ORAL/POSTER REFERENCE: ICF100576OR

EXPERIMENTAL FAILURE MODES AND FEA OF LIGHTWEIGHT CERAMIC ABLATORS UNDER IOSIPESCU TESTING

S. Nagasawa, K. E. Parmenter, K. Shuman, and F. Milstein

Departments of Mechanical Engineering and Materials
University of California, Santa Barbara, CA 93106, USA

ABSTRACT

Lightweight ceramic ablators (LCAs) consist of fibrous ceramic substrates impregnated with organic resins. The ablators were developed at NASA Ames Research Center for use as heat shields to protect space vehicles during planetary entry. In the present work, the fracture characteristics of LCAs are determined by Iosipescu shear testing, and finite element analysis (FEA) is used to approximate the stress distribution in the Iosipescu tests. The experimental failure modes are interpreted in terms of the FEA results; it is shown that the LCAs fracture as a result of localized peak tensile stresses, rather than from the shear stress along the notch-root axis. Tests are made for two modes of load; i.e., parallel and perpendicular to the LCAs' preferred plane of fiber orientation.

KEYWORDS

SIRCA, PICA, Iosipescu, shear, FEA, LCA, ablator

INTRODUCTION

Lightweight ceramic ablators (LCAs) were developed at NASA Ames Research Center for use as heat shields to protect space vehicles during planetary entry [1]. The materials consist of fibrous ceramic substrates impregnated with organic resins. In this work, two material systems were investigated, in their virgin and charred states, viz., Silicone Impregnated Reusable Ceramic Ablator (SIRCA) and Phenolic Impregnated Carbon Ablator (PICA). SIRCA was the heat shield on the aft-plate of Mars Pathfinder and was chosen for the leading edges and nose cap of the X-34 Vehicle. PICA was chosen as the heat shield for Stardust Sample Return Capsule's forebody, and is a candidate for future sample return missions. The fibers in the substrates of the LCAs tend to be randomly and uniformly aligned parallel to a preferred plane (i.e., the fibers tend to lie normal to a preferred axis, but randomly oriented about the axis); hence the composites' mechanical properties are anisotropic. Here we examine anisotropic fracture modes of the LCAs during Iosipescu shear testing, and interpret the results with FEA modeling.

EXPERIMENTAL IOSIPESCU SHEAR TESTS

Notched beam Iosipescu specimens [2] were loaded anti-symmetrically in an Adams and Walrath (A&W) fixture [3] as illustrated in Fig. 1. Load F_N was applied by a displacement-controlled Instron testing machine and measured with a compression load cell. Displacement *y* was determined from the Instron's internal displacement gage; the crosshead speed was set at 0.102 mm/min. Iosipescu tests were made on two types of LCAs, SIRCA 15F and PICA, in their virgin and charred states. To produce the charred materials, specimens were pyrolyzed in a tube furnace, in an argon environment, at 1000ºC for 10 minutes. Two modes of loading were employed (as illustrated in Fig. 2): (a) specimens were oriented with their preferred plane normal to the applied load, and normal to the notched cross-section (transverse loading), and (b) the preferred plane was parallel to the applied load, and parallel to the notched cross-section (parallel loading).

