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Procedia Engineering 67 (2013) 517 – 524
Procedia Engineering
www.elsevier.com/locate/procedia

7th Asian-Pacific Conference on Aerospace Technology and Science, 7th APCATS 2013

Stress State Analysis of Iosipescu Shear Specimens for Aerogel Composite with Different Properties in Tension and Compression

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Abstract

The objective of present research is to establish guidelines for preparing shear tests of ceramic-fiber-reinforced aerogel. The aerogel composite prepared by Sol-gel methods exhibits bi-modulus properties under tension and compression loadings. Bi-modulus constitutive model of the aerogel composite was built, and then verified by analysis of bending test. Finite element analysis (FEA) was presented on Iosipescu specimens with different V-notch and Round-notch configurations. Several trends have become evident: stress state of bi-modulus aerogel is different from that of isotropic material; stress concentration is a strong function of V-notch tip radius, and increasing V-notch tip radius can effectively reduce normal stress concentration at notch tips; shear stress distribution in the test region can be modified by varying notch angle when V-notch tip radius$\leqslant$1.3mm; increasing the Round-notch radius can also effectively reduce the normal stress concentration at notch tips. Based on these observations, Round-notch specimen seems to be a favorable choice for reducing the normal stress concentration at notch tips, especially the longitudinal tensile stress concentration. Round-notch specimen with r=4mm is favorable for the uniformly distributed shear stress in the test region. Digital image correlation (DIC) was suggested for shear strain measuring.

Keywords:
Thermal protection system, ceramic-fiber-reinforced aerogel, Iospescu shear test, finite element analysis, notch, digital image correlation.

1. Introduction

Aerogel comprised of nano-sized (1-100nm) particles linking as the open-cell framework is prepared by sol-gel method and special drying technology. Since its first preparation by Kislter [1] in 1931, it has been applied in various fields because of its fantastic properties. Among all potential applications, the field of thermal insulation is the most significant [2].

For load-bearing insulation, shear properties should be investigated. The major problem for shear test design is the influence of stress components other than shear stress on the final measurements [3]. There is a variety of shear test methods for introducing shear stress in materials. One of the most commonly used shear tests described in ASTM D 5379 [4] is the notch shear test, which was first suggested by Iosipescu [5]. Experimental and analytical researches have been extensively conducted on applying Iosipescu test to orthotropic composites [6-7].

doi:10.1016/j.proeng.2013.12.052

Research had shown that the stress state in the test region greatly depends on the tested material properties [8-9]. No research has been conducted to understand the stress state in the test region of bi-modular material, so there is a great challenge to develop this test method in measuring the shear properties of bi-modulus material.

However, most materials exhibit different tensile and compressive modulus [10]. Experiments also showed that the aerogel was also one of such materials exhibiting bi-modulus [4]. Iosipescu test has been applied to shear properties test of fiber-reinforced silica aerogel [11]. Shear strength, equal to approximately 0.1 MPa, was obtained. The experiential results showed that some specimens did not fail in shear mode but in tension mode. That indicates that for shear test of aerogel composite, the Iosipescu method should be well designed to reduce normal stress concentration at/near notch tips.

The goal of present research is to analytically model the stress state within Iosipescu shear test specimen for bi-modulus material. Once the stress state is understood, the specimen could be modified.

2. Constitutive model of bi-modulus material

2.1. Bi-modulus theory

Ambartsumyan [12] linearized the bi-modulus materials model by two straight lines whose tangents at the origin are discontinuous. The constitutive relation built on the principal direction is written as:

$$\{\varepsilon_I\} = [\alpha]\{\sigma_I\}, \quad \{\sigma_I\} = [D]\{\varepsilon_I\}, \quad [D] = [a]^{-1} \tag{1}$$

where, $\{\varepsilon_I\}$ is the principal strain, $\{\sigma_I\}$ is the principal stress, $[a]$ is a matrix of flexibility coefficients determined by the signs of the principal stresses, and $[D]$ is the elasticity matrix in the principal direction.

