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SUMMARY

Tests have been conducted at room temperature to determine the notch sensitivity of the thermal protection tile for the Space Shuttle. Two types of RSI tile were studied: LI-900 and LI-2200. Three-point bend specimens were cut from discarded tiles in the in-plane (ip) and through-the-thickness (ttt) directions. They were tested with or without a sharp notch. The LI-900 (ip and ttt) specimens were not very notch sensitive, but the LI-2200 (ip and ttt) specimens were. The LI-2200 material showed about a 35-percent reduction in strength due to the presence of the notch. This reduction in strength should be considered in the design of mechanically fastened tile concepts.

INTRODUCTION

Some of the tiles used for the thermal protection system of the Space Shuttle may be held in place with a mechanical fastener. One type of mechanical fastener requires twisting an auger into the tile. The auger has blades that will cut a sharp notch in the material. The present investigation will determine whether the notch influences the fracture strength of the tile materials.

Tests have been conducted to determine the notch sensitivity of LI-900 and LI-2200 RSI tile. Three-point bend specimens were cut from discarded tiles. The specimens were oriented in the in-plane (ip) and through-the-thickness (ttt) directions. They were tested with or without a sharp notch and were statically bent to failure at room temperature.

SYMBOLS AND ABBREVIATIONS

This paper presents physical quantities in both the International System of Units (SI) and U.S. Customary Units. All measurements and calculations were made in U.S. Customary Units, except for the measurement of load.

a	notch length, mm (in.)
B	specimen thickness, mm (in.)
F	applied force, kg (lbf)
K_Q	elastic fracture toughness, kPa $m^{1/2}$ $\left(\text{psi in.}^{1/2}\right)$
L	span length, mm (in.)
P	failure load, kg (lbf)
S_B	elastic nominal failure stress for bend specimen, kPa (psi)
S_{NB}	elastic nominal failure stress for notch-bend specimen, kPa (psi)
w	specimen width, mm (in.)
σ_u	uniaxial tensile strength, kPa (psi)

Abbreviations:

ip	in-plane
ttt	through-the-thickness

MATERIALS, SPECIMENS, AND TEST PROCEDURE

Materials

The materials used in this study were LI-900 and LI-2200 RSI tile. The LI-900 and LI-2200 tiles are made from rigidized silica fibers weighing about 145 kg/m^3 $\left(9\ lb/ft^3\right)$ and 354 kg/m^3 $\left(22\ lb/ft^3\right)$, respectively.

Specimens

The test specimens were cut from tiles as shown in figure 1. The specimens were oriented in the in-plane (ip) and through-the-thickness (ttt) directions.

So that they could be tested in the same bending test fixture as the ip specimens, the specimens in the ttt-direction had end tabs (made of the same material) bonded to each end with epoxy. The three-point bend specimens, shown in figure 2, were tested with or without a sharp notch. The sharp notch was cut with a thin-bladed coping saw. The width of the notch was about 0.25 mm (0.01 in.).

The nominal thickness, B, of all specimens was about 25.4 mm (1 in.). The specimen width, w, for the notch-bend specimens was about 25.4 mm (1 in.), and the notch-length-to-width ratio (a/w) was about 0.5. Some of the LI-2200 notch-bend specimens oriented in the ttt-direction had notch-length-to-width ratios ranging from 0.3 to 0.7. The specimen width for the unnotched bend specimens ranged from 7.1 mm (0.28 in.) to 25.4 mm (1 in.). The notched and unnotched specimens of each material and orientation were taken from the same tile in adjacent locations. The bend specimens were cut so that the width, w, was about equal to the net width (w - a) of the corresponding notch-bend specimens. Table I gives a summary of materials, specimen type (notch-bend or bend), orientation, ultimate tensile strength, and dimensions for all specimens tested. The ultimate tensile strengths were obtained from Volume 3 - Thermal Protection System Materials Property Manual (Rockwell International Corp., 1979).

Test Procedure

All specimens were tested in the same three-point loading test fixture, as shown schematically in figure 3. The span length, L, for the specimens was 127 mm (5 in.). The specimens were statically bent to failure at room temperature and the applied force, F, was visually recorded from the scale by two observers. The two observed values were then averaged. The failure load, P, was the sum of the applied force plus the weight of the scale, cord, and pin.