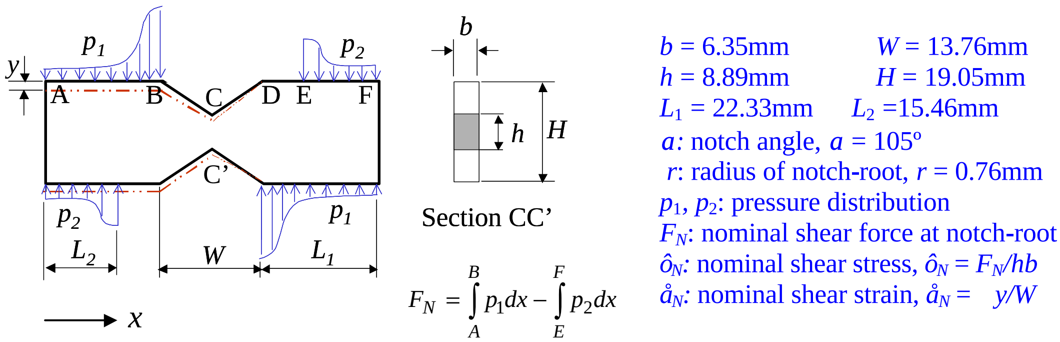
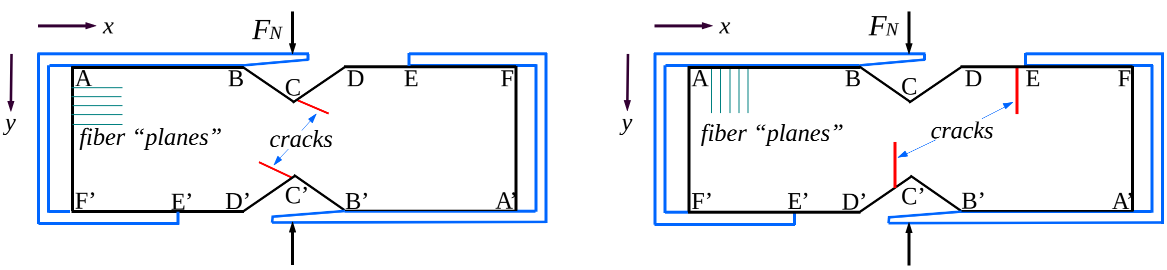


Figure 1: Boundary conditions and dimensions of Iosipescu specimen in A&W fixture

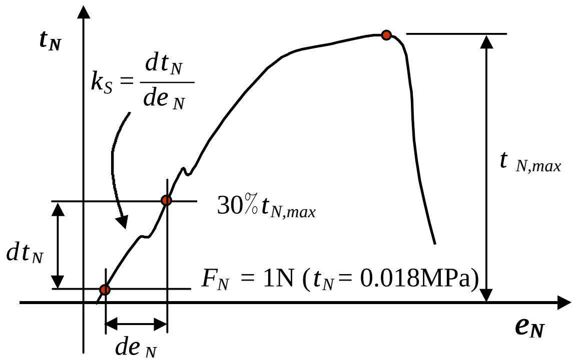
Figure 2 illustrates the predominant experimentally observed fracture patterns. Under transverse loading, cracks form at the surface, near top and bottom notch tips, at angles between 45º and 90º to the notch-root axis. This pattern was observed for virtually all of the transverse specimens, and is indicative of tensile failure. Under parallel loading, vertical cracks form at the surface at locations that are just to the left of surface points *E* and C'; the analyses presented in the next section suggest that these are locations of peak tensile stress. (The inverse scenario also occurred in which the cracks formed just to the right of surface points *E'* and *C*.)



(a) Transverse loading **(b)** Parallel loading

Figure 2: Illustration of fracture patterns during Iosipescu testing of LCA specimens

Values of nominal maximum shear stress, $t_{N,max}$, and "nominal shear modulus," k_s, were determined experimentally, as indicated in Fig. 3. The values of $t_{N,max}$, for each test series, are listed in Table 1. Numerical values following +/- signs are standard deviations. Generally, the $t_{N,max}$ values are comparable for virgin and charred specimens, and are about 100% greater in the transverse than in the parallel mode; charred SIRCA in parallel loading is an exception.



Material	Mode	k_s [MPa]
Virgin SIRCA	Transverse	12.3 +/- 3.5
Virgin SIRCA	Parallel	4.9 +/- 1.2
Charred SIRCA	Transverse	24.8 +/- 8.6
Charred SIRCA	Parallel	12.2 +/- 3.8
Virgin PICA	Transverse	6.3 +/- 1.2
Virgin PICA	Parallel	4.8 +/- 1.2
Charred PICA	Transverse	15.7 +/- 5.1
Charred PICA	Parallel	7.3 +/- 2.0

Figure 3: Illustration of Iosipescu Test Response and Determination of k_s

TABLE 1

MAXIMUM NOMINAL SHEAR STRESS $t_{N,max}$ DURING IOSIPESCU TESTING

Material	Density	Parallel Loading		Transverse Loading	
	[kg/m^3]	No. of Tests	$t_{N,max}$ [MPa]	No. of Tests	$t_{N,max}$ [MPa]
Virgin SIRCA	240	9	0.39 +/- 0.05	9	0.80 +/- 0.04
Charred SIRCA	250	10	0.57 +/- 0.08	12	0.78 +/- 0.16
Virgin PICA	210	8	0.15 +/- 0.03	10	0.37 +/- 0.03
Charred PICA	190	9	0.17 +/- 0.03	10	0.38 +/- 0.05

