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Energy-Absorption Capability and Scalability of Square Cross Section Composite Tube Specimens

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Gary L. Farley

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NASA
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

ENERGY-ABSORPTION CAPABILITY AND SCALABILITY OF SQUARE CROSS SECTION COMPOSITE TUBE SPECIMENS

by

Gary L. Farley

Aerostructures Directorate
U.S. Army Research and Technology Activity - AVSCOM
NASA Langley Research Center
Hampton, VA 23665-5225

ABSTRACT

Static crushing tests were conducted on graphite/epoxy and Kevlar/epoxy square cross section tubes to study the influence of specimen geometry on the energy-absorption capability and scalability of composite materials. The tube inside width-to-wall thickness (W/t) ratio was determined to significantly affect the energy-absorption capability of composite materials. As W/t ratio decreases, the energy-absorption capability increases nonlinearly. The energy-absorption capability of Kevlar/epoxy tubes were found to be geometrically scalable, but the energy-absorption capability of graphite/epoxy was not geometrically scalable.

INTRODUCTION

Crash energy-absorbing structure in helicopters primarily consist of landing gear and subfloor beam structure. An energy-absorbing landing gear typically consists of a circular tube structure. Considerable data have been developed on the crushing response of circular tubes, reference 1-7, that is directly applicable to landing gear structure. Far less is understood about crash energy-absorbing subfloor structure. Subfloor beam structures, such as sine-wave and integrally stiffened beams, typically consist of an assemblage of flat and curved elements. Farley, reference 8, reported that the crushing response of sine-wave and integrally stiffened beams resembled that of their constituent elements. The curved sections crushed in similar modes to those reported for circular cross section tubes and the flat sections of beams crushed in modes similar to square cross section tubes. These results suggest that a better understanding of the crushing response of circular and square cross section tubes will provide insight into the crushing response and design of subfloor beam structure.

Farley, reference 6, investigated the geometrical scalability of graphite/epoxy (Gr/E) and Kevlar/epoxy (K/E) [±45] tubes. In that study, tube internal diameter-to-wall thickness ratio (D/t) varied between 1.4 and 125.

Energy absorption was found to be a decreasing nonlinear function of tube D/t ratio. This trend was consistent for both Gr/E and K/E materials.

Thornton and Edwards, reference 3, conducted a study investigating the geometrical effects on energy absorption of circular, square, and rectangular cross section tubes. Although the range of the geometrical parameters was large, the actual number of test conditions was limited. The limited number of tests made it difficult to precisely define certain trends. Specimens were fabricated with graphite, Kevlar, glass, and hybrid combinations of these reinforcements in an epoxy matrix. Tape and fabric prepregs were utilized to fabricate tubes with ply orientations of [±45] and [0/90]. In that study, Kevlar and Kevlar hybrid composites were found to generally be unsuitable energy absorbers because of unstable crushing behavior, resulting in large undulations in the crushing load. These results are in contrast with results for crushable beams reported by Farley, reference 8. Farley found Kevlar reinforced beams to consistently crush in a stable manner without significant undulations in crushing load. The crushed glass and graphite tubes of reference 3 exhibited combined brittle fracturing and lamina bending crushing modes. Crushing loads of the glass and graphite composite tubes were more uniform than the crushing loads for the Kevlar reinforced composite tubes.

The present study focuses on the energy-absorption capability and scalability of [±45] square cross section tube specimens fabrication from Thornel 300/Fiberite 934 and Kevlar-49/Fiberite 934. Four different internal tube widths and three different wall thicknesses were utilized. These tube geometries and materials are representative of helicopter subfloor beam structure applications. The crushing mode and energy-absorption capability of each specimen were recorded, and the results are reported herein.

MATERIALS AND TEST SPECIMENS

Prepreg materials used to fabricate specimens included: Thornel 300/Fiberite 934 (Gr/E) and Kevlar-49/Fiberite 934 (K/E). Square cross section tubes were fabricated having ply orientations of [±45]. Tables 1 and 2 present details of tube geometry and ply orientations for the Gr/E and K/E materials, respectively. Figure 1 depicts a typical test specimen. Tubes nominally 10.16 cm in length having inside widths of 1.27 cm, 2.54 cm, 3.81 cm and 8.62 cm were tested. The ratio of tube inside width-to-wall thickness (W/t) was varied between 6 and 125 to study the effects of tube geometry on energy-absorption capability and scalability.

One end of each tube was chamfered, as shown in figure 1, so that crushing could be initiated without causing catastrophic failure of the tube specimen. Previous tests, reference 4, showed that modifying the end of circular cross section tubes greatly reduced peak loads without affecting the sustained crushing load.

The square cross section tubes were fabricated using a trapped rubber molding technique. Tubes were fabricated by wrapping the composite prepreg material around a metal mandrel. A flat metal plate was positioned on each side of the mandrel/prepreg assembly, and shrink tubing was slipped over the flat plates to prevent their movement. This assembly was inserted into a "trapped" rubber mold and placed into an oven at 176°C to cure the 934 epoxy matrix.

TEST PROCEDURES AND DATA ANALYSIS

Static crushing tests were performed in a 540 kN capacity universal hydraulic testing machine. Load platens were set parallel to each other prior to initiation of the tests. All tubes were compressed at a rate of approximately 0.02 cm/min until crushing was initiated at which time the test machine head speed was increased to 0.08 cm/min. Load and deflection of the crosshead were recorded by an automatic data acquisition system. Tests were stopped when the tubes had been crushed 5.08 cm, one-half of their original length. Three replicate tests were performed on each material and geometry unless otherwise indicated.

Specific sustained crushing stress was used for comparing the energy-absorption capability of the different tubes. Specific sustained crushing stress is defined as the sustained crushing load divided by the product of the cross-sectional area and density of the tube. The specific sustained crushing stress is used synonymously with energy-absorption for comparison purposes.