The accuracy of recording failure loads was estimated to be about ±25 grams. The scale was graduated in 25-gram increments.

ANALYSIS

Stress

The elastic nominal failure stress was calculated at the outer fiber of the bend specimen as

$$S_B = \frac{3PL}{2Bw^2} \tag{1}$$

and at the notch tip of the notch-bend specimen as

$$S_{NB} = \frac{3PL}{2B(w - a)^2} \tag{2}$$

Fracture Toughness

The elastic fracture toughness, K_Q, of the notch-bend specimen was calculated by

$$K_Q = S_B\sqrt{a}\, f(a/w) \tag{3}$$

where $f(a/w)$ was obtained from reference 1 by linear interpolation between results for $L/w = 4$ and 8, and was given by

$$f(\lambda) = 1.94 - 2.99\lambda + 14.31\lambda^2 - 24.83\lambda^3 + 25.66\lambda^4 \tag{4}$$

for $L/w = 5$ and $\lambda \leq 0.7$ where $\lambda = a/w$. (Note that the constant $\sqrt{\pi}$ is contained in the coefficients of $f(\lambda)$.)

RESULTS AND DISCUSSION

Table I gives a summary of materials, specimen type (notch-bend or bend), orientation, ultimate tensile strength, specimen thickness, specimen width, notch length, failure load, calculated elastic nominal failure stress, and calculated elastic fracture toughness of the specimens tested.

Table I shows that the elastic nominal failure stresses of all specimens exceed the ultimate tensile strength of the materials. This behavior is commonly observed in bend specimens made of metallic and composite materials. In metallic materials this behavior is caused by plastic yielding. In the tile this behavior may be caused by micro-cracking or fiber straightening.

The influence of the notch on the elastic nominal failure stress of LI-900 (ip and ttt) and LI-2200 (ip and ttt) RSI tile is shown in figure 4. The nominal failure stress for the notched specimen is normalized by the nominal failure stress for the corresponding unnotched specimen. The width of the corresponding unnotched specimen was about equal to the net width (w - a) of the notched specimen to minimize any size effect on strength. The notch-length-to-width ratio was about 0.5, and the specimen thickness was about 25.4 mm (1 in.). The results shown for LI-900 (ttt) and LI-2200 (ttt) are the average failure stresses for two or three tests. The LI-900 material was not very notch sensitive but showed an 8- to 18-percent reduction in strength due to the presence of the notch. However, the LI-2200 material was more notch sensitive than the LI-900 material and showed a 35-percent reduction in strength due to the notch. This behavior is consistent with failures of other materials: higher strength materials are usually more notch sensitive than lower strength materials. For comparison, calculated results on 7075-T6 and 2024-T3 aluminum alloy are also shown.

The influence of notch-length-to-width ratio on the elastic nominal failure stress for LI-2200 (ttt) RSI tile is shown in figure 5. Again, the nominal failure stress for the notched specimen is normalized by the nominal failure stress for the corresponding unnotched specimen and plotted against the notch-length-to-width ratio. The dash-dot curve shows the "expected" trend based on failure of other materials. For a/w ratios less than 0.5 and a/w ratios greater than 0.5, the strength of the notched specimen should approach the strength of an unnotched specimen whose depth equals (w - a).

The elastic fracture toughness, K_Q, for LI-900 (ttt) and LI-2200 (ttt) as a function of notch-length-to-width ratio (a/w) is shown in figure 6. The fracture toughness of the LI-2200 material is considerably larger than that for the LI-900 material. This is primarily due to the higher strength of the LI-2200 material. The toughness for LI-2200 appears to be independent of a/w based on the limited number of tests conducted here. However, the fracture toughness may be a function of specimen width. In other materials, larger specimen widths give larger values of fracture toughness. Only in perfectly brittle materials is K_Q a material constant (independent of crack length and specimen width).

The reduction in strength due to the presence of the notches should be considered in the design of mechanically fastened tile concepts.

