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Experiments and optimization design of light-weight multilayer TPS

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Abstract

This paper aimed on optimization design of typical light-weight multilayer TPS based on experiments and numerical analysis. Radiation heating experiment is used to obtain both the true temperature distribution of the multilayer TPS and the thermal load. The transient heat transfer for the FEM model of typical multilayer TPS is analysed with the thermal load which is obtained through experiment. And the parameter correction model of multilayer TPS is obtained through comparing the temperature field between experiment and numerical analysis. Finally, the multilayer TPS with optimal dimensions was obtained by using multi-objective nonlinear constrained optimization method.

1. Introduction

Thermal protection system (TPS) is widely used in aerial and aerospace field, and many kinds of TPS are developed newly. The work conditions of the aerospace structures demand the thermal protection materials and structures should have combined features of light-weight, high thermal resistance and anti-collision stiffness. Thus the thermal protection materials and structures are in the trend of integration. Multilayer TPS[1-4] both fulfilling the function of thermal protection and load bearing has simple structure form and high structural efficiency, in which this form of TPS are developed with high prospect.A lot of work has been carried out for TPS all over the world. The main research themes for TPS are thermal-structural testing projects, analytical methods and optimization design, respectively.

Re-entry vehicle undergoes the extreme aerothermal environment. In order to verify integral design of aerospace vehicles and to validate anti-thermal performances of hot structures, many thermal-structural testing projects need to be carried out, such as radiation heating, airflow heating, etc. Advantages of the radiation heating method are the long heating time, high heating ability and multi-region temperature control. It is an effective thermal testing method of full scale aerospace structures[5]. On the contrary, the airflow heating method is restricted by testing space or heating time and it only plays important roles in some special aspects, such as aerodynamics scaled models, surface protrusions. It is certain that radiation heating of aerothermal simulation is still the main method in optimum design and performance verification of aerospace hot structures.

Analytical methods aimed to find simple and fast solutions of transient thermal problems in order to size multilayered TPS and hot structures. Compared with thermal-structural testing projects, analytical methods are more efficient and lower cost. Analytical method[6], whether exact or approximate, are always useful in engineering analysis. As a result, analytical methods are commonly used by researcher. Several analytical and semi-analytical solutions for composite slabs can be found in literature[7-10]. The integral method is usually adopted to solve transient heat conduction problems for finite and semi-infinite slabs and can take non-linear boundary conditions such as radiation into account[11-13]. In the suggested solution, the integral method has been marked for composite medium applications. A procedure based on one-dimensional analytical solutions of transient non-linear analysis has been developed in order to estimate the temperature variation with time and space of a multi-layered body subjected to aerodynamic heating inside a radiating space [14].

The optimal design of thermal protection system is an important means for optimization and weight reduction of re-entry vehicles, so it has attracted the attention of scholars all over the world. Sunil, et all[15] researched on multi-layer thermal protection systems and carried out the probabilistic optimization design of the integrated heat protection/bearing thermal protection system. Diane, et all [16] explores the trade-off between the probability of redesign and the mass at the design stage and observed that to minimize mass, designs should initially satisfy safety requirements such that most redesigns concern overly conservative designs. Gongnan Xie [17] established an optimization procedure aiming to design an integrated thermal protection system (ITPS) with minimum weight and the parametric design language code in conjunction with the globally convergent method of moving asymptotes (GCMMA) had been developed for heat transfer analysis and thermalemechanical analysis. Based on the three-dimensional heat