In a plane problem, the principal stress $\{\sigma_I\}$ and strain $\{\varepsilon_I\}$ may be written as:

$$\{\sigma_I\} = \{\sigma_\alpha \quad \sigma_\beta \quad \tau_{\alpha\beta}\}^T, \ \{\varepsilon_I\} = \{\varepsilon_\alpha \quad \varepsilon_\beta \quad \varepsilon_{\alpha\beta}\}^T \tag{2}$$

where, $\tau_{\alpha\beta} = \varepsilon_{\alpha\beta} = 0$. In present paper, we assume that $\sigma_\alpha \geq \sigma_\beta$.

According to the signs of principle stresses, 3 different conditions should be concerned for the element determination of $[a]$ and $[D]$:

1) For $\sigma_\alpha \geq 0$ and $\sigma_\beta \geq 0$, the constitutive model in the principal direction is:

$$\begin{Bmatrix} \varepsilon_\alpha \\ \varepsilon_\beta \\ \varepsilon_{\alpha\beta} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E^+} & -\frac{\mu^+}{E^+} & 0 \\ -\frac{\mu^+}{E^+} & \frac{1}{E^+} & 0 \\ 0 & 0 & \frac{2(1+\mu^+)}{E^+} \end{bmatrix} \begin{Bmatrix} \sigma_\alpha \\ \sigma_\beta \\ \tau_{\alpha\beta} \end{Bmatrix} \tag{3}$$

2) For $\sigma_\alpha < 0$ and $\sigma_\beta < 0$, the constitutive model in the principal direction is:

$$\begin{Bmatrix} \varepsilon_{\alpha} \\ \varepsilon_{\beta} \\ \varepsilon_{\alpha\beta} \end{Bmatrix} = \begin{bmatrix} \dfrac{1}{E^-} & -\dfrac{\mu^-}{E^-} & 0 \\ -\dfrac{\mu^-}{E^-} & \dfrac{1}{E^-} & 0 \\ 0 & 0 & \dfrac{2(1+\mu^-)}{E^-} \end{bmatrix} \begin{Bmatrix} \sigma_{\alpha} \\ \sigma_{\beta} \\ \tau_{\alpha\beta} \end{Bmatrix} \tag{4}$$

3) For $\sigma_\alpha > 0$ and $\sigma_\beta < 0$, the constitutive model in the principal direction is:

$$\begin{Bmatrix} \varepsilon_{\alpha} \\ \varepsilon_{\beta} \\ \varepsilon_{\alpha\beta} \end{Bmatrix} = \begin{bmatrix} \dfrac{1}{E^+} & -\dfrac{\mu^-}{E^-} & 0 \\ -\dfrac{\mu^+}{E^+} & \dfrac{1}{E^-} & 0 \\ 0 & 0 & \dfrac{2(1+\mu^+)E^-\sigma_\alpha - 2(1+\mu^-)E^+\sigma_\beta}{E^+E^-(\sigma_\alpha - \sigma_\beta)} \end{bmatrix} \begin{Bmatrix} \sigma_{\alpha} \\ \sigma_{\beta} \\ \tau_{\alpha\beta} \end{Bmatrix} \tag{5}$$

The elasticity matrix mapped onto general coordinates may be written as:

$$\left[\bar{D}\right] = [L]^T [D][L] \tag{6}$$

where, [L] is the conversion matrix.

In present paper, iterative technology is used for numerical analysis of bi-modulus problem based on FEA. Because the stress state of the point in question is unknown in advance, we have to begin with a single modulus problem to gain the initial stress state for forming a corresponding elasticity matrix for each element. Based on the elasticity matrix formed in previous step, new analysis is conducted until the convergence criterion is fulfilled.

The convergence criterion is defined as follow:

$$\left| \frac{U_{\max}^{I+1} - U_{\max}^{I}}{U_{\max}^{I}} \right| \le \lambda_0 \tag{7}$$

where, U^I_{max} is the maximum displacement of the iteration number I, U^{I+1}_{max} is the maximum displacement of the iteration number $I+1$ and λ_0 is the maximum relative displacement error allowed. In present paper λ_0 is set as 5×10^{-5}.