CONCLUDING REMARKS

Tests have been conducted at room temperature to determine the notch sensitivity of materials used for the thermal protection system of the Space Shuttle. The materials investigated were LI-900 and LI-2200 RSI tile. Three-point bend specimens were tested with or without a sharp notch. The specimens were oriented in the in-plane (ip) and through-the-thickness (ttt) directions. The results of these tests are summarized as follows:

1. The LI-900 (ip and ttt) tile material was not very notch sensitive. It showed an 8- to 18-percent reduction in strength due to the presence of the notch.

2. The LI-2200 (ip and ttt) tile material was notch sensitive and showed a 35-percent reduction in strength due to the presence of the notch.

3. The elastic fracture toughness of the LI-2200 material was about double that for the LI-900 material.

4. The reduction in strength due to the presence of notches should be considered in the design of mechanically fastened tile concepts.

REFERENCES

1. Brown, W. F., Jr.; and Srawley, J. E.: Plane Strain Crack Toughness Testing of High Strength Metallic Materials. ASTM STP-410, 1966.

TABLE I.- THREE-POINT BEND SPECIMEN TEST RESULTS

(S.I. Units)

Material	Specimen Type	σ_u, kPa	B, mm	w, mm	a, mm	P, kg	S, kPa	K_Q, kPa $m^{1/2}$
LI-900	NB (ttt)	152	25.9	24.6	11.7	613	266	19.1
	NB (ttt)		25.4	25.4	12.2	588	248	18.1
	B (ttt)		25.4	12.9	0	713	313	--
	B (ttt)		25.4	13.2	0	763	314	--
LI-900	NB (ip)	469	25.4	25.1	13.0	1368	676	47.7
	B (ip)		25.4	11.2	0	1268	753	--
	B (ip)		25.4	12.2	0	1403	693	--
LI-2200	NB (ttt)	414	25.4	24.9	7.6	2138	525	42.0
	NB (ttt)		24.9	25.4	12.2	1475	647	46.2
	NB (ttt)		25.9	25.4	11.7	1413	581	40.4
	NB (ttt)		22.6	25.1	11.9	1088	521	37.5
	NB (ttt)		24.9	25.4	17.8	598	747	42.1
	B (ttt)		25.4	17.5	0	3113	749	--
	B (ttt)		25.9	13.2	0	2263	931	--
	B (ttt)		25.4	12.7	0	1813	814	--
	B (ttt)		25.4	7.1	0	651	936	--
LI-2200	NB (ip)	1000	25.4	25.4	12.4	2088	932	66.0
	B (ip)		25.9	12.7	0	3138	1393	--
	B (ip)		24.1	12.2	0	2763	1444	--

TABLE I.- THREE-POINT BEND SPECIMEN TEST RESULTS

(U.S. Customary Units)

Material	Specimen Type	σ_u, psi	B, in.	w, in.	a, in.	P, lbf	S, psi	K_Q, psi in.$^{1/2}$
LI-900	NB (ttt)	22	1.01	0.97	0.46	1.36	38.5	17.4
	NB (ttt)		1.00	1.00	0.48	1.31	36.0	16.5
	B (ttt)		1.00	0.51	0	1.58	45.4	--
	B (ttt)		1.00	0.52	0	1.69	45.6	--
LI-900	NB (ip)	68	1.00	0.99	0.51	3.04	98.0	43.4
	B (ip)		1.00	0.44	0	2.82	109.2	--
	B (ip)		1.00	0.48	0	3.12	100.5	--
LI-2200	NB (ttt)	60	1.00	0.98	0.30	4.75	76.1	38.2
	NB (ttt)		0.98	1.00	0.48	3.28	93.8	42.0
	NB (ttt)		1.01	1.00	0.46	3.14	84.3	36.8
	NB (ttt)		0.89	0.99	0.47	2.42	75.5	34.1
	NB (ttt)		0.98	1.00	0.70	1.33	108.4	38.3
	B (ttt)		1.00	0.69	0	6.92	108.6	--
	B (ttt)		1.01	0.52	0	5.03	135.0	--
	B (ttt)		1.00	0.50	0	4.03	118.0	--
	B (ttt)		1.00	0.28	0	1.45	135.7	--
LI-2200	NB (ip)	145	1.00	1.00	0.49	4.64	135.2	60.1
	B (ip)		1.01	0.50	0	6.97	202.0	--
	B (ip)		0.95	0.48	0	6.14	209.5	--

