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FRACTURAL PROCESS AND TOUGHENING MECHANISM OF LAMINATED CERAMIC COMPOSITES ⋆⋆

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ABSTRACT Based on the model of multi-layer beam and the assumption of micro-inhomogeneity of material, the 3D fractural characteristics of laminated ceramic composites have been studied with numerical simulation. Under three-point bending load, crack initiation, coalescence, propagation, tuning off in the weak interface and final rupture have been simulated. The spatial distribution and evolution process of acoustic emission are also presented in the paper. The simulation verifies the primary mechanism of the weak interface inducing the crack to expand along there and absorbing the fractural energy. The disciplinary significance of the effect of strength and properties of material on the toughness and strength of laminated ceramic composites is, therefore, discussed in this paper.

KEY WORDS laminated ceramic composite, toughening, numerical simulation

I. INTRODUCTION

Ceramic composites are now widely applied in aeronautical and space engineering, metallurgy, civil engineering and automotive manufacturing due to the advantages such as high strength, high stiffness, good endurance of high temperature and corrosion, etc. However, the most critical obstructs on such applications is brittleness. How to strengthen and toughen the ceramic composite is a hot topic in recent years.

Soft layers are combined with ceramic's brittle structure, so the laminated ceramic composites could be treated as a bionic structure, similar to that of shelves and bones in nature. Traditionally, the approaches to improving toughness could be simply summarized as faults elimination. However, toughening mechanism of the laminated ceramic is different and particular. Since Clegg et al.[1] published their work in 'Nature', many studies have been carried out in material preparation, fractural characteristics, mechanical characteristics and toughening mechanism in this field[2–5].

In these studies, some researchers, like Chang[6] and Guo[7] tried to apply numerical methods to this field. Up to date, however, most of these studies were two-dimensional ones. If a three-dimensional

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model could be developed, the spatial distribution of crack initiation, coalescence, propagation, and thus a real fractural process in composite could be studied, which is of great importance and significance for understanding of the mechanism of the fractural process and toughening of composite ceramics.

II. NUMERICAL MODELING

Solid material is always heterogeneous because of the presence of micro-weakness or fault in meso-scale. Thus the heterogeneity of material is essential to model verification. Compared to the traditional numerical method, where laminated composite ceramic is usually treated as homogeneous material by many researchers, great improvement has been made with a code named RFPA^{3D} (3D Realistic Failure Process Analysis).

The ceramic matrix here is divided into cells of a hexahedron, and the heterogeneity of mechanical features is represented with a two parameters Weibull distribution. The probability distribution function can be described as follows:

$$f(\alpha) = \frac{m}{\alpha_0} \cdot \left(\frac{\alpha}{\alpha_0}\right)^{m-1} \cdot \mathrm{e}^{-(\alpha/\alpha_0)^m} \tag{1}$$

where α stands for mechanical characteristic parameters, such as Young's modulus, strength, the Poisson's ratio, etc. α_0 is the mean value of α, m is the shape factor of Weibull, defined as the homogeneity index of material.

The choice of a proper fracture criterion is crucial to cracking simulation. A Coulomb criterion[8] envelope with a tensile cut-off is adopted in this paper for brittle materials. The tensile failure will occur when the principal stress in an element is greater than its tensile strength, see formula (2). Meanwhile, to simulate the shear failure, the second valve criterion as formula (3) is also used.

$$\sigma_1 \geq \sigma_t \tag{2}$$

and/or

$$\frac{1+\sin\phi}{1-\sin\phi}\sigma_1 - \sigma_3 \geq \sigma_c \tag{3}$$

where ϕ is the frictional angle, σ_1 and σ_3 are the maximum and minimum principal stresses, respectively, σ_t and σ_c are the uniaxial tensile and compression strength of an element, respectively.

After a displacement vector is applied to the model, stress and deformation in each element are then computed. When the fracture criterion is met in an element, the element is considered to be weak or failed. The failed element has been applied a very low elastic modulus instead of being removed from the mesh. The stress and the deformation distribution throughout the model are adjusted instantaneously after each element ruptures in an equilibrium state. In the areas with increased stress due to stress redistribution, the stress may exceed the critical value so that further ruptures will occur. The process would be repeated until no more elements exceed the fracture criterion under the same load. Then, the calculation would move to the next step by a small increment and the procedure can be repeated until the whole specimen fractures.

