博 士 論 文 の 内 容 の 要 旨

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学位授与年月日	2022 年 3 月 20 日
論文題目	Study on development of three-dimensional woven composites and their mechanical behavior （三次元織物複合材料の開発とその力学挙動に関する研究）

（博士論文の内容の要旨）

Three-dimensional (3D) woven textiles with three groups of yarns arranged in three perpendicular directions have drawn much attention from researchers as reinforcement materials in fiber-reinforced composites. 3D woven textile-reinforced composites exhibit excellent out-of-plane mechanical performance compared to traditional laminated composites owing to the reinforcement in through-thickness direction. Developing 3D woven composites with various reinforcement woven structures is of interest to the composite research area for specific engineering applications.

In this study, a new weaving technology with a modified heddle position system based on a self-built 3D weaving loom is designed, and four typical 3D woven-structure textile groups are manufactured: layer-to-layer orthogonal woven, through-thickness orthogonal woven, layer-to-layer angle-interlock woven, and through-thickness angle-interlock woven. The new weaving technology has great potential for manufacturing various 3D woven structures effectively and efficiently. The developed glass/aramid fiber hybrid 3D woven textile-reinforced epoxy-resin composites underwent three-point bending tests and low-velocity drop-weight impact tests to study the influence of the woven structure on the quasi-static and dynamic flexural performance as well as failure modes of these composites. On the other hand, car-bon fiber 3D woven textile-reinforced epoxy-resin composites with four types of 3D/2.5D reinforcement structures (named as 3D-a, 3D-b, 3D-c and 2.5D) are developed based on a traditional weaving technology and their quasi-static and dynamic flexural performance are also studied. The four types of 3D/2.5D woven composites with special structural design in which binder yarn lies in weft direction, have same yarn densities along textile warp and weft directions in textile preforms during weaving process as well as same composite fiber volume fraction.

For the glass/aramid fiber hybrid 3D woven composites, the beam specimens which are along the textile warp and weft directions are tested under three-point bending tests. The composites along the weft direction have a larger flexural modulus but smaller failure strain compared with the warp direction for all woven-structure types. Among the designed 3D woven composites, the angle-interlock woven structures have a larger flexural strength (50%), modulus (40%), and failure resistance than have the orthogonal-woven structures. Overall, the through-thickness angle-interlock woven structure has the best quasi-static flexural-failure resistance among all textile structures, and is the optimal structural design based on this modified weaving technology. Woven structure has an obvious influence on the composite failure modes after three-point bending test. Low-velocity drop-weight impact tests on the 3D woven composites were conducted under impact energy levels of 10, 20, and 30 J. Load-bearing capacity, deflection characteristics, and energy characteristics of the composites were studied to clarify their impact resistance. Among the developed 3D woven composites based on this new weaving technology, it is found that the through-thickness angle-interlock woven structure is the optimal structure with a quasi-penetration energy of 30 J, whereas the other structures have a quasi-penetration energy of 20 J. The results also confirmed that the woven structure has an obvious influence on the composite failure modes: angle-interlock woven structures exhibit more limited delamination failure and keep a structural completeness after impact, whereas orthogonal woven structures exhibit more fiber fracture failure. Angle-interlock woven structures are more suitable for manufacturing based on the new weaving technology to develop impact-resistance composite materials.

For the carbon fiber 3D woven composites, the textile warp- and weft-direction beam specimens are also tested under three-point bending tests. Woven structures with different weft-to-binder yarn ratio and yarn waviness degree, have an obvious influence on the quasi-static flexural mechanical performance. Among the four de-signed 3D woven composites, 3D-a exhibits the best quasi-static flexural mechanical performance, followed with 2.5D, 3D-b, and 3D-c. Binder yarn with small waviness has both inter-layer binding/interlacing ability and in-plane load-carrying ability. Compared with 2.5D structure in which weft yarn interlaces with warp yarn, 3D-a structure in which there is no interlacement between weft and warp yarns could achieve a better quasi-static flexural mechanical performance. Low-velocity drop-weight impact tests on the carbon fiber 3D woven composites were conducted under impact energy levels of 3, 6, and 9 J. There is an opposite mechanical behavior be-tween quasi-static three-point bending tests and dynamic low-velocity drop-weight impact tests for these designed carbon fiber textile composites. 3D-c exhibits the best dynamic flexural mechanical performance, followed with 3D-b, 3D-a, and 2.5D. In-plane yarn waviness and through-thickness binder-yarn path may contribute to better impact performance. woven structure has an obvious influence on the failure mode in impacted composites, the binder yarn lies more in through-thickness direction will survive more from through-thickness crack failures, exhibit more limited delamination or debonding failures, leaving better impact-resistance ability for the developed 3D woven composites.

With the new weaving technology based on the proposed modified heddle position system and special structure design based on the traditional weaving technology, various 3D woven structures could be designed and manufactured to develop advanced fiber-reinforced composite materials. These weaving technologies have great potential to develop complex net-shaped woven composites such as composite engine fan blade with additional modifications. The through-thickness angle-interlock woven composite developed based on the new weaving technology has superior out-of-plane mechanical performance and may meet requirements of specific engineering applications. With successful development of these 3D woven composites and comprehensive studies of their quasi-static and dynamic flexural performance, some textile design parameters could be drawn out for future development of advanced 3D woven composites. Proper structural design of 3D woven composite based on specific fiber selection and weaving technology is key issue to develop advanced composites with better flexural performance.