CRUSHING PROCESS

The crushing process of brittle fiber (graphite or glass) reinforced composite materials is a cyclic process of interlaminar cracks that propagate between plies in the crushed region of the tube and form lamina bundles. The lamina bundles resist the applied load and buckle when the applied load and/or the length of the lamina bundle reach a critical value. The bundle will fracture or bend depending upon the failure strain of the lamina bundle. This cyclic process of crack propagation and buckling of lamina bundles repeats itself. If the failure strain of the matrix is sufficiently large, the interlaminar crack can be suppressed, references 5 and 7. If all interlaminar cracks are suppressed, the laminate may fail catastrophically or exhibit a local folding-crushing mode similar to that of Kevlar composites.

Kevlar reinforced composites exhibit a crushing mode similar to that of metallic tubes. In the crushed region of the tube, the Kevlar fiber plastically deforms. Interlaminar cracks form ahead of the crush region of the material. The interlaminar cracks locally destabilize the lamina bundles, which precipitates the local folding-crushing mode of Kevlar composites.

RESULTS AND DISCUSSION

Graphite/Epoxy Tube Specimens

Figures 2 and 3 show the energy-absorption capability trend and typical crushing characteristics of square cross section Gr/E tubes, respectively, with respect to tube W/t ratio. The energy-absorption trend is nonlinear. The energy-absorption capability of square cross section tubes is less than comparable circular cross section tubes, reference 6. These results, whether plotted in terms of similar tube internal widths as in figure 2 or similar wall thicknesses, suggest that no single nonlinear function represents the overall response. Figure 4 depicts a family of unique curves representing the effects of W/t ratio on energy-absorption capability for tubes having similar internal widths or wall thicknesses. With respect to tubes of similar internal widths at small values of W/t energy absorption increases with increasing W/t until a maximum is reached. Energy absorption then decreases nonlinearly as W/t increases. It is suspected that at sufficiently large W/t ratios the tube will not crush and fails catastrophically. The W/t ratio corresponding to the maximum sustained stress increases with increasing tube width. With respect to tubes having similar wall thickness, energy absorption decreases nonlinearly with increasing W/t.

The square cross section tubes exhibit lamina bending or a combined brittle fracture and lamina bending mode coupled with laminate tearing at the corners of the tubes, as shown in figure 3. Figure 5 shows photomicrographs of the crushed tube cross sections. As seen for all [±45] tubes, the predominate crushing mode is a lamina bending mode with the formation of a center crack. As W/t ratio increases, less brittle fracturing occurs and for a W/t= 125 the [±45] tubes exhibits mostly a lamina bending mode. As the number of plies increases, the tubes still exhibit the formation of a center crack,and secondary interlaminar cracks are formed between other plies. Furthermore, as the number of plies increases more brittle fracturing occurs. As more brittle fracturing occurs, the energy-absorption capability increases until a maximum value is reached, as previously described. As W/t further decreases more secondary interlaminar cracks are formed which results in a reduction in local bending stiffness and a decrease in energy-absorption capability.

For the tests conducted in this study, square cross section Gr/E tubes were not geometrically scalable. That is for a given W/t ratio, tubes with different widths and wall thicknesses, multiple energy-absorption capabilities exist. This difference in energy-absorption capability is related to the changing of the crushing modes exhibited by the different geometry tubes. The non-scalability of Gr/E square cross-section tubes is consistent with results reported by Farley, reference 6, for circular cross-section Gr/E tubes.

Kevlar/Epoxy Tube Specimens

The energy-absorption capability of K/E square cross section tube specimens is a nonlinear function of tube W/t ratio. Figure 6 shows this trend for four different internal width and three different wall thickness tube configurations. Energy-absorption trends correspond to a single nonlinear function similar to that described in reference 6 for circular cross section tubes. The increase in energy absorption with decreasing W/t ratio is related to the reduced interlaminar cracking and the buckling load of an equivalent edge supported plate. This energy-absorption trend is consistent with the buckling load characteristic of edge supported plates.

All of the K/E specimens crushed in a progressive local folding manner, as shown in figure 7, similar to that described in reference 6 for circular cross-sectional K/E tube specimens. The buckle wave length is a function of tube geometry (width and wall thickness). Unlike results reported in reference 3, no unstable crushing modes occurred, and the beveled crushing initiator worked in all cases. The undulations in the crushing force were a function of W/t ratios. The greater the W/t ratio the smaller the undulations in the crushing force as shown in figure 8.

For the tests conducted in this study, square cross-section K/E tubes are geometrically scalable. That is for a given W/t ratio, tubes with different widths and wall thicknesses have comparable energy-absorption capability. This result is consistent with results reported by Farley, reference 6, for circular cross section K/E tubes.

CONCLUDING REMARKS

Static crushing tests were conducted on square cross-section Gr/E and K/E tube specimens. Four different tube widths and three different wall thicknesses were investigated for each material. Based upon the results of these tests the following conclusions can be drawn:

Both Gr/E and K/E tubes exhibit a nonlinear relation between tube W/t ratio and energy-absorption capability. Energy absorption generally increased with decreasing W/t ratio. Changes in crushing modes occurred for Gr/E tubes having W/t ratios of between 20 and 50, resulting in a decrease in energy-absorption capability as W/t decreased. Both Gr/E and K/E tubes crushed in a progressive and stable manner. Tubes of K/E were found to be geometrically scalable whereas Gr/E tubes were not generally scalable.

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Table 1. Graphite/Epoxy Square Cross-Section Tubes.

Tube Layup	Average Inside Width (W), cm	Average Wall Thickness (t) cm	W/t Ratio
$[\pm 45]_2$	1.27	0.046	27.77
$[\pm 45]_4$	1.27	0.089	14.28
$[\pm 45]_8$	1.27	0.198	6.41
$[\pm 45]_2$	2.54	0.069	37.03
$[\pm 45]_4$	2.54	0.117	21.74
$[\pm 45]_8$	2.54	0.221	11.49
$[\pm 45]_2$	3.81	0.051	75.00
$[\pm 45]_4$	3.81	0.114	33.33
$[\pm 45]_8$	3.81	0.216	17.65
$[\pm 45]_2$	7.62	0.061	125.00
$[\pm 45]_4$	7.62	0.132	57.69
$[\pm 45]_8$	7.62	0.229	33.33

Table 2. Kevlar/Epoxy Square Cross-Section Tubes.