In this calculation, the stress and strain can be obtained by introducing a damage factor D.

$$\varepsilon = \frac{\sigma}{E} = \frac{\sigma}{(1-D)E_0} \tag{4}$$

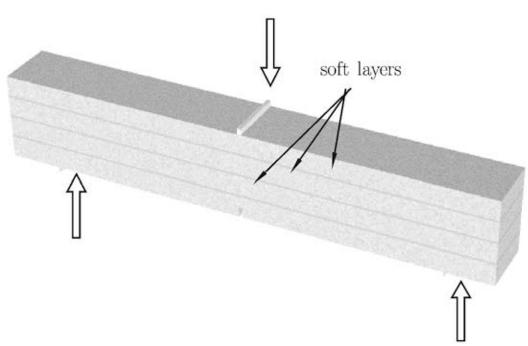


Fig. 1. Three-dimensional numerical model of laminated ceramic.

and/or

$$\sigma = E_0(1 - D)\varepsilon \tag{5}$$

where E_0 and E are Young's moduli for the initial stage and damaged stage, respectively.

For damage factor D, when no damage happens in the cell, $D = 0$, and when the cell is completely damaged, $D = 1$. Corresponding to a given damage status, D is in the range of 0 and 1, i.e. $0 < D < 1$.

The beam model under the three-point bending load adopted in this paper is presented in Fig.1. An ideal interface is applied between the soft and the hard layers to ignore the effect of the real interface. The beam with dimensions of $50 \times 250 \times 30$ mm comprises a total number of $50 \times 250 \times 30 = 375000$ cells. A notch with dimensions of $5 \times 2 \times 30$ mm is in the central bottom of the beam. For each soft and hard layer, the ratios to the thickness, Young's modulus, and the strength are $1:10$, $1:10$ and $1:8$, respectively. This calculation was completed on a parallel computer system.

III. THE FRACTURAL PROCESS AND TOUGHENING MECHANISM

The load-displacement curve of a laminated ceramic is presented in Fig.2, comparing a curve of a ceramic block. From the figure, the strength of the laminated ceramic is higher than that of the ceramic block. Simultaneously, the fractural work increases 122%. Here the fractural work K is defined as the area the load-displacement curve envelopes divided by the cross section of the beam[9]. An explanation of such a phenomenon can be obtained from the failure process of the specimen, which will be discussed in the following text.

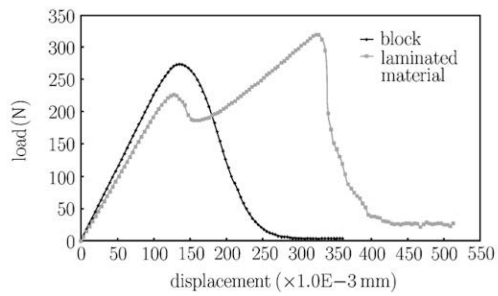


Fig. 2 Load-displacement curves of laminated ceramic.

