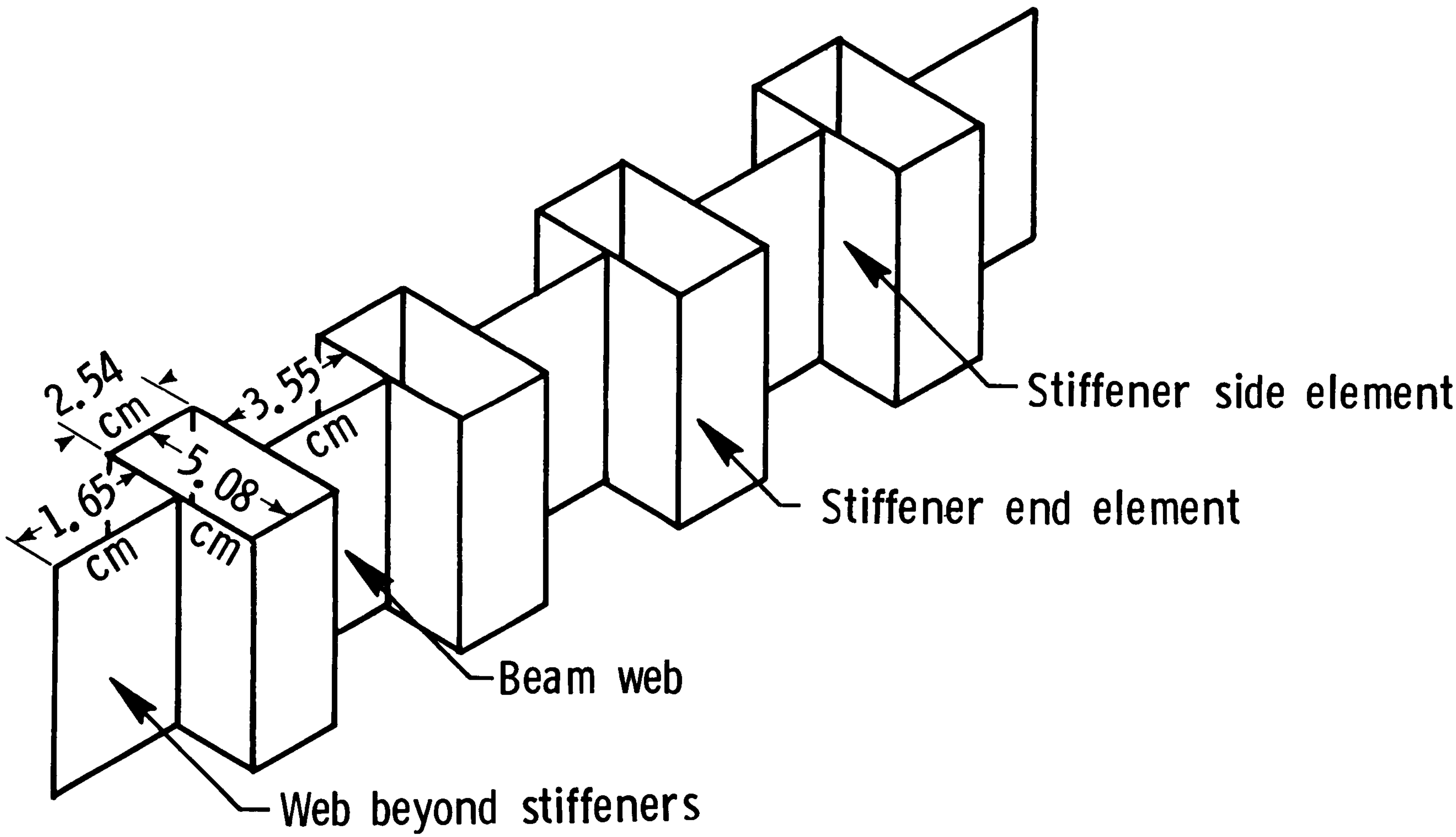


Figure 11. Sketch of four stiffener rectangular cross-section tube stiffened beam.

Standard Bibliographic Page

1. Report No. USA AVSCOM TM-87-B-4
NASA TM- 89088

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
A METHOD OF PREDICTING THE ENERGY-ABSORPTION CAPABILITY OF COMPOSITE SUBFLOOR BEAMS

5. Report Date
March 1987

6. Performing Organization Code
505-63-01-06

7. Author(s)
Gary L. Farley

8. Performing Organization Report No.

9. Performing Organization Name and Address
NASA Langley Research Center, Hampton, VA 23665-5225
U.S. Army Aviation Research and Technology Activity (AVSCOM) Aerostructures Directorate (USAARTA)
Hampton, VA 23665-5225

10. Work Unit No.

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546 and
U.S. Army Aviation Systems Command, St. Louis, MO 63166

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes

Gary L. Farley, Aerostructures Directorate, USAARTA (AVSCOM), Langley Research Center, Hampton, Virginia.

16. Abstract

A simple method of predicting the energy-absorption capability of composite subfloor beam structure has been developed. The method is based upon the weighted sum of the energy-absorption capability of constitutent elements of a subfloor beam. An empirical data base of energy absorption results from circular and square cross section tube specimens were used in the prediction capability. The procedure is applicable to a wide range of subfloor beam structure. The procedure was demonstrated on three subfloor beam concepts. Agreement between test and prediction was within 7 percent for all three cases.

17. Key Words (Suggested by Authors(s))
Energy-Absorption Capability
Subfloor Beams
Prediction
Graphite
Kevlar

18. Distribution Statement
Unclassified - Unlimited

Subject Category - 24

19. Security Classif.(of this report)
Unclassified

20. Security Classif.(of this page)
Unclassified

21. No. of Pages
20

22. Price
A02

For sale by the National Technical Information Service, Springfield, Virginia 22161
NASA Langley Form 63 (June 1985)