Tube Layup	Average Inside Width (W), cm	Average Wall Thickness (t) cm	W/t Ratio
$[\pm 45]_2$	1.27	0.046	28.66
$[\pm 45]_4$	1.27	0.089	14.28
$[\pm 45]_8$	1.27	0.185	6.85
$[\pm 45]_2$	2.54	0.053	47.62
$[\pm 45]_4$	2.54	0.091	27.77
$[\pm 45]_8$	2.54	0.216	11.76
$[\pm 45]_2$	3.81	0.064	60.00
$[\pm 45]_4$	3.81	0.089	42.85
$[\pm 45]_8$	3.81	0.193	19.74
$[\pm 45]_2$	7.62	0.051	150.00
$[\pm 45]_4$	7.62	0.112	68.18
$[\pm 45]_8$	7.62	0.221	34.48

TYPICAL SQUARE TUBE SPECIMEN

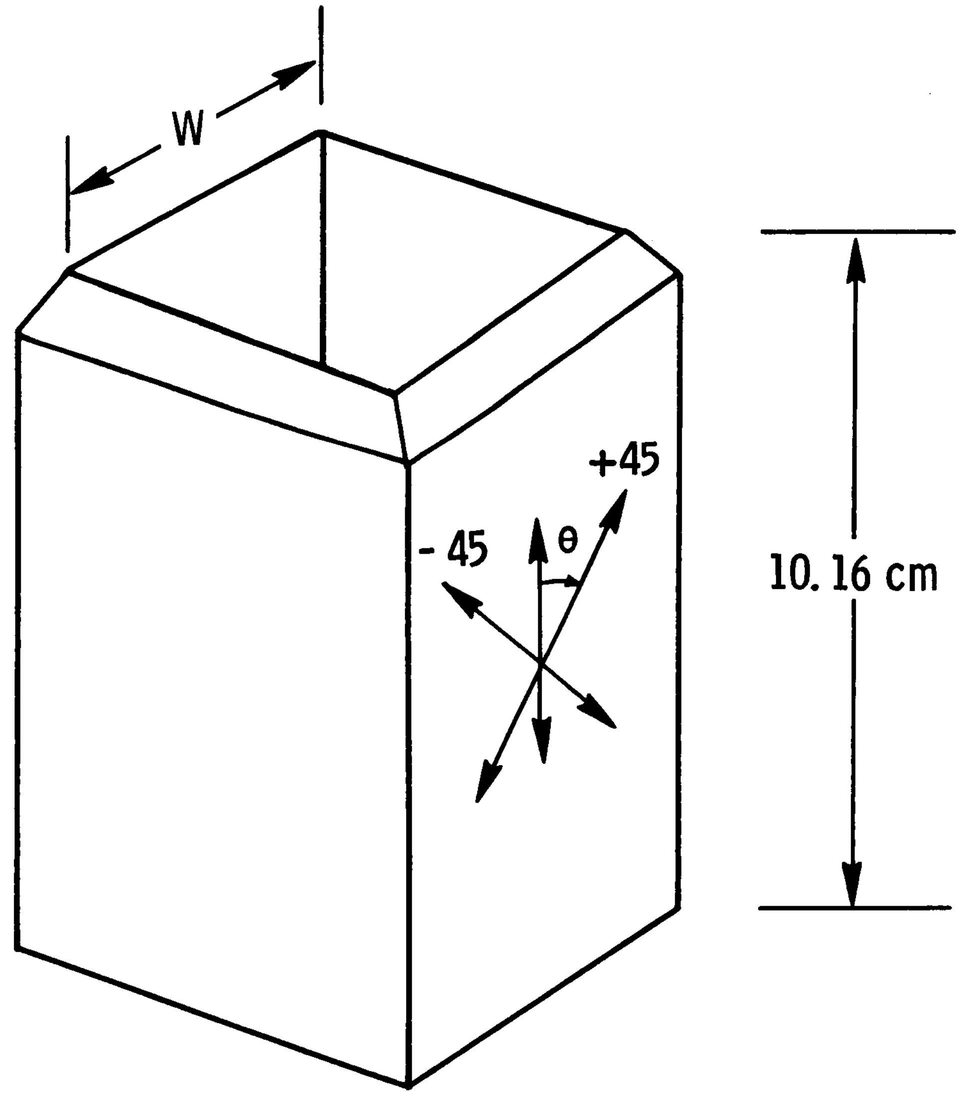

Figure 1. Sketch of typical square cross section tube specimen.