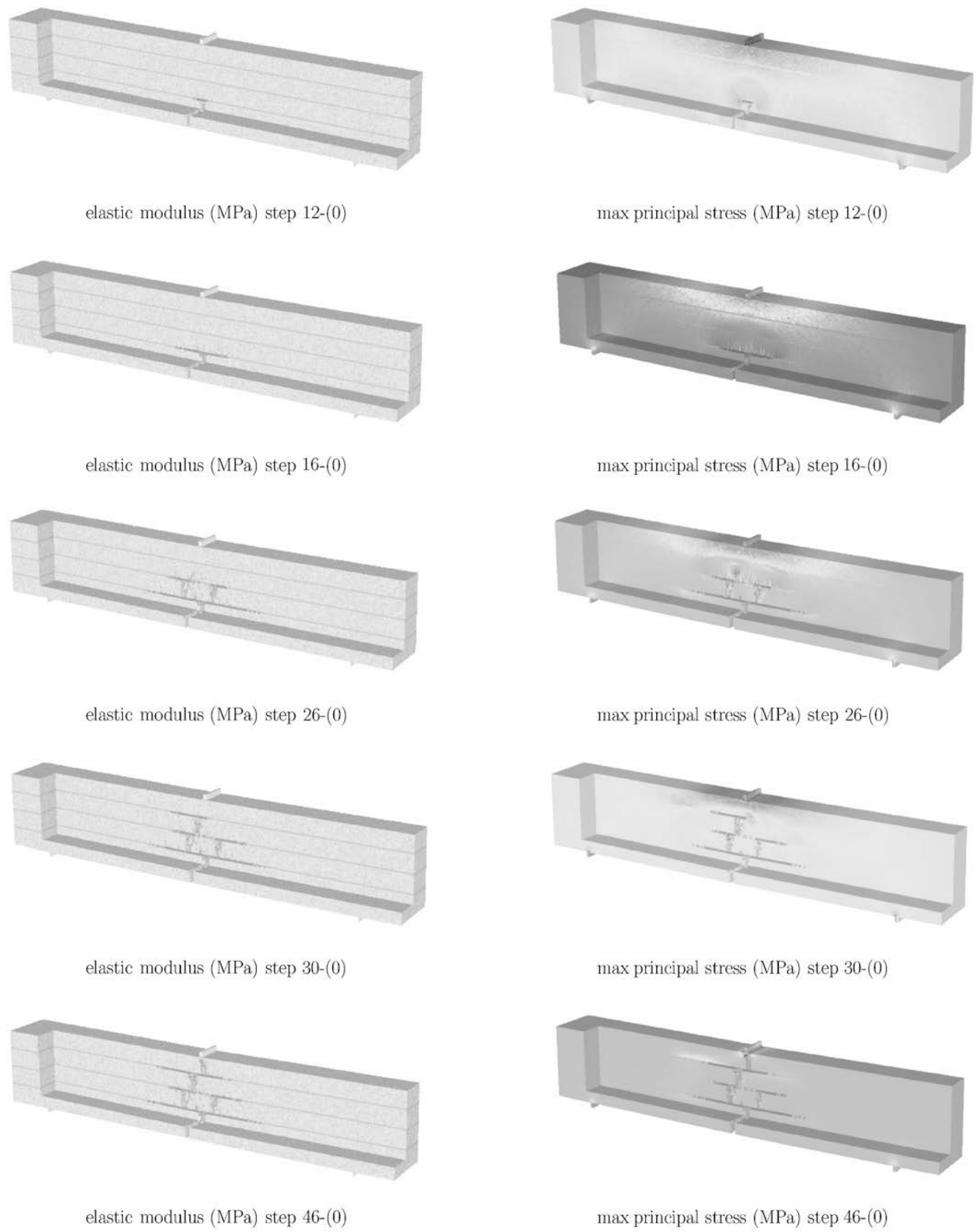
For a ceramic block, when load is applied, the maximum tensile stress zone first appears near the tip of the notch. The micro cracks will initiate near this tip due to the stress concentration. With an increase in the load, the crack will coalesce in this area and propagate upwards until the upper boundary of the beam is reached. Figure 2 also shows that for the block the curve has only one peak point which illustrates that the fracture is a one-off event; and the development of the crack is rapid while the residual stress is small.

The fractural process of laminated ceramic specimen is presented in Fig.3 through the images of modulus and maximum principal stress. From Fig.3(a), i.e. the modulus images, it can be found that the crack propagates upwards first and then deflects into the soft layer when the soft-hard interface is met. After that the crack develops horizontally within the soft layer. With the increase of the load, the crack turns back and develops vertically again. This procedure is repeated at each soft layer, so vertical and horizontal cracks appear alternately until the beam finally fractures. As a result, the fracture is no longer a rapid process but a layer by layer one.

Moreover, from Fig.3(b), the maximum principal stress images, the crack appears first near the tip of the notch due to stress concentration. Then the main crack develops upwards. When the first soft layer is met, a 3D stress field is changed to a 2D field[10,11]. A 'dummy plastic zone' appears near the tip of crack and a so-called passivation will release the stress concentration in this zone, as a result the vertical trend of the cracking is restrained and the crack develops horizontally. In this procedure, the soft layer acts as a shield.

