EFFECTS OF RESIDUAL STRESS ON STRENGTH OF CARBON FIBER-REINFORCED CERAMIC COMPOSITE: THEORETICAL INVESTIGATION AND NUMERICAL SIMULATION

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ABSTRACT

The effect of residual stresses on strength of carbon fiber-reinforced ceramic composite was theoretically analysed and simulated by means of XFEM (extended finite element method) with commercial software, ABAQUS. Theoretical analysis indicated that the crack evolution was influenced by the residual stresses existing in the ceramic composites and the fracture strength of the ceramic composites would be increased when the compressive stresses occurred in the matrix. Uniaxial tensile simulation revealed that the final failure strength of ceramic composite was improved by ~8% in comparison with monolithic ceramic. The simulated results of the stress state of each component in the ceramic composites were in well accordance with the theoretical ones.

1 INTRODUCTION

Fiber-reinforced ceramic composites have attracted more and more attention in the past few years due to their high specific strength, excellent oxidation resistance and outstanding high-temperature mechanical stability under high-temperature oxidation environment [1-5]. While the residual stresses in the ceramic composites were inevitable, which were caused from fabrication process or service environment due to the mismatch of thermal and elastic properties between fiber and matrix. Such residual stresses may generate the micro cracks in the matrix, leading to the performance degradation of the composites.

Many researchers have made a great effort to clarify the residual stresses in the ceramic composite. For example, Ochiai [6] characterized the distribution and state of residual stresses in Al_2O_3/YAG composite by means of finite element method (FEM) and indentation fracture test technique. Chou [7] investigated the residual stress of the interface of the Al_2O_3/A356 with X-ray diffraction method. Saouma [8] investigated the residual stress of the aluminate-based composite with different toughening particles by spectroscopy method and then the distribution of the residual stress as well as its variation with particles' volume fraction were simulated through building a two-phase model. Most of these works focused on the characterization of residual stress in composites to some degree through the different techniques, but rarely investigate the influence of the residual stresses on the mechanical properties of the composites quantitatively.

For the purpose of quantitatively elucidating the influence of residual stresses on the uniaxial tensile strength of ceramic composites, theoretical analysis and numerical simulation were employed in this work. Firstly, the internal stress of the carbon fiber-reinforced ceramic composite and its effect on the strength were theoretically analysed. Then finite element models under uniaxial tensile test were conducted by XFEM method provided by the commercial software, ABAQUS. In this work, monolithic ceramics were used as references. At last, the quantitative effect of the residual stress on strength was obtained through the difference of simulated values of the ceramic composites and corresponding monolithic ceramics.

2 THEORETICAL ANALYSIS

During the cooling process from high fabrication- to room temperature, residual stresses in the carbon fiber reinforced ceramic composites were inevitably accumulated due to the mismatch of elastic modulus, Poisson's ratios and coefficients of the thermal expansions of the carbon fibers and ceramic matrix. Because coefficients of the thermal expansions of the carbon fiber in its radial direction is usually larger than that of the ceramic matrix, tensile stresses in the radial direction of the fibers are therefore generated at the ambient temperature. In this research, T700S carbon fibers and zirconium diboride (ZrB_2) are chosen as the reinforcement phase and matrix, respectively. What's more, in order to simplify the problem, assuming that there no defeats exist in the ceramic composite, that is to say, no pores or other defects exist in it.

Fig 1 shows the variation of the stress state of the matrix and reinforcement phase in the ceramic composite in the uniaxial tension test. Due to the difference of the coefficients of thermal expansion of T700S and ZrB_2, which were served as α_{T700S} and α_{ZB}, respectively, T700S carbon fiber would contract more than ZrB_2 matrix during the cooling process while ZrB_2 would inhibit the contraction behavior of T700S in its radial direction. Therefore, according to the displacement continuity, T700S was in tensile while ZrB_2 was in compressive along the fiber's radial direction. When the uniaxial tensile load was applied on the ceramic composite, ZrB_2 would firstly consume certain parts of the loads. With the load increasing, the stress state of ZrB_2 gradually changed from being compressive to tensile until the final failure of the ceramic composite.