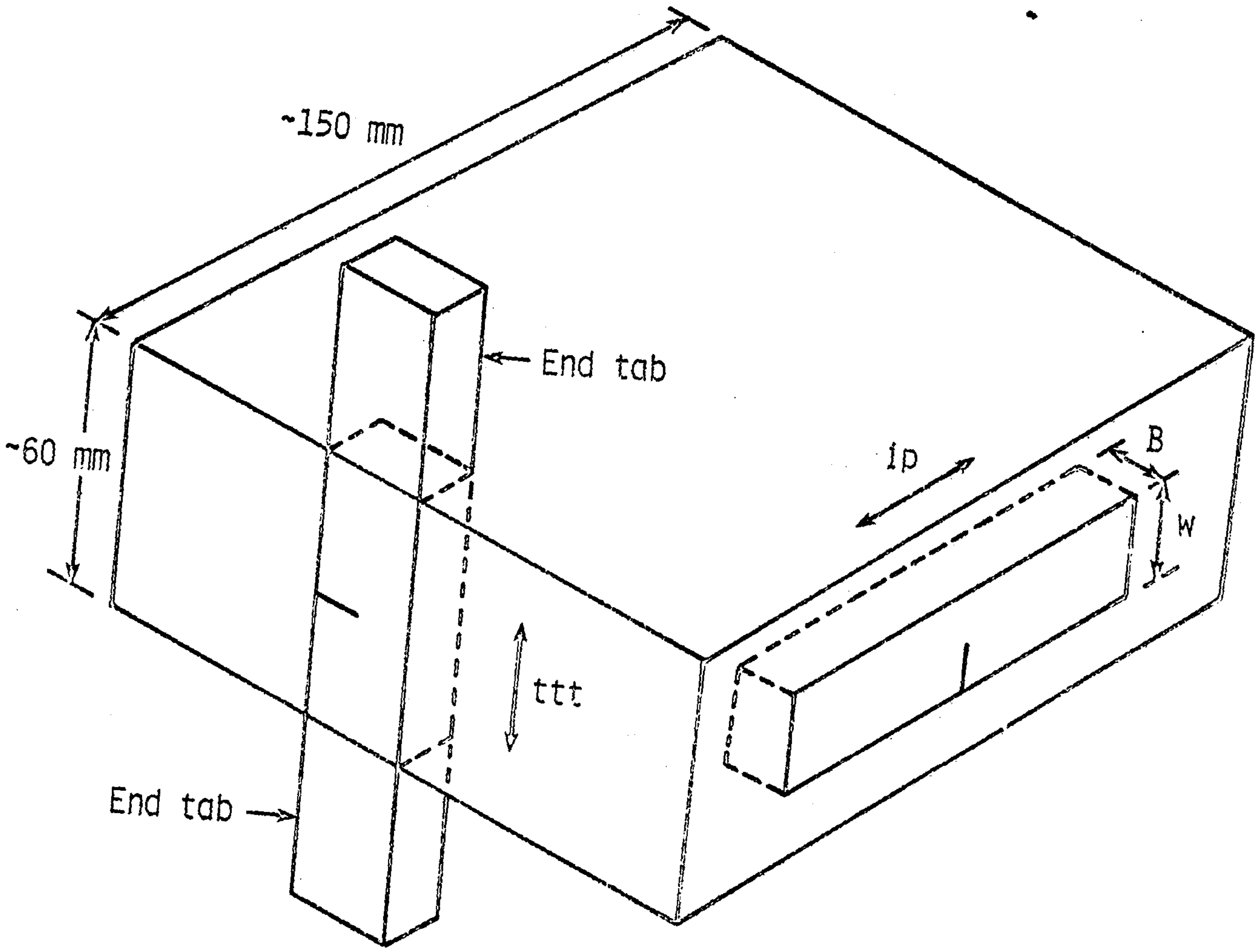
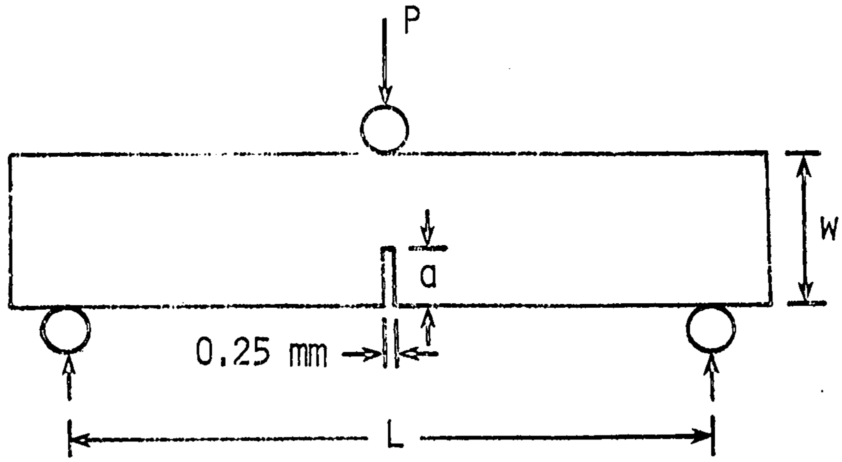
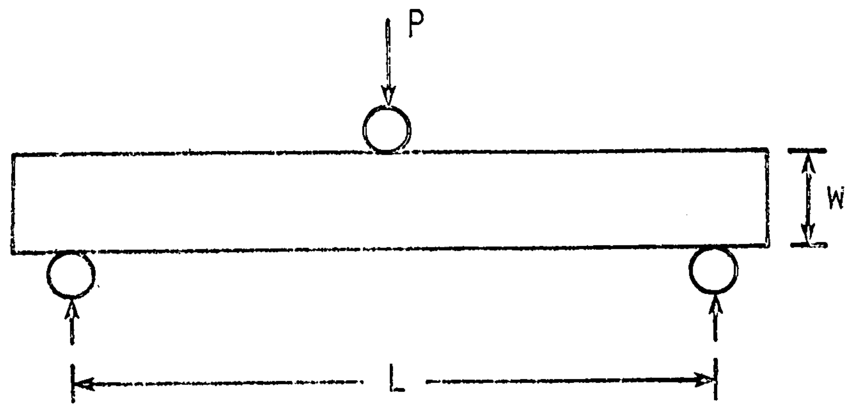