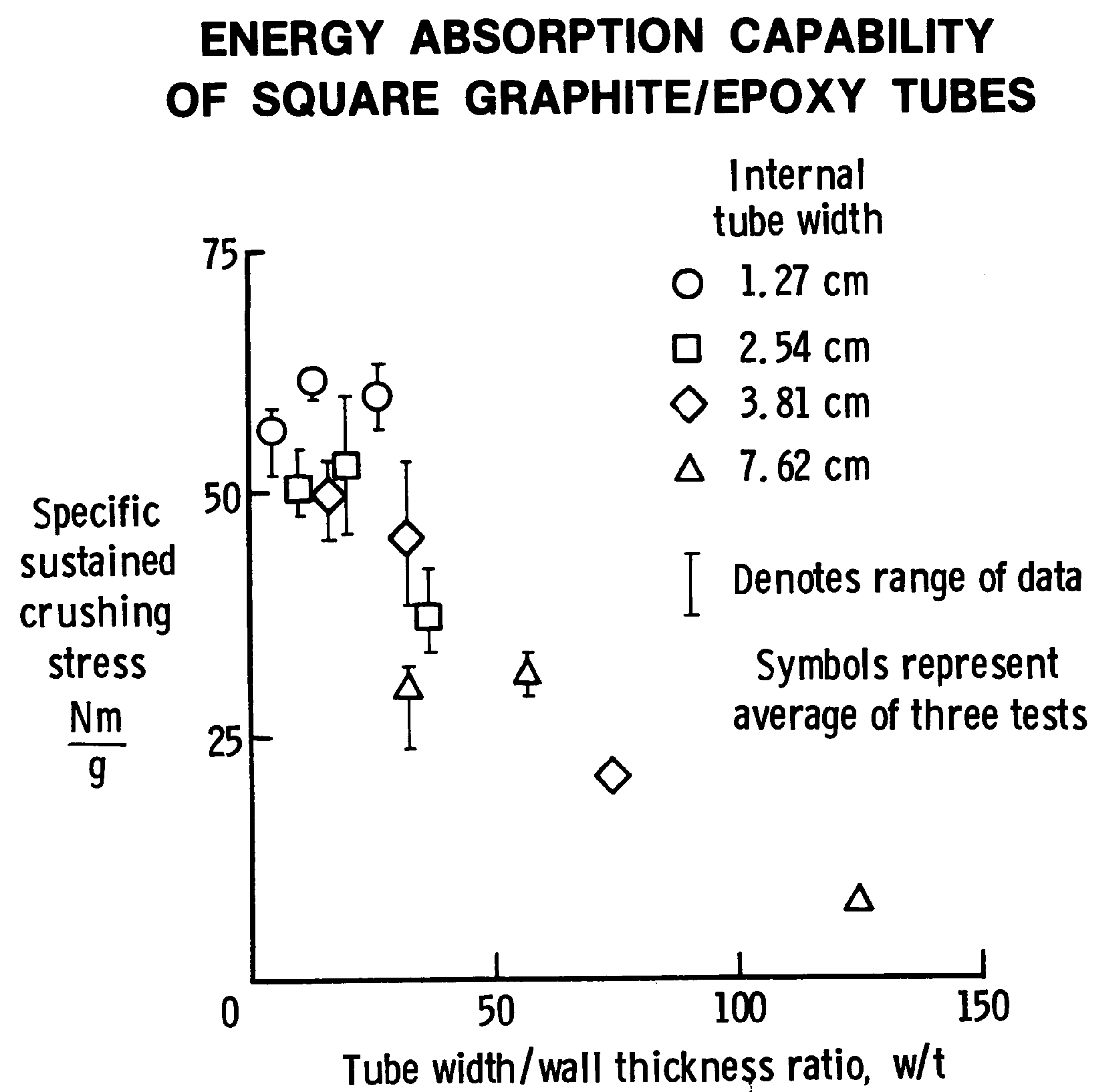

Figure 2. Energy-absorption capability of $[\underline{+}45]_N$ square graphite/epoxy tubes.

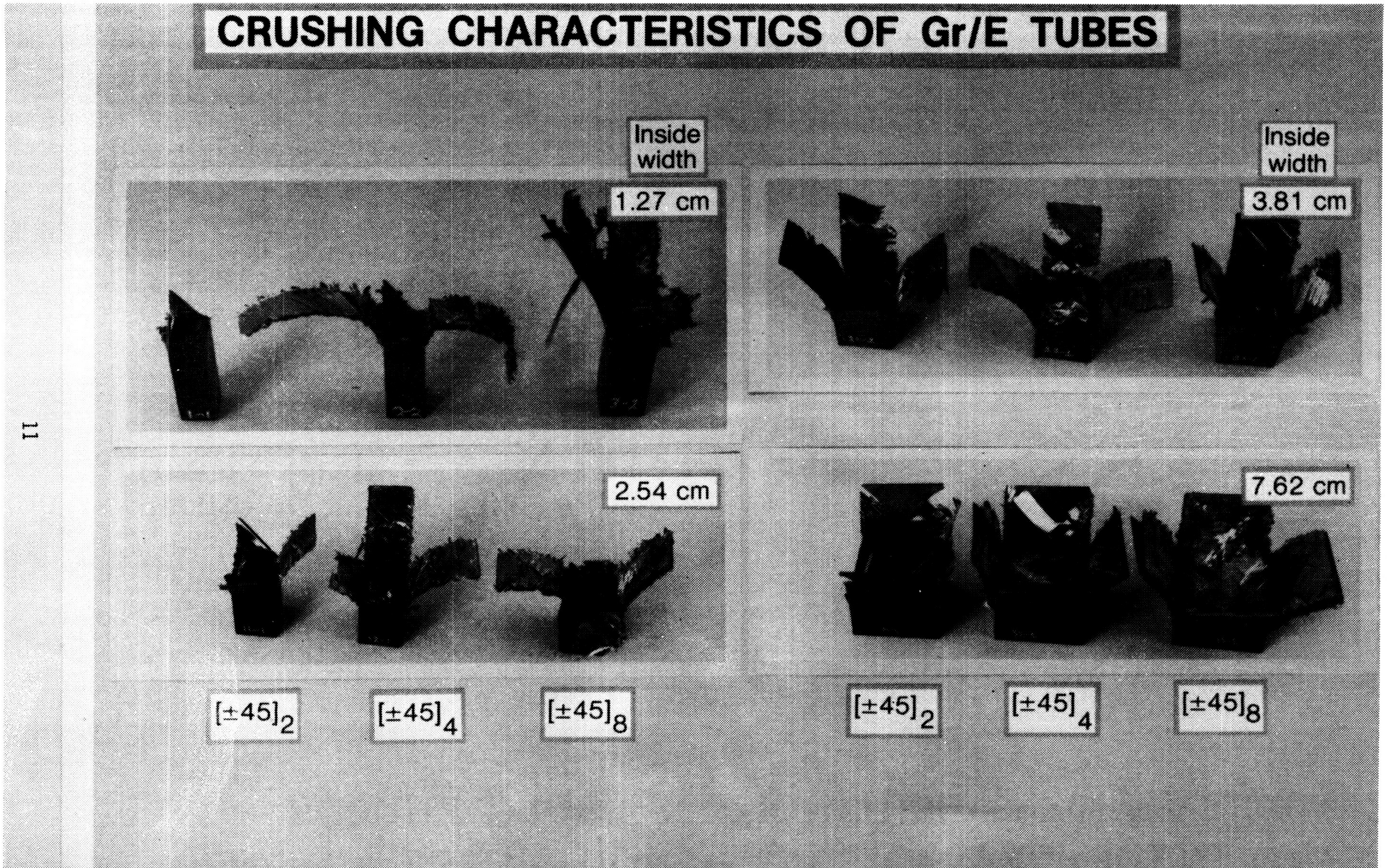

Figure 3. Crushing characteristics of $[\pm 45]_2$, $[\pm 45]_4$, and $[\pm 45]_8$ Gr/E tubes.