FINITE ELEMENT ANALYSIS OF IOSIPESCU TESTS

In this section, we show that a relatively simple, anisotropic, linear elastic, model provides good qualitative understanding of the experimentally observed failure modes. In the analyses, the elastic properties of the model will be associated with two types of composites. In Type I, the fibers are unidirectional, and in Type II, the fibers are randomly and uniformly aligned parallel to a preferred plane. At this time, Iosipescu modeling of Type I is complete and is discussed here; modeling of Type II is in progress. For Iosipescu testing of both types of composites, under transverse loading, the load is normal to the fibers' axes and, under parallel loading, the composites may be envisioned as parallel planes of fibers that are parallel to the load; thus qualitative similarities may be expected among FEA results for both types. The FEA used an ANSYS meshed model, with geometric parameters shown in Fig. 1. The element library type is PLANE STRESS (quadrilateral, 8 nodes), the sizes of the elements and nodes are 1694 and 5377, respectively. The minimum side length of subdivided elements is 10.5% of the notch-root radius r, and the maximum length is 14.3% of the notched cross-section h. The computations employed a "standard" downward stroke, Δy = 0.1mm, of the left fixture, while the right fixture was fixed. For the CONTACT model, a friction coefficient of 0.25 was assumed. For the Type I composites, if the fibers are aligned in the "1-direction," the 2-3 plane is the plane of isotropy, and there are five independent compliances: S_{11}, $S_{22} = S_{33}$, $S_{12} = S_{13}$, S_{23}, and $S_{55} = S_{66}$ (with $S_{44}/2 = S_{22} - S_{23}$) [4]. For modeling purposes, we take $S_{11} = 1/E_P$ and $S_{22} = 1/E_T$, where E_P and E_T are the experimental Young moduli of the LCAs under uniaxial loads, parallel and transverse, respectively, to the preferred plane [5]. Further simplifying assumptions are that the compliances S_{44} and S_{55} are equal and the Poisson ratios $í_{12} = í_{23} = 0.46$. With these assumptions and the known values of E_P and E_T, the remaining compliances are calculated from $S_{12} = -í_{12}/E_P$, $S_{23} = -í_{23}/E_T$, and $S_{44} = 2(S_{22} - S_{23}) = S_{55}$. The experimental values of E_P and E_T are listed in Table 2; the values of both moduli, E_P and E_T, were found to depend on whether the uniaxial load was tensile or compressive. FEA was carried out using both tensile and compressive values of E_P and E_T. As a check on the suitability of the modeling approximations, the nominal shear modulus k_s was calculated in the analyses and compared with the experimental values of k_s. There was generally good agreement between these quantities, with the calculated values tending to be somewhat greater than the corresponding experimental values when the tensile values of E_P and E_T were used in the FEA and vice versa when the compressive values of E_P and E_T were used; i.e., the experimental response was intermediate to the FEA responses computed with the tensile and compressive Young moduli (suggesting an "averaging" effect of the moduli in the Iosipescu experiments).

TABLE 2

EXPERIMENTAL VALUES OF YOUNG'S MODULUS USED IN THE FEA

Material	Under Uniaxial Tension		Under Uniaxial Compression	
	E_P [MPa]	E_T [MPa]	E_P [MPa]	E_T [MPa]
Virgin SIRCA	380	67	130	34
Charred SIRCA	630	170	138	89
Virgin PICA	N/A	N/A	143	12
Charred PICA	N/A	N/A	107	33