After the crack traverses at a distance within the soft layer, some new vertical cracks appear with the increase of the load. As more energy is needed for this crack initiation, the strength of laminated ceramic is in general higher than that of the ceramic block. Figure 3 also illustrates that the crack is no longer a straight line but in a zigzag shape or a brick shape. This phenomenon is also observed in the description of a similar test by Guo[12]. The conclusion drawn in this section is also in agreement with the laboratory tests carried out by Cai[13] and Tan[14].

Images of acoustic emission (AE) for both block and laminated ceramic are presented in Fig.4, where a circle represents an AE event. The radius is directly proportional to the energy dissipated from the damaged cell. For the ceramic block, Fig.4(a) shows that most AE events are located in a narrow belt developing along the load direction, and almost no horizontal events present. This illustrates that cracks



(a) modulus (b) max principal stress

Fig. 3. Fractural processes of laminated model.

in this block do not propagate horizontally. On the other hand, from Fig.4(b), though most AE events occur along the vertical direction, more AE events could be found in the horizontal one. It is quite clear that most horizontal AE events are located within soft layers. In addition, the radii of AE events shown in Fig.4(a) do not change rapidly from the area near the bottom of the beam to the upper part. This shows that the energy dissipated from each cells in the fracture belt is almost at the same level. But it can be seen from Fig.4(b) that the energy dissipated from the vertical cracks is much greater than that in the horizontal direction. The same conclusion can also be obtained from Ref.[15] in the 2D condition.

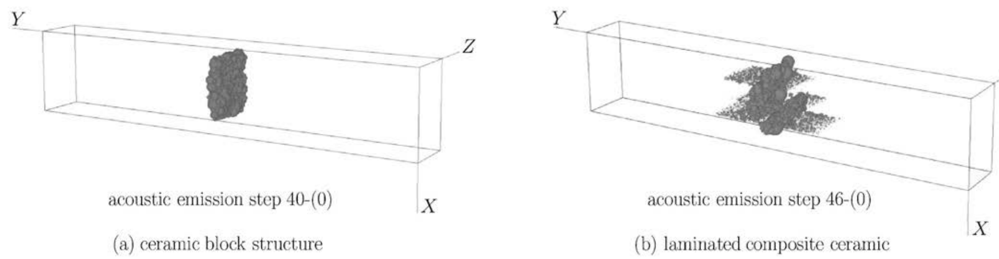


Fig. 4. Numerical simulation of AE in laminated model.

IV. THE EFFECT OF STRENGTH OF SOFT LAYERS

To investigate the effect of strength of soft layers using the same beam models presented in the previous section (Fig.1), numerical simulation on a group of eight specimens with different strengths of the soft layer has been conducted. The strength ratios of soft layers to hard layers are set to be 0.12, 0.16, 0.2, 0.24, 0.28, 0.32, 0.36 and 0.4 for each specimen, while other features remain unchanged.

The results of the simulation are presented in Fig.5, where the curves of fractural work K and the peak load versus strength ratio are plotted as Fig.5(a) and 5(b), respectively. From these figures, it is clear that the fractural work K and the peak load P decrease while the strength of the soft layers increases. In particular, when the strength ratio is in the range 0.24-0.28, both K and P decrease rapidly. This implies that if the strength of the soft layer is very high, the deflection and the softening of the crack tips can hardly happen. Meanwhile, if the strength of the soft layer is very low, it will not be advisable to improve the mechanical characteristics of the composite ceramic. In fact, a specimen with strength ratio of 0.08 is also tested, and it is found that all the fractures occur along the soft layer, so that no crack initiates or propagates vertically.