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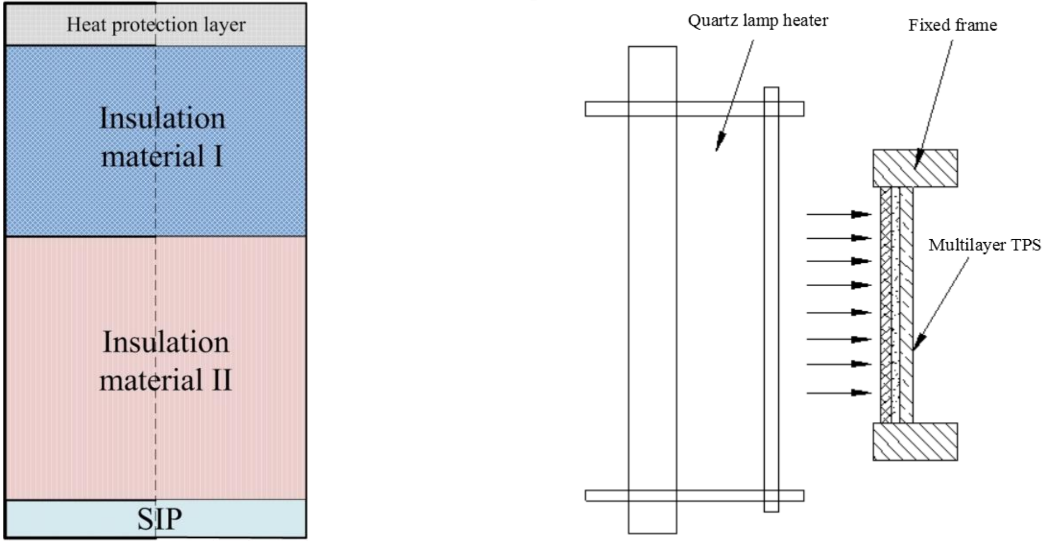
conduction theory, Dong Yongpeng [18] established an array-type multi-layer thermal protection structure optimization design process suitable for engineering applications. Xin, et all [19] proposed a probabilistic analysis tool for multi-layer TPS under re-entry aero-dynamic-heating based on Latin Hypercube sampling and response surface method. The paper indicates that uncertainties of the heat insulation material thickness and thermal conductivity had a great effect on the maxi-mum structure temperature, and uncertainties of the coating radiation emissivity had a great effect on the maximum TPS temperature.

In summary, most papers focus on single method researching for TPS, and there are almost no paper combine thermal-structural testing projects, analytical methods and optimization design. It makes more sense to combine the three method. Based on this tendency, this paper aimed on optimization design of typical light-weight multilayer TPS based on experiments and numerical analysis.

The objective of this paper is to establish a numerical procedure aiming at determination of the optimal thickness of the insulation layers subjected to the thermal load. In order to establish an effective and accurate optimization model, radiation heating experiment is used to obtain both the true temperature distribution of the multilayer TPS and the thermal load at the same time. The FEM model of typical multilayer TPS is established by using the Abaqus. Then the transient heat transfer for the FEM model of typical multilayer TPS is analyzed with the thermal load which is obtained through experiment. Parameter correction is one of the most important works in this paper which is the premise of the next step. We obtained the parameter correction model of multilayer TPS through comparing the temperature field between experiment and numerical analysis. Therefore the design process can be formulated as a multi-objective nonlinear constrained optimization problem. Finally, the multilayer TPS with optimal dimensions was obtained.

2. Radiation heating method

In this paper, the radiation heating test is carried out for multilayer TPS components of re-entry vehicles. The typical multilayer TPS has four insulation layers with different materials, as shown in Figure 1 (a). And the typical multilayer TPS is a square flat plate structure of 300 mm × 300 mm, and the total thickness of which is 60mm. The schematic diagram of the radiant heating tests installation is shown in Figure 1(b). The typical multilayer TPS is mounted vertically on the work frame and parallel to the plane of the quartz lamp heater. Considering different boundary conditions, several thermal tests were conducted separately with or without heat insulation frame.



（a）The typical multilayer TPS

(b) The schematic diagram of the radiant heating tests installation

Figure 1: Structure scheme and schematic diagram of the radiant heating tests installation

The front side of the typical multilayer TPS was heated according to the temperature profile given in Figure 2(a). In order to consider the boundary condition effect, the temperature at five positions was measured on the back side of the typical multilayer TPS. Five temperature measuring points were arranged on the back side of the typical multilayer TPS by means of K-type thermocouple bonding as shown in Figure 2(b).