Figure 1.- Tile and orientation of bend specimens.



(a) Notched.



(b) Unnotched.

Figure 2.- Three-point bend specimens with or without a sharp notch.

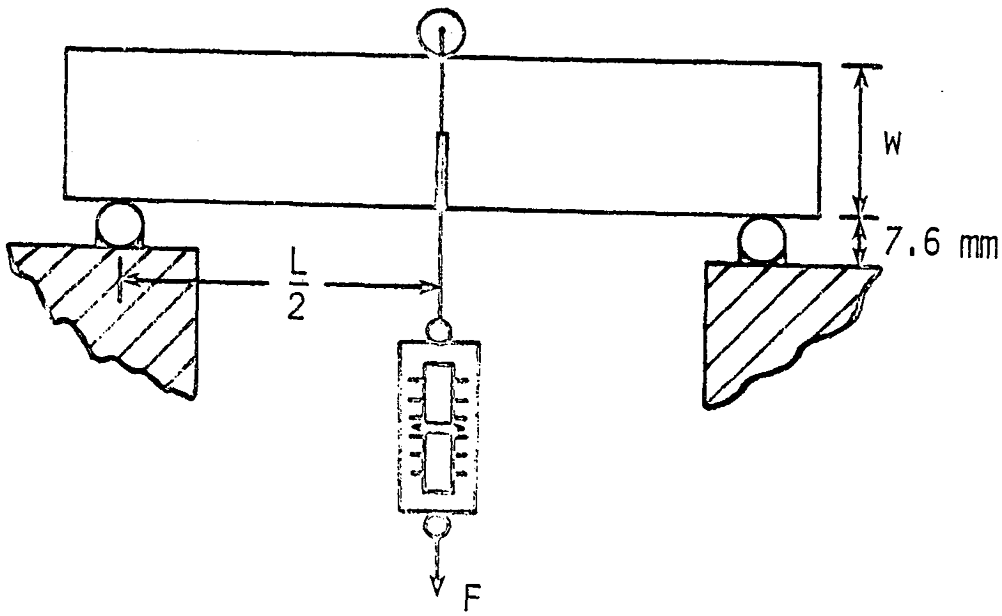


Figure 3.- Schematic of three-point bend loading fixture and scale.