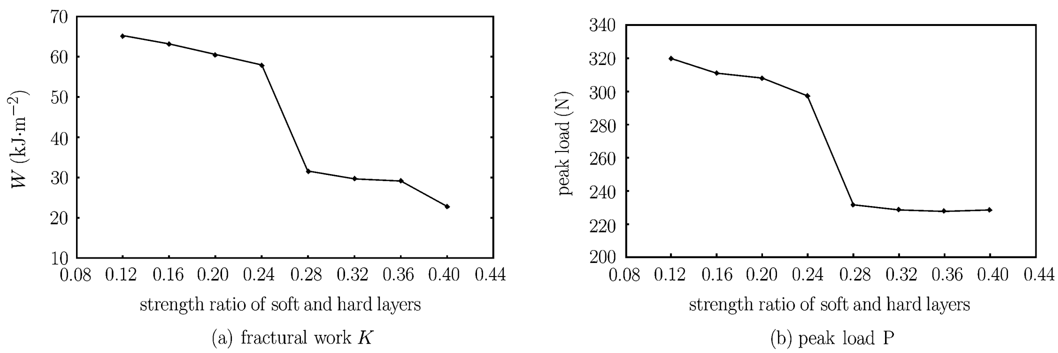
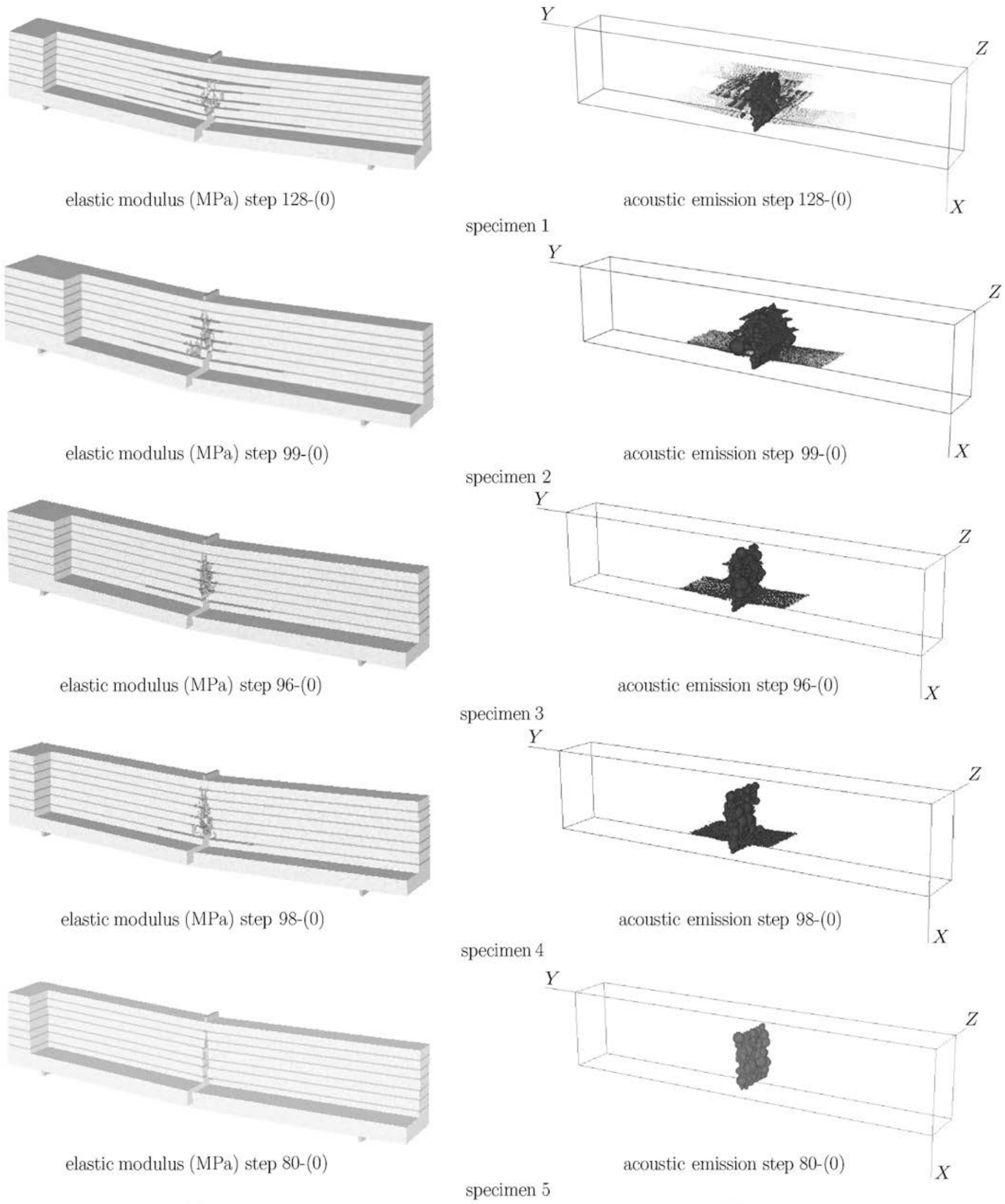


Fig. 5. Curves of fracture energy and peak load of the laminated models versus the strength of soft layer.