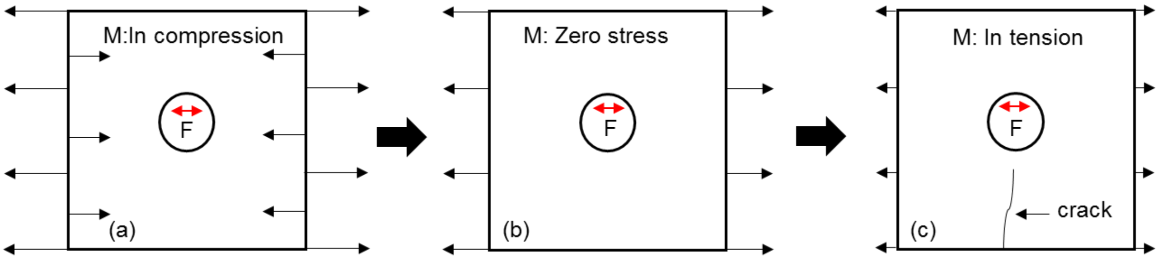

Fig 1: The schematic of the variation of stress state for the matrix and reinforcement component under uniaxial tensile load. (a): the initial stress state; (b): the equilibrium state under internal and external stress; (c): the unstable stress state with the external load surpassing the load capability of the matrix. The fiber was in tension all the time until the fracture occurred.

The same displacement loads and boundary conditions are applied on the monolithic ceramics. The magnitude of the stress in the monolithic ceramic directly increased from zero to the maximum one that corresponds to the beak carrying capability and then to decrease with damage or failure occurred. Due to the tensile stress of the monolithic ceramic increased from zero to its maximum failure stress without a stress state changing from compressive to tensile, the uniaxial tensile strength of the ceramic composite would be therefore improved in comparison with that of the monolithic ceramic. In the whole process, residual stress consumed some extra energy, resulting in a larger force in comparison with the monolithic ceramic that needed to cause the sample failure. This may be the strengthening mechanism of the residual stress.

3 SIMULATION

In order to investigate the effect of residual stress on the strength of ceramic composites, uniaxial tensile simulation tests were performed using the extended finite element methods provided by commercial software, ABAQUS. The main analysis steps were briefly described as follows: firstly, residual stresses were accumulated from the stress-free temperature to the room temperature, and then a displacement-controlling load was applied on the top edge of the model with the residual stress being applied in the model. Hereinto, all the simulation problems were simplified to plane strain problems and the maximum principal stress criterion was adopted as the damage initiation criterion to examine the stress state of every element in the whole model until the fracture occurred.

What's more, the fracture strength of the ceramics follows a statistical strength distribution. In order to model the properties of the model accurately, a Weibull modulus of 11 was chosen as a statistical fracture strength of the ZrB_2[9]. The stress-free temperature was set to be 1320C°[10]. The properties of T700S and ZrB_2 at ambient temperature were shown in Table 1. There were five independent modes created for each case.

Material property		ZrB_2	T700S
Elastic modulus	[GPa]	480	230
Poisson's ratio	–	0.16	0.2
Coefficients of thermal expansion	[×10-6/C°]	1.55	2.7
Weibull modulus	–	11	–
Tensile strength	[MPa]	450	4900

Table 1: Properties of T700S and ZrB_2 at ambient temperature.

Fig 3 shows the representative crack evolution process of the monolithic ceramic and ceramic composite. From Fig 3(a)~(d), it can be seen that almost zero residual stress appeared in the monolithic ceramic. This is attributed to the same properties of all the elements of the model. At the same time, the crack initiated from the middle zone of the model and then propagated along the nearly straight line. The final fracture strength of the monolithic ceramic models were 466.4 ± 8.5 MPa. While for ceramic composite model, all the T700S fibers were in tension and most regions of the ceramic matrix were in compression, as shown in Fig 3e. This mainly was caused by the mismatch of the thermos-physical properties of the T700S and ZrB_2. From Fig 3f, it can be seen that muti-cracks almost appeared meanwhile when the model was applied on uniaxial tensile load. With the load increasing, the cracks furtherly propagated until the model cannot bear external load any more, as shown in Fig 3g and Fig 3h. The final fracture stress of the ceramic composite was about 505.0 ± 15.7 MPa. It's obvious that the fracture strength of the ceramic composite was improved, about 8%.