2.2. Verification of bi-modulus theory as applied to aerogel

Aerogel composite was prepared by Sol-gel methods and supercritical drying, of which tension, compression and bending tests have been conducted. The tension and compression modulus derived from tests are 97.8 and 56 MPa respectively. A schematic model of the bending test is shown in Fig.1, showing the physical size of sample and boundary condition used in FEA. Bending load-displacement curve was obtained from bending test as shown in Fig.2.

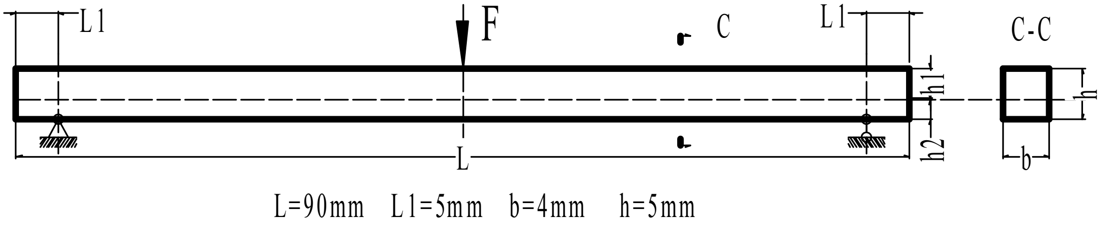


Fig.1. Schematic model of the three point bending test.

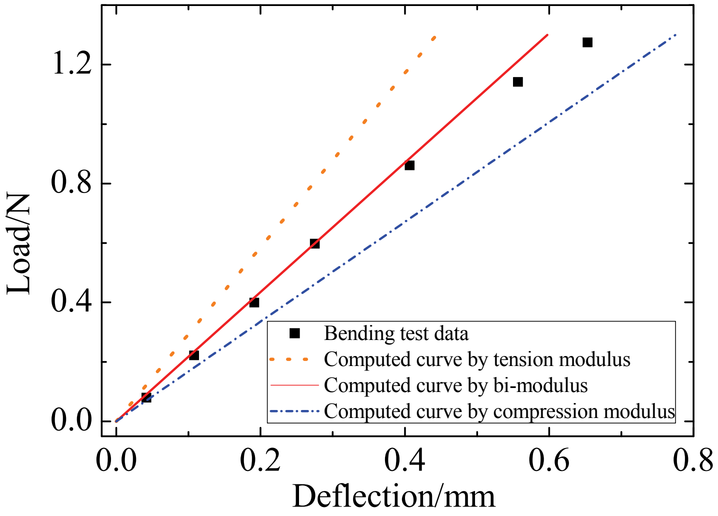


Fig.2. Load-deflection curves of the bending analysis.

To verify the bi-modulus constitutive model, bending test was simulated by FEA model with bi-modulus theory. Two-dimensional model was built by FEA software ABAQUS consisting of 1800 Eight-Node Quadrilateral Elements (CPS8R). Convergence study has been conducted for the element grid size, and geometric nonlinearity was also included in the simulation.

As shown in Fig.2, the curve computed with bi-modulus fits well with the test data except at larger loads. That is because of the appearance of nonlinearity in experiments.

3. Stress state analysis of Iosipescu specimen as applied to bi-modulus aerogel

3.1. Model description

Two-dimensional model of Iosipescu specimen was built by FEA Software ABAQUS. Bi-modulus constitutional model and iterative technology were adopted. Loading was applied by prescribing displacement boundary conditions as can be seen in Fig.3.