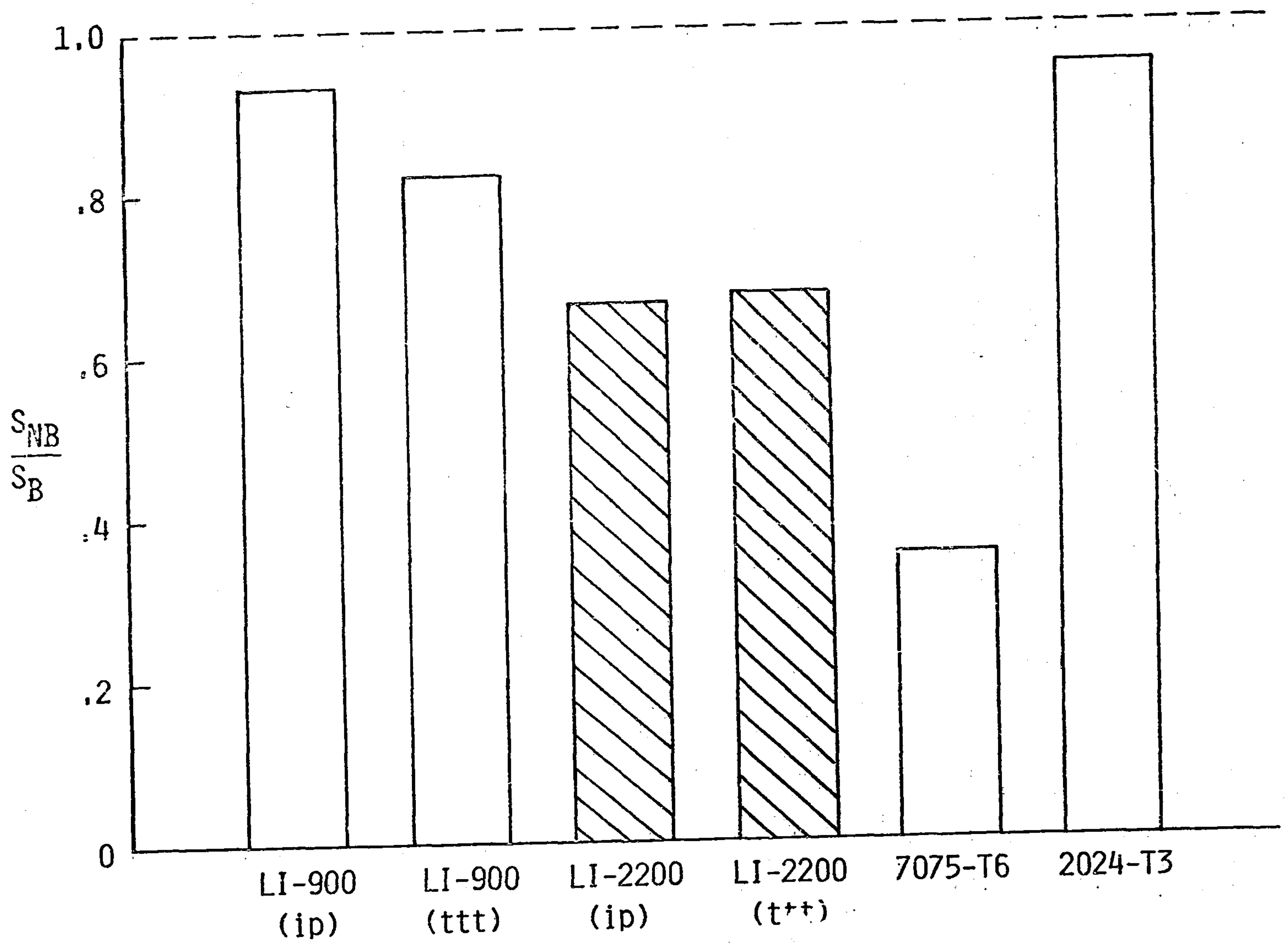


Figure 4.- Ratio of notch strength to unnotch strength for a/w ratio of 0.5.