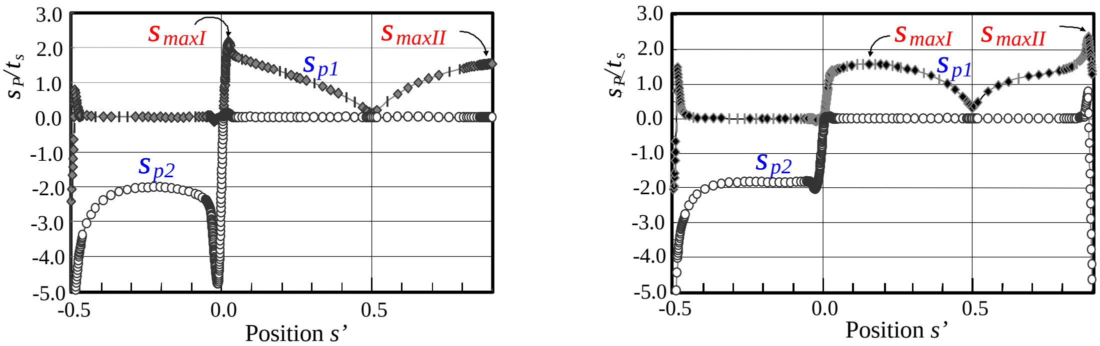
Earlier studies [6,7] have analyzed the shear stress in the notched cross-section for various composite materials. However, comparisons among the experimental failure modes and the normal stress contours calculated in the present work indicate that the LCA specimens fail in a tensile mode. Therefore, in addition to calculating the shear stress distribution along the notched cross-section *CC'*, we have focused on the principal stress distributions on the surface of the specimens. Since the FEA employs PLANE STRESS, the normal stress in the *z* direction, which is a principal stress, is always zero. The other two ordered principal stresses in the *xy* plane are $ó_{p1}$ and $ó_{p2}$. The maximum shear stress, $t_p = (ó_{p1} - ó_{p2})/2 \equiv t_p(y')$, was determined along the cross-section *CC'* (where $y' \equiv 0$ half-way between *C* and *C'* and $y' = +0.5$ and -0.5, respectively, at the notch-roots *C* and *C'*). In accord with earlier work [6,7] we found that $t_p(y')$ increases as $y' \rightarrow \pm 0.5$ under transverse loading and it decreases as $y' \rightarrow \pm 0.5$ in parallel loading. In transverse loading, t_p also exhibited a local maximum, t_{max}, at $y' = y'_{max}$. The normalized values of t_{max} and their locations are listed in Table 3 ($t_s \equiv t_N$ in the "standard" FEA, i.e., with $\Delta y = 0.1$mm); the maximum shear stress was observed to obey the relation $t_{max}/t_s \approx 0.028(E_P/E_T) + 1.05$, where $1.55 < E_P/E_T < 11.92$.

TABLE 3

NORMALIZED MAXIMUM SHEAR STRESSES $t_{max}/ô_s$ AND THEIR LOCATIONS y'_{max} IN FEA TRANSVERSE IOSIPESCU MODEL

Material	Modeling Parameters		E_P/E_T	$t_{max}/ô_s$	y'_{max}
	E_P [MPa]	E_T [MPa]			
Virgin SIRCA	380	67	5.67	1.211	0.469
Charred SIRCA	630	170	3.71	1.160	0.450
Virgin SIRCA	130	34	3.82	1.163	0.449
Charred SIRCA	138	89	1.55	1.088	0.419
Virgin PICA	143	12	11.92	1.385	0.487
Charred PICA	107	33	3.24	1.139	0.449

The Iosipescu principal stress distributions were investigated under parallel and transverse loading, using both the compressive and the tensile values of E_P and E_T of SIRCA and using the compressive moduli of PICA in the FEA. Attention was focused on the region along surface *BCDE*, since that is where cracking was observed in the experiments. Figure 4 shows a representative example of the normalized, ordered, principal stresses $ó_{p1}/t_s$ and $ó_{p2}/t_s$ along *BCDE*, for transverse and parallel Iosipescu tests. The compressive values of E_P and E_T of virgin SIRCA were used in the calculations of Fig. 4. The position on the surface *s'* is normalized by $2L_{CD}$ (twice the length of *CD*), so that *s'* = -0.5, 0, 0.5, and 0.9, respectively, correspond to positions at *B*, *C*, *D*, and *E* (*s'* = 0 is at the notch-root). During transverse loading (Fig. 4a), the tensile stress $ó_{p1}$ is highly concentrated in the neighborhood of the notch-root, where it reaches a peak value of $ó_{maxI}$ at $s' = s'_{maxI}$, while the compressive stress $ó_{p2}$ is concentrated on the opposite side of the notch-root; $ó_{p1}$ also reaches a secondary maximum $ó_{maxII}$ at *s'* = 0.900, which is at position E. The stress concentration at the notch-root explains why fracture occurs in a tensile mode near the notch tips during transverse loading (Fig. 2a). During parallel loading (Fig. 4b) $ó_{p1}$ is not peaked near the notch-root, but has a broad local maximum $ó_{maxI}$ at s'_{maxI} in the region between *C* and *D*; in this mode, $ó_{p1}$ also reaches a peak value, $ó_{maxII}$, at *s'* = 0.888 which is close to *E*. These results are consistent with fracture patterns observed under parallel loading (Fig. 2b). Normalized tensile stress maxima, $ó_{maxI}/t_s$ and $ó_{maxII}/t_s$, and the locations of $ó_{maxI}$ are listed in Table 4 for all of the materials and modeling conditions. During transverse loading, position s_{maxI} is at a distance of roughly 5% of L_{CD} from the notch-root, and in parallel loading it is at a distance of about 30% of L_{CD}. It was also found that the maximum stresses in the region *CD* of the notch could be expressed as $ó_{maxI}/t_s = 0.459\ln(E_P/E_T) + 1.530$, where $1.55 < E_P/E_T < 11.92$, in the Iosipescu modeling under transverse loading, and $ó_{maxI}/t_s = 0.0426\ln(E_P/E_T) + 1.638$, where $3.24 < E_P/E_T < 11.92$, in the parallel loading models.