The explanation about this effect can be deduced from Fig.6, where the fractural process is presented for each specimen. For the specimens No.1 to 4 with relatively low strength soft layers, an obvious crack deflection can be observed. First the cracks initiate near the tip of the notch, and then propagate vertically along the load direction. Passivation on the crack tips happens when a soft layer is met and the crack deflects along the horizontal direction, i.e. along the soft layer. The lower the strength of the soft layer is, the longer distance the crack goes over horizontally and more energy is dissipated in the cracking process. On the other hand, for the specimens No.5 to 8 with relatively high strength soft layers, the cracks develop upwards quickly but over a shorter distance horizontally. Compared with the cases in previous specimens, less deflection happens and less energy is dissipated. So the toughening effect is not manifest and the laminated ceramic has nearly similar fractural work K as the ceramic block, i.e., no critical improvement has been made on the toughness of the ceramic.

Based on the previous discussion, the strength of the soft layers is crucial to the attempt at improving the toughness of the laminated ceramic material. Only those soft layers of adequate strength can increase the fractural work K, make the crack deflected and more energy dissipated and, therefore, reduce the brittleness of the material. The numerical simulation is in excellent agreement with the laboratory tests carried out by Cai[13] and Tan[14]. The results from 2D numerical simulation performed by Chang[6] do not conflict with the present ones.

The approaches adopted in this study can also be applied to other materials with laminated structure. As a matter of fact, several toughening mechanisms may work together, however, the energy dissipation discussed in this section is the primary one.



(a) modulus (b) AE

V. CONCLUSION

A large-scale three-dimensional simulation was conducted using parallel computer approaches. The fractural process of a beam model with soft layers under three-point loading was simulated. In the course

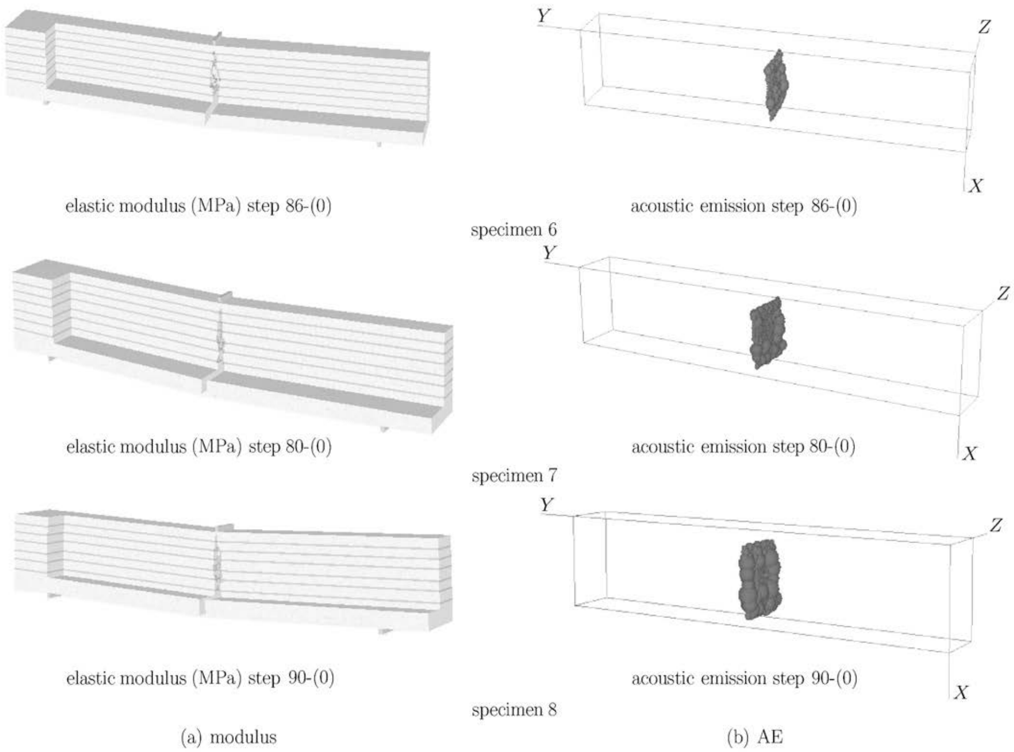


Fig. 6. Curves of fracture energy and peak load of the laminated models versus the strength of soft layer.