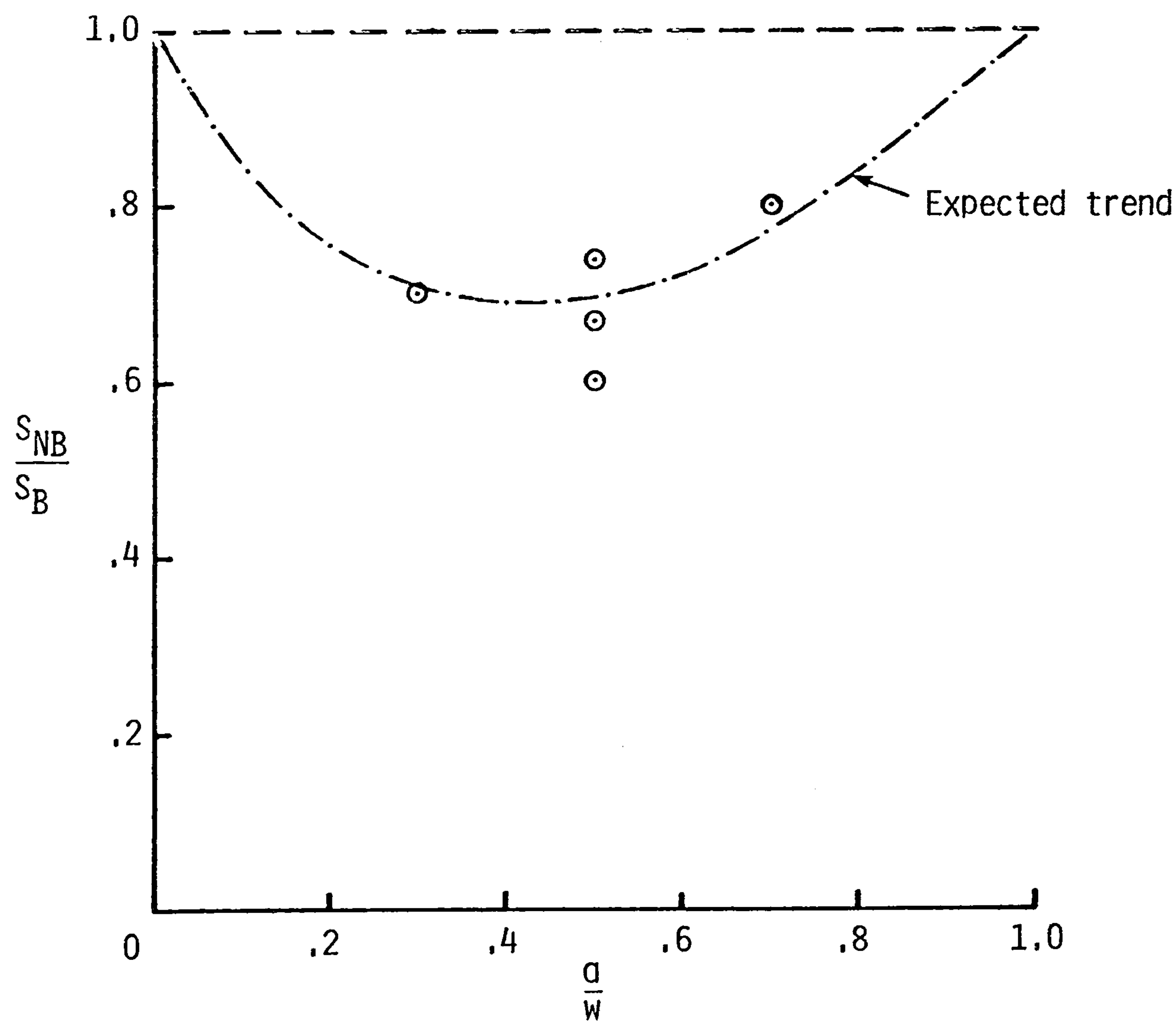


Figure 5.- Ratio of notch strength to unnotch strength as a function of notch-length-to-width ratio for LI-2200 (ttt).