(a) Transverse loading **(b)** Parallel loading

Figure 4: Principal stress distribution on the surface *BCDE* of the Iosipescu specimen

TABLE 4

NORMALIZED MAXIMUM TENSILE STRESSES $ó_{maxI}$ AND $ó_{maxII}$ AND LOCATION s'_{maxI} OF $ó_{maxI}$

Material	Moduli [MPa]		Iosipescu Mode	$ó_{max}/\hat{o}_s$	s'_{maxI}	$ó_{maxII}/\hat{o}_s$
	E_P	E_T				
Virgin SIRCA	380	67	Transverse	2.344	0.024	1.691
Virgin SIRCA	130	34	Transverse	2.171	0.024	1.544
Charred SIRCA	630	170	Transverse	2.146	0.024	1.529
Charred SIRCA	138	89	Transverse	1.694	0.029	1.297
Virgin PICA	143	12	Transverse	2.633	0.024	2.072
Charred PICA	107	33	Transverse	2.082	0.024	1.485
Virgin SIRCA	380	67	Parallel	1.558	0.162	2.195
Virgin SIRCA	130	34	Parallel	1.584	0.149	2.394
Charred SIRCA	630	170	Parallel	1.584	0.147	2.367
Charred SIRCA	138	89	Parallel	1.531	0.117	1.633
Virgin PICA	143	12	Parallel	1.535	0.176	1.913
Charred PICA	107	33	Parallel	1.588	0.147	2.274

CONCLUSIONS

Iosipescu shear tests were conducted on composite LCA materials, under parallel and transverse loading conditions, and the experiments were modeled with anisotropic, linear elastic, FEA. The maximum nominal shear stress was measured, although the observed fracture patterns and FEA results indicated that the materials failed in a tensile mode rather than by shearing. The maximum values of principal stress in FEA occurred in regions where fracturing was observed in the experiments. The shear stress distribution along the notched cross-section was also computed.

ACKNOWLEDGEMENTS

NASA Ames Grant #NCC2-1049 provided financial support for this work. S. Nagasawa was an Overseas Research Scholar of the Japan Ministry of Education, Science and Culture, on leave from Nagaoka University of Technology. Support from K. Fields, C. Johnson, H. Tran, and D. Rasky is gratefully acknowledged.

REFERENCES

1. Tran, H.K. (1994). NASA TM 108798.
2. Iosipescu, N. (1963). *Rev. Mec. Appl.* 1, 147.
3. Adams, D.F. and Walrath, D.E. (1986). *Experimental Mechanics*. 27(2), 113.
4. Daniel, I.M. and Ishai, O. (1994). *Eng. Mechanics of Composite Materials.* Oxford Univ. Press.
5. Parmenter, K.E., Shuman, K., Milstein, F., Johnson, C.E., Tran, H.K. and Rasky, D.J. (2001). *Journal of Spacecraft and Rockets*. 38(2), in press.
6. Adams, D.F. and Walrath, D.E. (1987). *Journal of Composite Materials*. 21, 494.
7. Chiang, Y.J. (1996). *Journal of Testing and Evaluation, ASTM*. 24(1), 1.