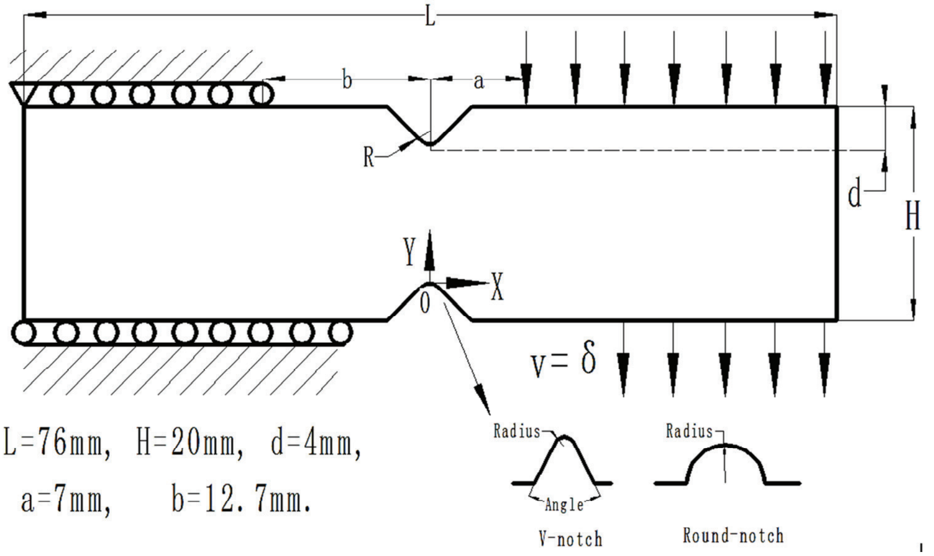


Fig.3. Boundary conditions used in modeling the Iosipescu shear specimen.

The major region of interest is the notch region. Consequently, specimen configuration variations are related to notch geometry. Effects of different notch types, notch angles and tip radii are studied. Matrix of possible computer runs is presented in Table 1.

Table.1. Iosipescu shear specimen analysis variations

Notch type	Property	Variation considered				
V-Notch	V-Notch angel / degree	50		90		110
	V-Notch radius / mm	0		1.3		4
Round-Notch	Round-Notch radius / mm	1.3	2.5	4	6	7

3.2. Analysis of different specimen configurations

The ideal shear testing of a material means loading which produces in the test section only shear stresses, without normal stresses of any kind, until breaking of the specimen occurs. Both experimental and analytical results have shown that this ideal situation can hardly happens. The objective of present research is to determine how closely the Iosipescu test would meet the requirement of ideal shear test and whether we can obtain a more favourable stress state by varying specimen geometries.

We use the following parameters as the basis for making comparisons for different specimen configurations: uniformity of shear stress distribution at center of the test section, magnitudes of normal stresses at center of the test section, and magnitudes of the stress concentrations at the notch tips.

3.2.1. Uniformity of shear stress distribution at center of the test section

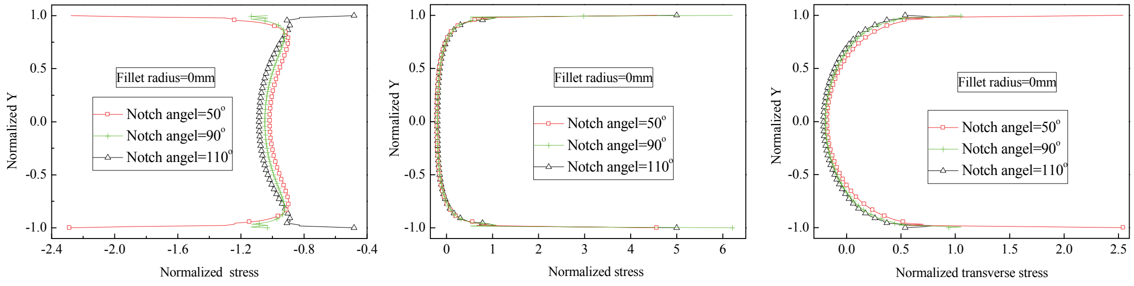
The normal and shear stress, normalized with respect to the average shear stress across the test section, are shown in Fig.4-7 for specimen with sharp V-notch, V-notch with 1.3mm fillet, V-notch with 4mm fillet and Round-notch respectively.

As can be seen, for all cases analyzed, the shear stress is fairly uniformly distributed, and close to the average applied shear stress throughout entire test section except near the notch tips.

The shear stress magnitudes of the test section center increase with increasing V-notch angle, as shown in Fig.4a, Fig.5a and Fig.6a.