ENERGY ABSORPTION TRENDS OF GRAPHITE/EPOXY SQUARE CROSS-SECTION TUBE SPECIMENS

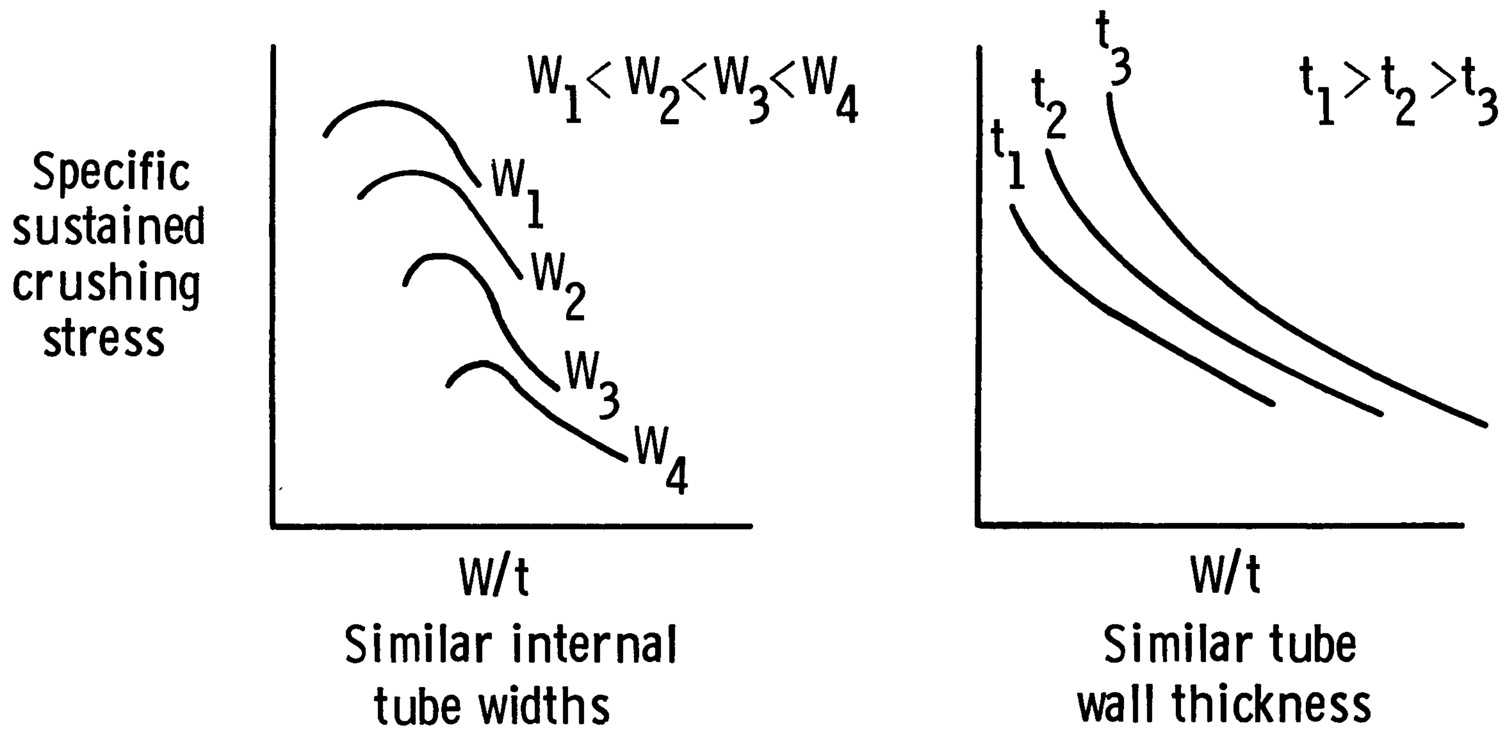

Figure 4. Energy-absorption trends of graphite/epoxy square cross section tube specimens.