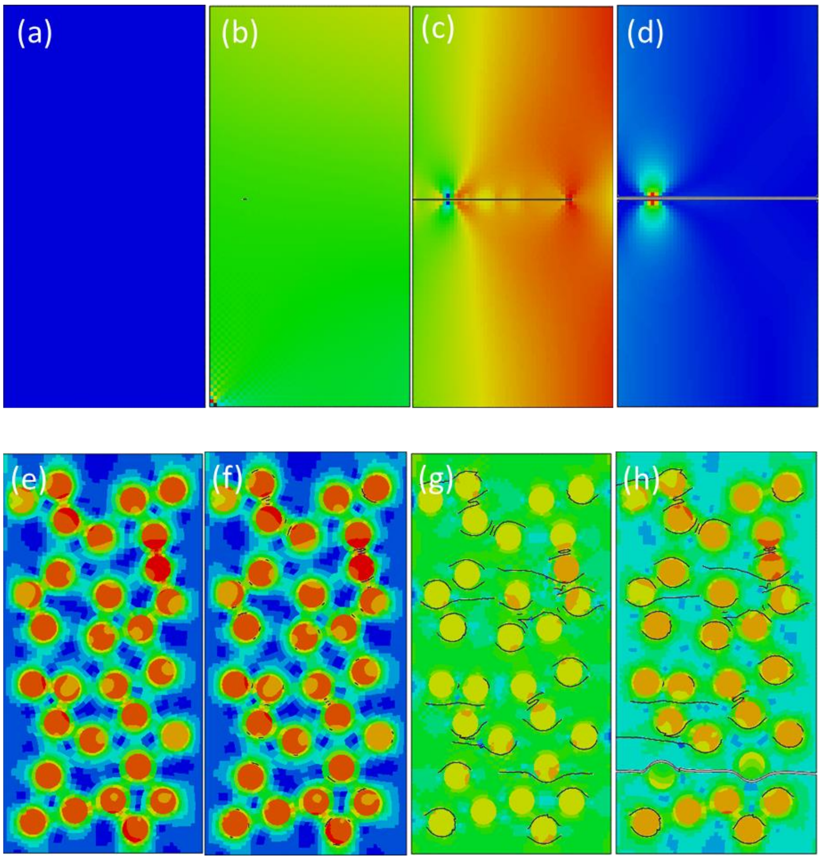

Fig 3: The crack evolution process of the monolithic ceramic (a-d) and ceramic composite (e-h). (a) represents a stress state caused by residual stress. (b) is initiation state when the load is just applied on the top edge of the monolithic ceramic. (c) is the stress state that monolithic ceramic model could bear the maximum load. (d) is the stress state that the model finally broken out. (e)~(f) corresponds to the stress state of the ceramic composite.

According to the well-known weakest linking hypothesis, a single crack would usually initiate from the weakest part of the model and then propagates until the structure runs into failure[11]. In the failure analysis process, the strength of the element that first appeared crack for the monolithic ceramic was actually the smallest one in the all elements. This simulated phenomenon was in well accordance with the theoretical result.

For the ceramic composite model, multiple cracks almost appeared at the same time. The first cracked element actually wasn't the element having the smallest fracture strength in all the elements. This was caused by the uneven residual stresses in the ceramic composite. Due to the random arrangement of the fibers, inhomogeneous residual stress would be accumulated at the ambient temperature during the fabrication process from stress-free temperature to the room temperature. Especially for the region that surround two or more adjacent fibers, which even was close to interact each other, the residual stress may unexpectedly large enough to cause microcracks. This didn't go against the weakest linking hypothesis, because the weakest region for the ceramic composite became very complex on account of the inhomogeneous residual stress. The element that having the smallest fracture strength in the ceramic composite model may have a better carrying capability in comparison with one that was affected by the significant residual stress.