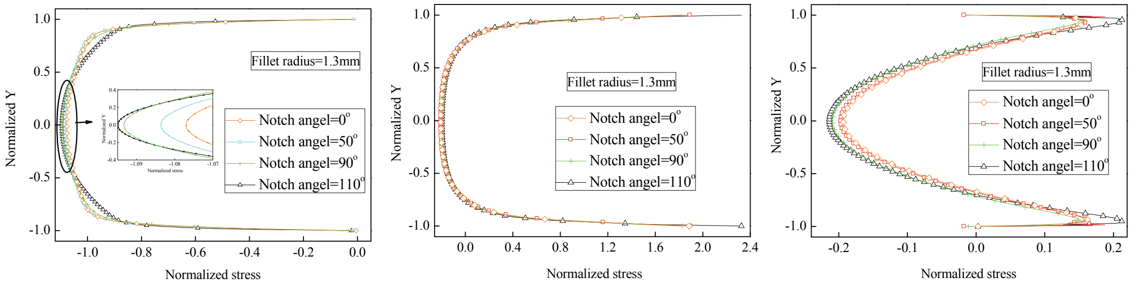
General trend to increase the shear stress magnitudes at the specimen center is found with increasing fillet radii.

The Round-notch specimen with r=4mm performs the most uniform shear stress comparing with specimen with r= 1.3, 2.5, 6, 7mm, as shown in Fig.7.



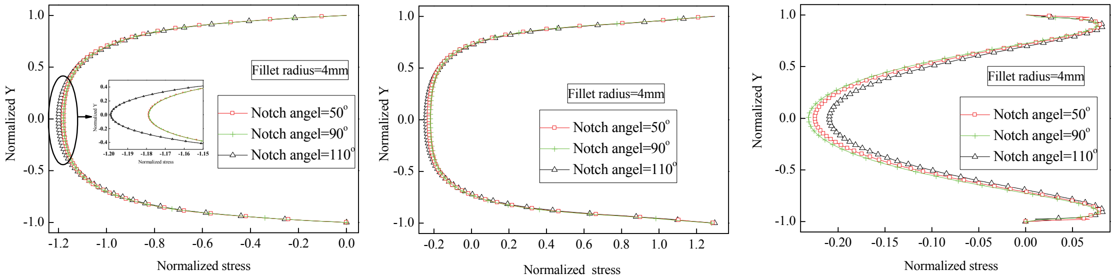
(a) Normalized shear stress (b) Normalized longitudinal stress (c) Normalized transverse stress

Fig.4. Stress distribution between notch tips of the sharp V-notch.



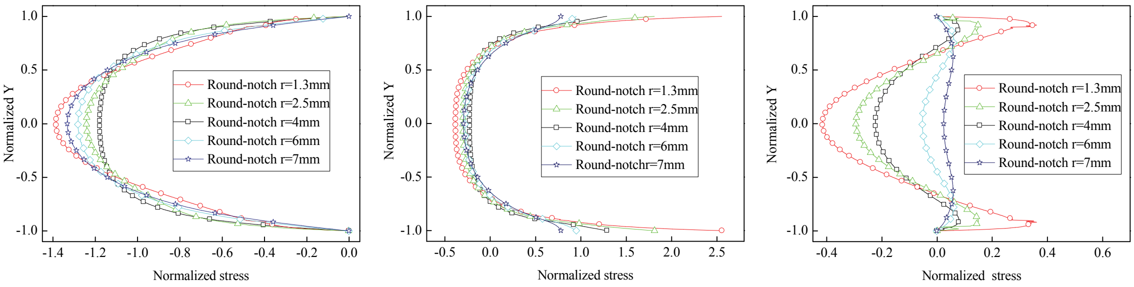
(a) Normalized shear stress (b) Normalized longitudinal stress (c) Normalized transverse stress

Fig.5. Stress distribution between notch tips of V-notch with 1.3 mm fillet.



(a) Normalized shear stress (b) Normalized longitudinal stress (c) Normalized transverse stress

Fig.6. Stress distribution between notch tips of V-notch with 4 mm fillet.