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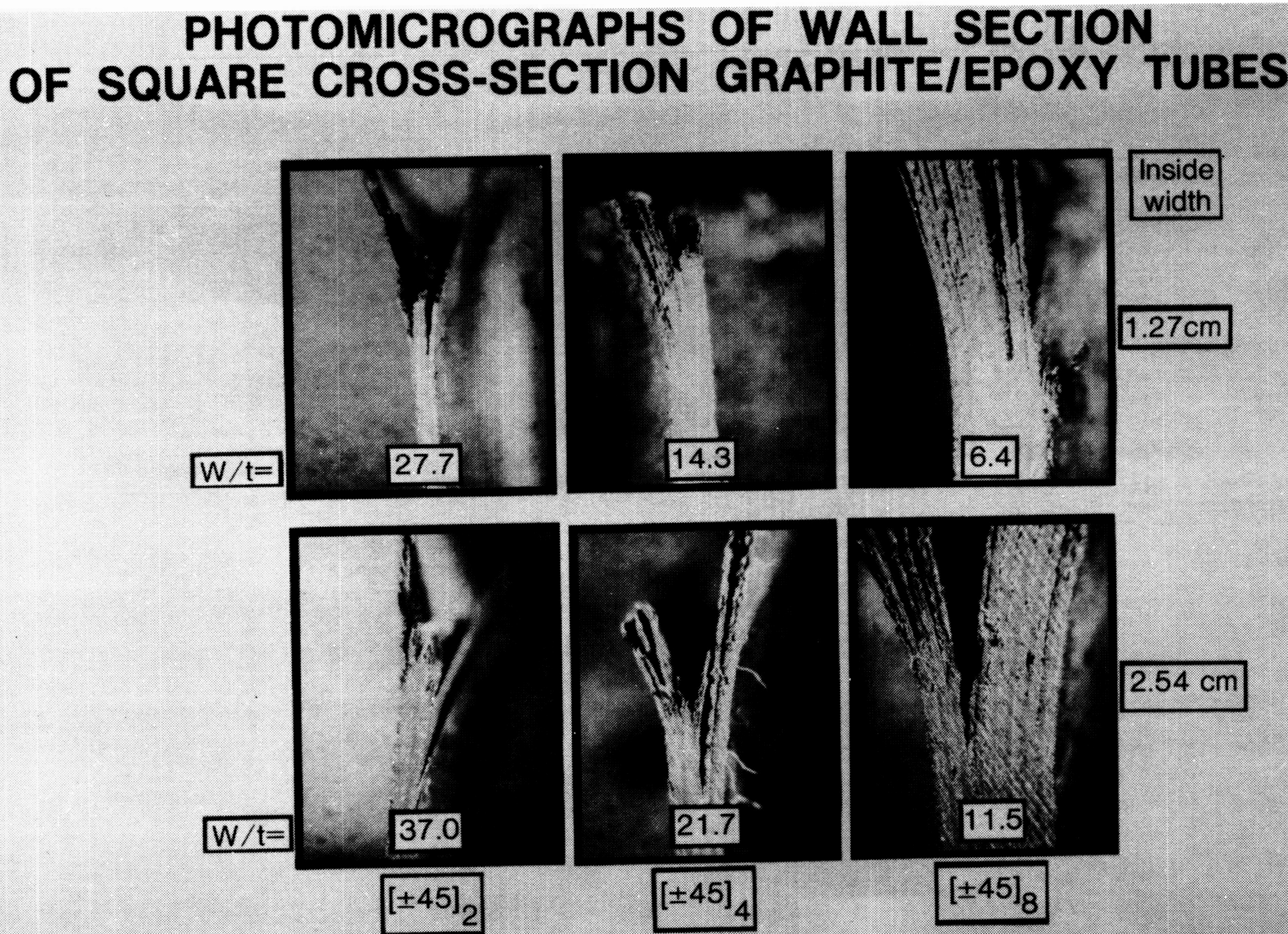

Figure 5. Photomicrographs of wall section of square cross section graphite/epoxy tubes (Cont.).

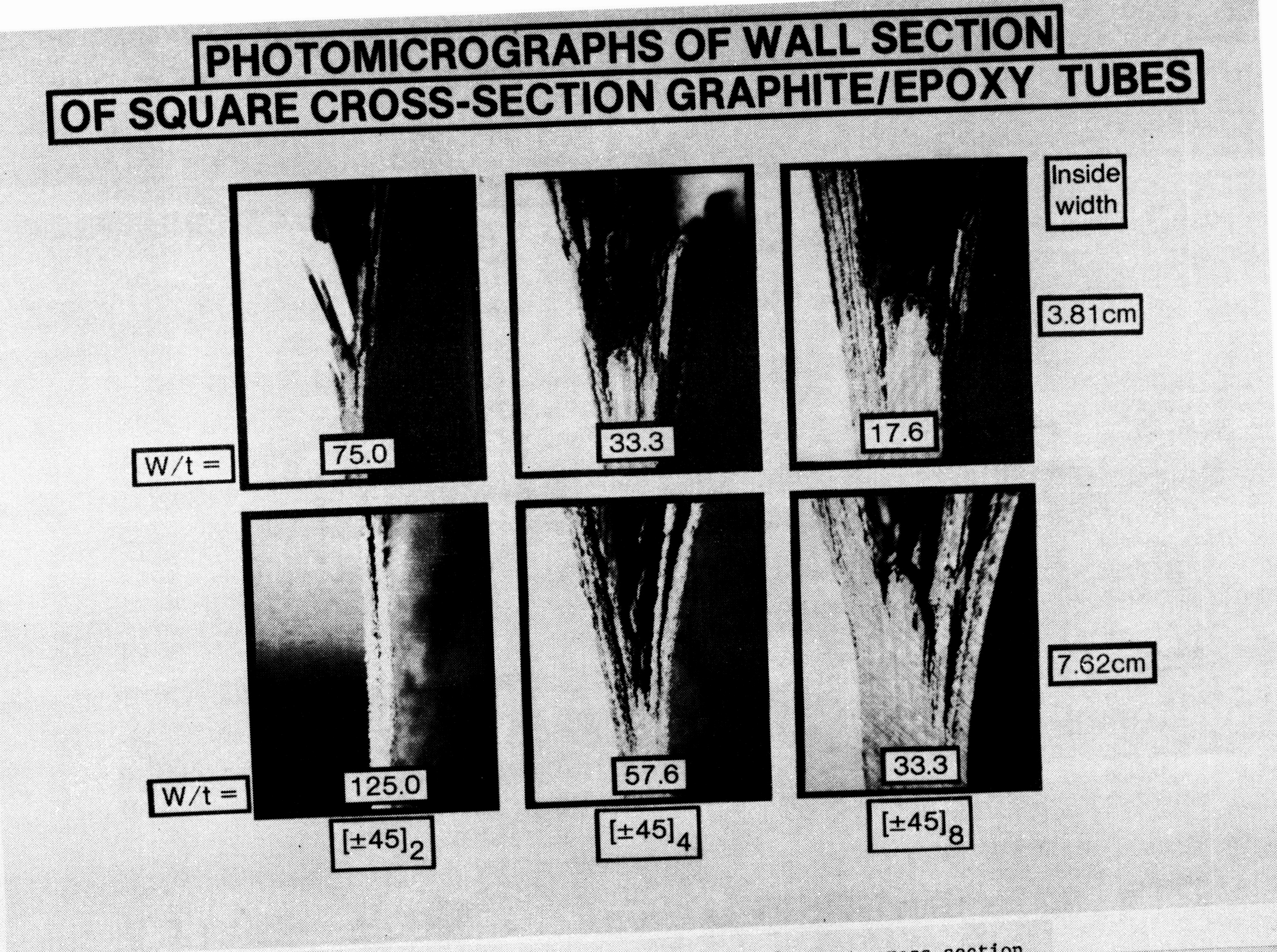

Figure 5. Photomicrographs of wall section of square cross section graphite/epoxy tubes (Concluded).