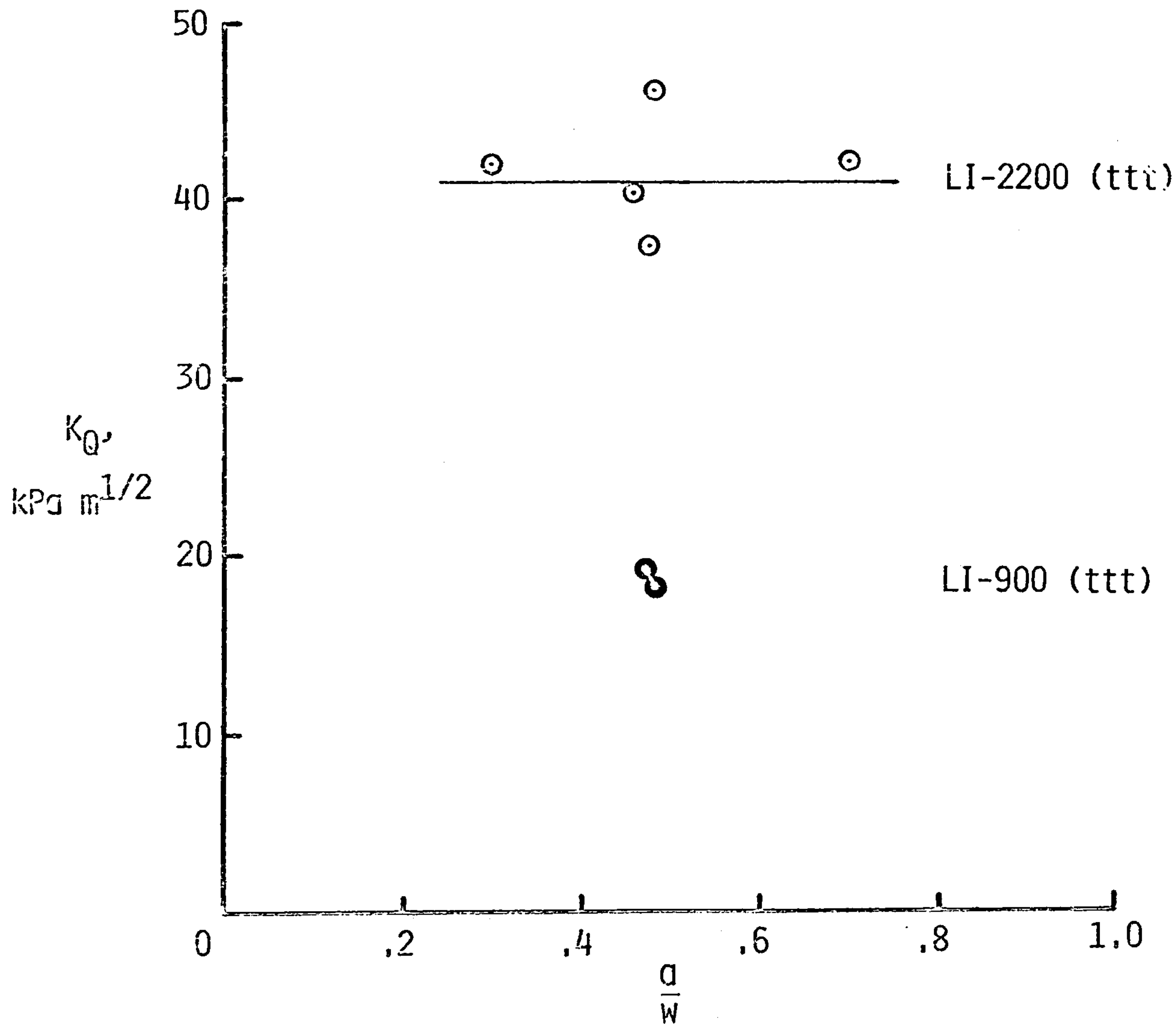


Figure 6.- Elastic fracture toughness as a function of notch-length-to-width ratio.