(a) Normalized shear stress (b) Normalized longitudinal stress (c) Normalized transverse stress

Fig.7. Stress distribution between Round-notch tips.

3.2.2. Magnitudes of normal stresses at center of the test section

Undesirable longitudinal (X direction) and transverse (Y direction) compressive stresses are present at the center of the test section, which can be seen from Fig.4 to Fig.7.

The longitudinal stresses changed slightly with V-notch angle and Round-notch radius. But the transverse stress is a function of the V-notch angle and Round-notch radius. Increasing V-notch angle Round-notch radius will decrease the transverse compressive stresses at specimen center.

3.2.3. Stress concentration at notch tips

Localized shear and normal stress concentrations are predicted to be present at notch roots or a small distance away from roots. These stress concentrations give an indication that premature failure might occur. Consequently, one objective of present analytical study is to minimize the stress concentration.

As can be seen in Fig.4a, higher notch angles tend to reduce the shear stress concentration of V-notch specimen. While the V-notch tip radius ⩾1.3mm, there seems to be no shear stress concentration at notch tips, as can be seen from Fig.5a and Fig.6a.

The larger notch tip radii can also reduce the stress concentration at or near notch tips as can be seen in Fig.4, Fig.5 and Fig.6. From the point of decreasing stress concentration at notch tips, larger notch tip radius should be designed for shear test.

As shown in Fig.7, increasing the Round-notch radius can also effectively reduce the longitudinal stress concentration at notch tips.

3.3. Optimum specimen configuration

Based on the above observations, we can conclude that the Iosipecu test can be used for the shear testing of the bi-modular aerogel composite when notch parameters are correctly chosen. The main concern, as shown in experiential result [11], is that the normal stress concentration near notch tips is significant. As shown in Fig.4, the longitudinal tensile stress at notch tips of the sharp V-notch specimen is relatively large. Hence, shear test using this specimen might fail by tension as former experiments showed.

To reduce the normal stress concentration at notch tips, especially the longitudinal tensile stress concentration, Round-notch specimen seems to be a favorable choice for shear test. The lager notch tips tend to reduce normal stress concentration. From this point of view, lager notch radius should be chosen.

But as can be seen in Fig.7a, increasing notch radius from 4 to 7 mm will change the relatively uniform distributed shear stress to a more parabolic state. Decreasing notch radius from 4 to 1.3 mm also change the relatively uniform distributed shear stress to a more parabolic state. To obtain a more uniform shear stress state, the round notch radius 4 mm might be chosen.

3.4. Strain measuring

It is suggested in ASTM shear standard [4] that the shear strain of Iosipescu specimen can be measured by placing two strain gage elements in the middle of the specimen oriented at ±45° to the loading axis. But the contact measuring method is not so good for the 'soft' aerogel composite. In addition, if a shear modulus were calculated from the experimentally measured shear strain by strain gages, erroneous results would be obtained [13].

DIC is an optical-numerical full-field surface displacement measurement method [14]. It is based on a comparison between two images of a specimen coated by a random speckled pattern in the undeformed and in the deformed states. Its special merits encompass non-contact measurements, simple optic setups, no special preparation of specimens and no special illumination.

Using DIC method, we can obtain full-field strain state between notch tips during Iosipescu shear test. Hence the average shear strain can be easily calculated. Then the shear modulus can be calculated from the average shear strain and average shear stress (the applied force divided by the net section area). In addition, using the DIC method we can also obtain normal stress distribution in the test section, which can help us to analyze whether the fracture specimen is in shear model.

4. Conclusion

FEA analysis was presented on Iosipescu specimens with different V-notch and Round-notch configurations. Several trends have become evident for designing shear test for the aerogel composite with bi-modular properties. Based on these observations, Round-notch specimen is selected. DIC method was suggested for shear strain measuring.

Acknowledgements

The research was supported by National Natural Science Foundation of China (Grant NO. NSFC 51275023) and the Innovation Foundation of BUAA for PhD Graduates (Grant NO. YWF-12-RBYJ-007).

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