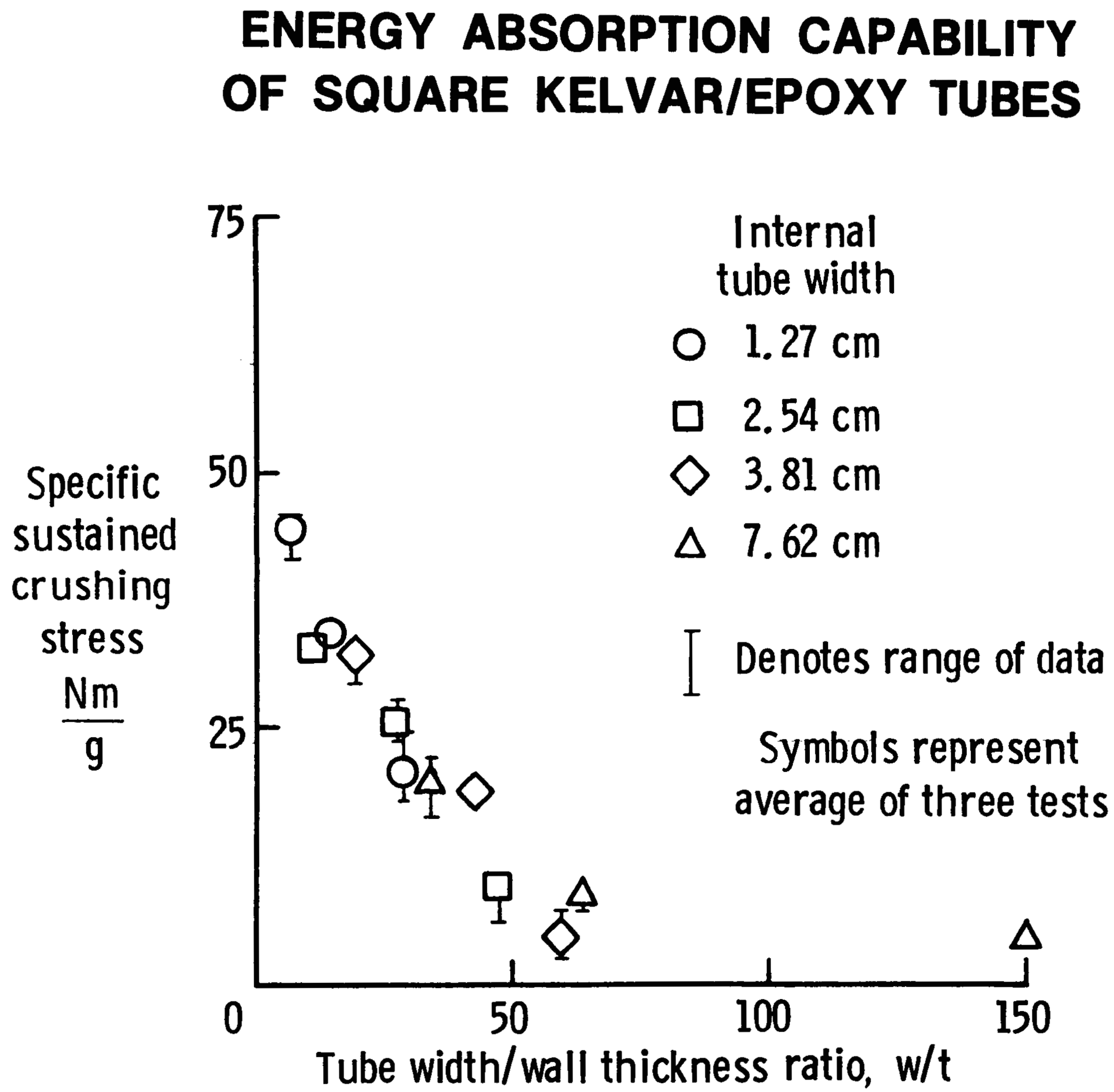

Figure 6. Energy-absorption capability of $[\pm 45]_N$ square Kevlar/epoxy tubes.

