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Multi-scale strength analysis of bolted connections used in Integral Thermal Protection System

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Abstract Efficient and accurate strength analysis of bolted connections is essential in analyzing the Integral Thermal Protection System (ITPS) of hypersonic vehicles, since the system bears severe loads and structural failures usually occur at the connections. Investigations of composite mechanical properties used in ITPS are still in progress as the architecture of the composites is complex. A new method is proposed in this paper for strength analysis of bolted connections by investigating the elastic behavior and failure strength of three-dimensional C/C orthogonal composites used in ITPS. In this method a multi-scale finite element method incorporating the global–local method is established to ensure high efficiency in macro-scale and precision in meso-scale in analysis. Simulation results reveal that predictions of material properties show reasonable accuracy compared with test results. And the multi-scale method can analyze the strength of connections efficiently and accurately.

1. Introduction

Thermal Protection System (TPS) is a key structure of hypersonic vehicles to keep the temperature of internal structure in a certain range and ensure safety of the vehicles in the elevated temperature environment. Conventional TPS is incapable of bearing external loads and costly in maintenance due to its poor mechanic properties. With the increasing demand for structural efficiency, a new concept of TPS called 'Integral Thermal Protection System (ITPS)' was proposed.[1–3] ITPS has the function of thermal insulation and the capability to withstand aerodynamic and structural loads; besides, it is reusable and can reduce the overall weight of hypersonic vehicles.

The materials of ITPS are mainly C/C and C/SiC because of their high specific strength, high specific stiffness and excellent ablation resistance. However, there is a contradiction in ITPS: the material with strong bearing capacity usually has good thermal conductivity, which is not conducive to structural thermal protection, while lightweight insulation material is low in bearing capacity. To find suitable materials, an

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enormous number of research including experiments and numerical simulations is needed. In numerical simulations, the Finite Element (FE) method is mainly considered, thanks to its efficiency and economy, to shorten development cycle and reduce research risk.

The strength of bolted connections in ITPS is a main concern because failures usually occur at the connections. The homogenization method, which uses macroscopic homogenized properties of composites to characterize the structure, is widely used in bolted connection strength analysis. Egan et al.[4] used the nonlinear finite element code to model the single-lap joints with countersunk fasteners, and analyzed the stress distribution at the countersunk hole boundary. The results showed that the finally compressive through-thickness stresses are presented at the damageable region of the countersunk hole, and increase with bolt-hole clearance. Li et al.[5] calculated the nonlinear stress distribution of C/SiC joints with pins or bolts and investigated the influences of hole parameters on the mechanical properties of C/SiC substrates. The simulation results were consistent with the experimental fracture loads and damage modes. Tang et al.[6] used the Hashin's theory as the damage initiation criteria to study the mechanical property and failure mechanism of Carbon–Carbon braided composites (C–Cs) bolted joints structure subjected to unidirectional tensile load, the FEM results had a good agreement with the test values. Du et al.[7] investigated failure behavior of Pultruded Fiber Reinforced Polymer (PFRP) bolted joints and proposed a Progressive Damage Analysis (PDA) material model integrating nonlinear shear response, Hashin-type failure criteria and strain-based continuous degradation rules. Hu et al.[8] proposed an explicit finite element analysis to model progressive failure of bolted composite joints under high bearing strains, the results of which showed the errors could be acceptable if very fine mesh is employed around the bolted area. All material properties in the above studies were established by experiments or numerical methods based on the macroscopic strength theory. The modeling strategies and numerical approaches did not consider stress localization mechanisms in microscale constituents. Besides, corresponding macroscopic strength theory should be developed independently for different materials.

An alternative method is analyzing the mechanical behavior of bolted composite joints considering the heterogeneous mesostructure at mesoscopic scale based on micromechanics. Lomov et al.[9,10] proposed a finite element model, called meso-FE, to investigate the mechanical behavior of 3D orthogonal woven composite and 2D woven composite by modeling of meso-scale geometric representations. Tsukrov et al.[11] developed a meso-scale finite element model to predict cure-induced microcracking of 3D orthogonal woven. The model showed good agreement between areas of high parabolic stress within the orthogonal woven material and actual microcracking observed by micro-CT scans. Dai and Cunningham[12] developed a full finite element meso model and a mosaic macro model to simulate the elastic and damage progression behavior of the 3D woven composite architecture. Both models predicted the tensile modulus and strength within 20% of the experimentally measured values, and the predicted failure sequence was similar to the experimental observation. Warren et al.[13] developed a three-dimensional progressive damage meso-FE model to capture the onset and initial propagation of damage within a three-dimensional woven composite in a single-bolt, double-shear joint. The onset of damage and trends seen in the model were found to be in agreement with experimental findings. Although meso-FE is a powerful tool to study the relationship between damage patterns and local stress fields in meso-scale, it is very time consuming to establish and analyze the structure.

Thus, multi-scale method, in which information is shared across two or more different length scales, is an efficient method for heterogeneous composite materials. The method establishes the relationship between macro appearance and meso structure, so it has both advantages of high efficiency in macro-scale and high precision in meso-scale. Feng[14] and Wang[15] et al. used multi-scale methods to predict the effective modulus of 3D braided composites. Smilauer et al.[16] predicted the fracture energy, G_f, and the effective length of the fracture process zone, c_f, of two-dimensional triaxially braided composites using the multi-scale method. Mao et al.[17] presented a multi-scale modeling approach for the progressive failure analysis of carbon-fiber-reinforced woven composite materials. Kwon and Park[18] developed a general-purpose micromechanics model for the multi-scale analysis of composite structures. Li et al.[19] proposed a new stress-based multi-scale failure criterion based on a series of off-axis tension tests, and determined their corresponding fiber failure modes and matrix failure modes. Zhang et al.[20] presented a mechanics based multiscale computational model to predict the deformation, damage and failure response of Hybrid 3D Textile Composites (H3DTCs) subjected to three-point bending. Nerilli and Vairo[21] developed a nonlinear multi-scale finite-element computational approach to analyze the pin-induced progressive damage of fiber-reinforced laminates employed in composite bolted joints. The results showed a good agreement with experimental evidence. However, most of the publications were concentrated on studying material properties using the multi-scale method. There were a few investigations focusing on multi-scale strength analysis of bolted connections.

In this work, a multi-scale method was established to investigate the strength of bolted connections used in ITPS. The method was mainly based on Asymptotic Expansion Homogenization (AEH) method incorporating the global–local method. The AEH method, which is used to decompose a function into global and local components, offers a base tool for this modeling strategy. Bensoussan et al.[22] detailed the method as the application of mathematical expansion to describe the macroscopic behavior of a system from the description of structure at micro-scale. Many investigations of composite materials with 3D structures were presented by AEH method.[14,15,23–26] The homogenized solution from the AEH method can be used in a macro-scale analysis, and additionally the AEH method also allows determination of the meso-scale state from point conditions in a macro-scale analysis. The global–local method, based on Saint Venant's principle, was used to reduce the modeling and computational complexity with reasonable accuracy,[27–30] as there were hundreds of bolted connections in ITPS. A global model was established with coarse mesh. The stress fields of global model were analyzed approximately with homogenized material properties. According to the stress results of the global model, the most highly loaded region was selected and modeled with refined mesh. The progressive failure analysis was applied for the most critical region by AEH method. Based on this

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