of crack propagation, the crack will change direction when a soft layer is met. After propagating in the soft layer a certain distance, the crack will turn back to the load direction again, where the distance is determined by the strength of the layer. With such a cyclic procedure, the fracture path is much longer than that in a ceramic block. The energy dissipation mechanism, therefore, gives laminated ceramic a toughness better than that of the brittle ceramic material.

Furthermore, the effect of the strength of soft layers has been investigated in details. Extremely high and low strength of the soft layers is not good at improving the toughness of the laminated composite ceramic. So, the strength of the soft layer should be designed property.

Finally, as the fractural process and the location of cracks is difficult to be observed in laboratory tests, this simulation is helpful for further optimization to improve the characteristics of composite materials.

References

[1] Clegg W.J., Kendall K., Alford N.M., A simple way to make tough ceramics. *Nature*, 1990, 347(10): 445-447.

[2] de Portu G., Micele L., Pezzotti G., Laminated ceramic structures from oxide systems. *Composites: Part B*, 2006, 37: 556-567.

[3] Pinho S.T., Robinson P., Iannucci L., Fracture toughness of the tensile and compressive fibers failure modes in laminated composite. *Composites Science and Technology*, 2006, 66: 2069-2079.

[4] de Portu G., Micele L., Guicciardi S., etc., Effect of residual stresses on the fracture behavior of notched laminated composites loaded in flexural geometry. *Composites Science and Technology*, 2005, 65: 1501-1506.

[5] Yuan Xu-xuan, Jia De-chang, Study on fracture behavior of BN-SiC laminated composite ceramics. *Material Science & Technology*, 2005, 13(4): 378-380.

[6] Chang X., Tang, C.A. and Zhang, H.Q.. Numerical Simulation on Toughening Mechanism of Laminated Composite Ceramic. *J. Inorganic Materials*, 2005, 20(2): 459-464.

[7] Guo X.H., Hu L. and Cai Q.H., Numerical Simulation and Laboratory Test on Toughening of Ceramic Nappe. *J. Chinese Ceramic Society*, 2000, 28(3): 234-239.

[8] Tang C.A., Wang S.H. and Fu Y.F., Numerical Test on Rock Failure Process. Beijing: Sci. & Tech. Publisher, 2003: 42-43.

[9] Liu H.Y., Hsu S.M., Fracture behavior of multilater silicon nitride/boron nitride ceramics. *J. Am. Ceram. Soc.*, 1996, 79(9): 2452-2457.
[10] Tong J.F., Chen D.M., Liu X.G., Preparation of AL_2O_3(YAG)/$LaPO_4$ laminated ceramics composites. *J. of Aeronautical Materials*, 2006, 26(3): 163-167.
[11] Li D.Y., Qiao G.J. and Jing Z.H., Recent development in research of laminated ceramic composites. *J. Inorganic Materials*, 2002, 17(1): 10-16.
[12] Guo H., Huang Y. and Li J.B., Properties and structure of Si3N4 laminated composite ceramics. *J. Chinese Ceramic Society*, 1997, 25(5): 532-536.
[13] Cai S.Y., Li J.L. and Xie Z.P., The effect of interface on the properties of Si3N4 laminated composite ceramics. *J. Comp. Mater.*, 1999, 16(2): 110-115.
[14] Tan Y., Yang H. and Ge M.Z., Technique of preparation of laminated composite ceramic and the properties of its interface. *Journal of Ceramics*, 1997, 18(2): 113-117.
[15] MISTRAS 2000, Users Manual. Princeton (NJ): Physical Acoustics Corporation, 1995.