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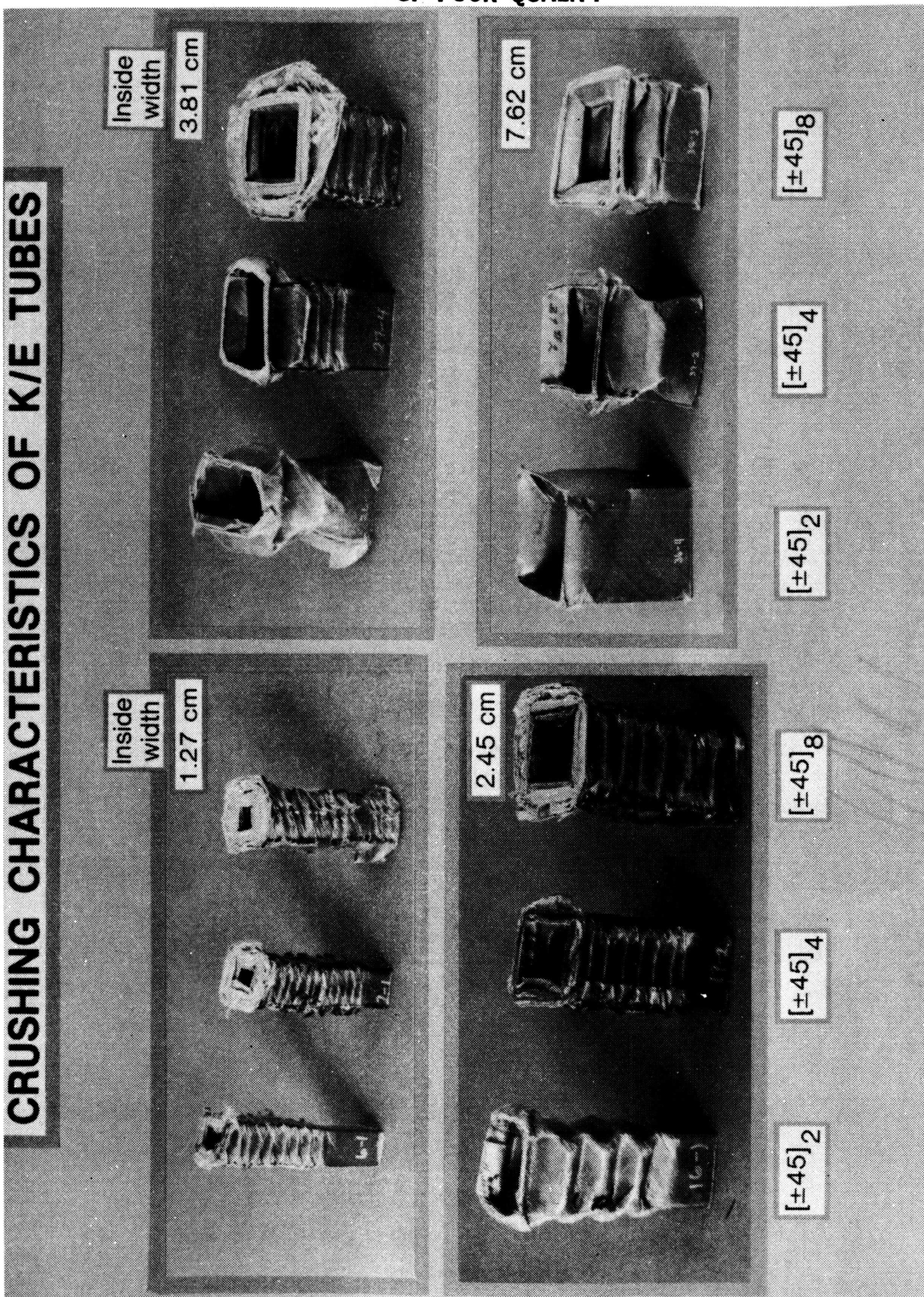

Figure 7. Crushing characteristics of $[\pm 45]_2$, $[\pm 45]_4$, and $[\pm 45]_8$ K/E tubes.

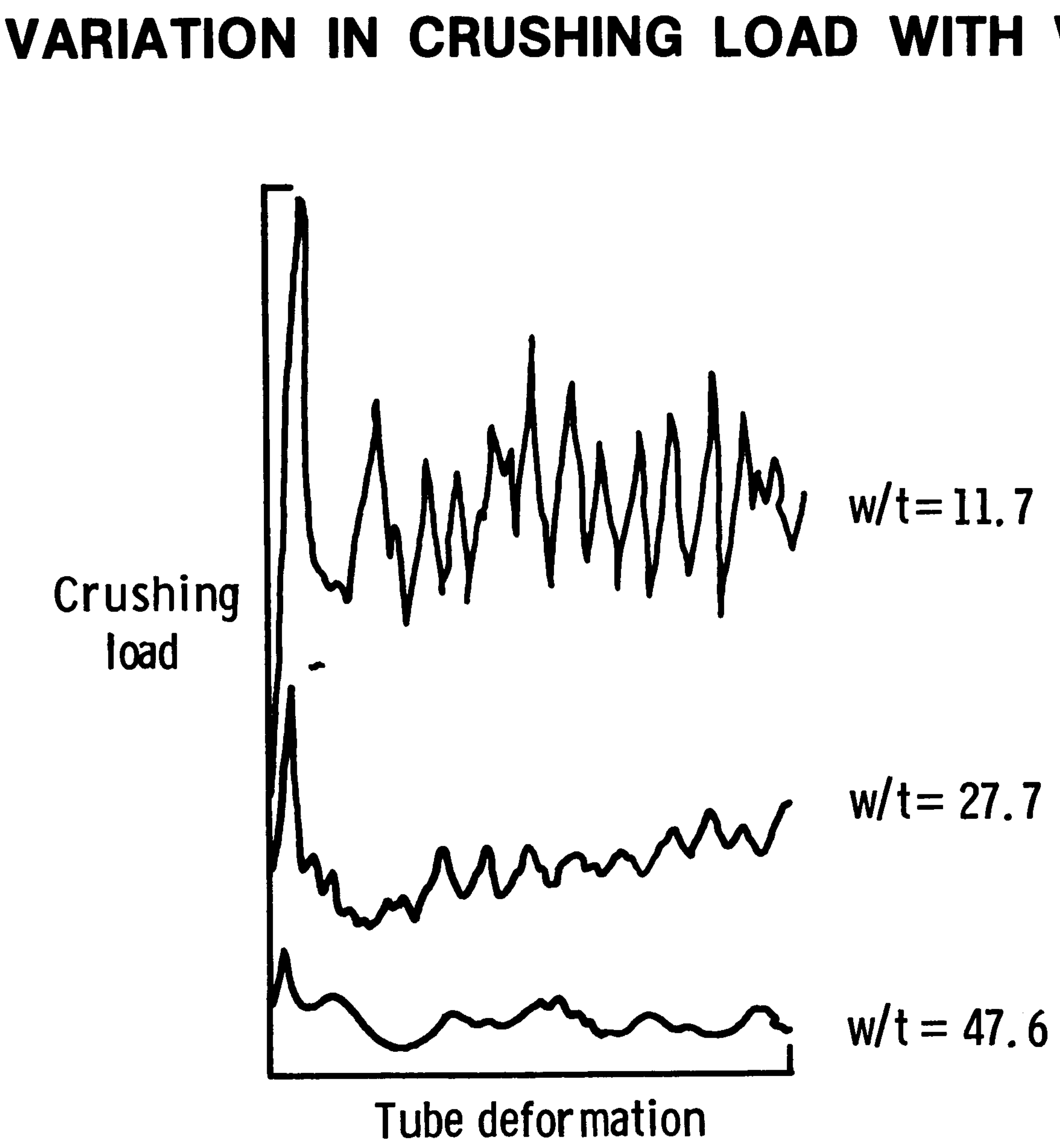

Figure 8. Variation in crushing load with w/t ratio.