The first cracked element in the ceramic composite model may not be the element having the smallest fracture strength. This demonstrated that fiber arrangement is very important for fiber reinforced ceramic composite.

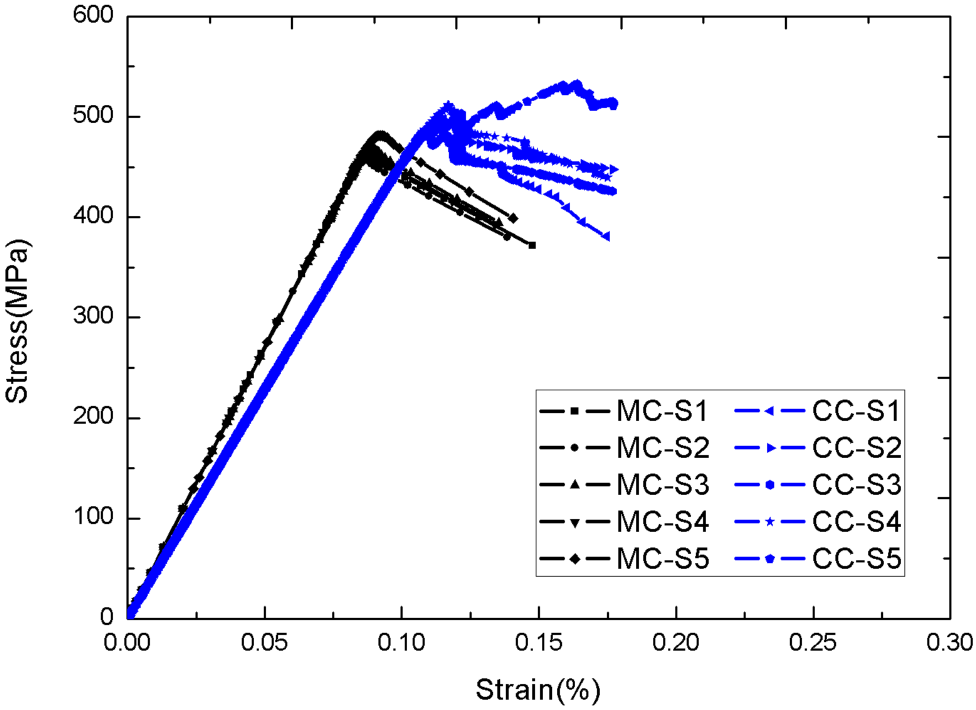

Fig 4: The stress and strain curves of the monolithic ceramic and ceramic composite. MC-T and CC-T (i=1,2,3,4,5) represent the monolithic ceramic and the ceramic composite, respectively.

4 CONCLUSION

In this research work, the effect of residual stress on strength of the carbon fiber reinforced ceramic composite were theoretically investigated and simulated by means of extended finite element method provided by commercial software, ABAQUS. Hereinto, T700S carbon fibers zirconium diboride (ZrB_2) were chosen as the reinforcement phase and matrix, respectively. The monolithic ceramic models were served as references through the whole analysis process. Main results from this research were obtained as follows:

(1) Due to the mismatch of thermal and elastic properties in the carbon fiber reinforced ceramic composite, residual stresses would inevitably accumulate in each phase. For T700S carbon fiber reinforced ZrB_2 ceramic composite, carbon fiber was in tension while the ZrB_2 ceramic was in compression at ambient temperature.

(2) Simulated results revealed that residual stress existing in the ceramic composite would affect the failure strength of the ceramic composite. Compared with the monolithic ceramic, the final failure strength has an improvement of ~8%.

(3) Fiber arrangement is very important for fiber-reinforced ceramic composite. When designing it, one has to consider the effect of residual stress of the ceramic composites.

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