The radiation heating test carried out basing on the test plan, as shown in Figure 3. The measurement shows a maximum back temperature was about 70℃, which verifies the rationality of the typical multilayer TPS. The test results show that the boundary conditions have a great influence on the test results. The test obtained the temperature response on the back side of the typical multilayer TPS. Under different boundary conditions, the temperature change on the back

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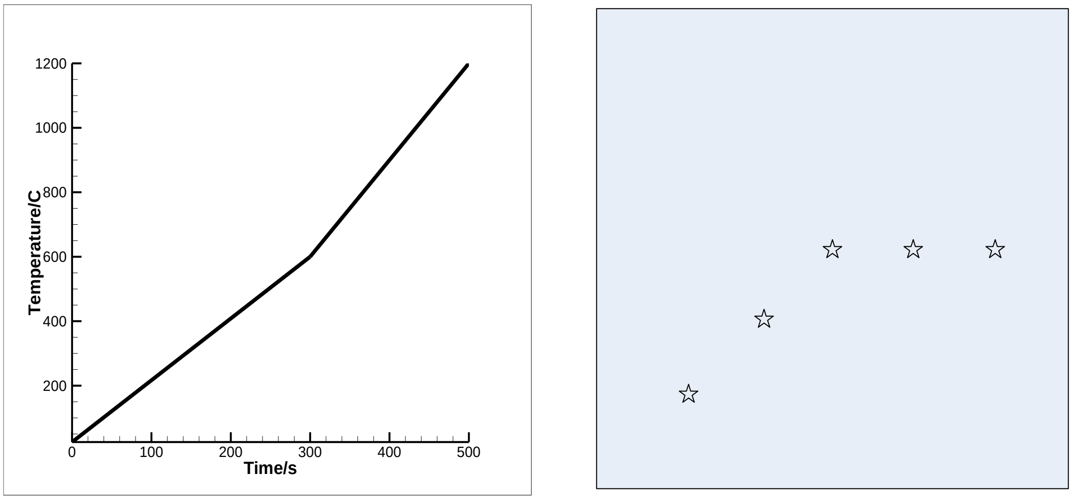
side of the typical multilayer TPS has a large difference. As a result, the test needs to be designed according to the actual used boundary conditions. At the same time, it is found that the measured point data far from the boundary has better consistency. Therefore, in order to avoid the interference of boundary conditions and external factors and to obtain more effective measurement data, the measuring point position away from the boundary condition should be selected.



(a) Thermal load (b) The temperature measuring points

Figure 2: Thermal load and The temperature measuring points

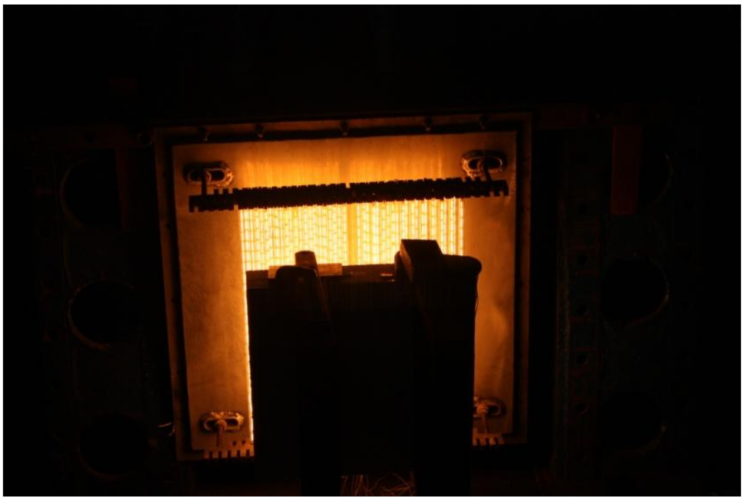


Figure 3: The photo of the Radiation heating experiment

3. Numerical optimization design

The numerical optimization design of TPS is an important means for optimization and weight reduction of re-entry vehicles. The accuracy of numerical method is directly related to the success or failure of re-entry vehicle engineering. Therefore, it is necessary to combine numerical method and heating test method by using thermal test data to modify thermal analysis model. Based on the modified model, the optimization and redesign of TPS can effectively avoid model error and ensure the correctness of optimization results.

As for this paper, the FEM model of typical multilayer TPS is established by using the Abaqus. Then the transient heat transfer for the FEM model of typical multilayer TPS is analyzed with the thermal load which is obtained through heating test. Parameter correction is one of the most important works in this paper which is the premise of the next step. We obtained the parameter correction model of typical multilayer TPS through comparing the temperature field between heating test data and numerical analysis data. Therefore the design process can be formulated as a multi-objective nonlinear constrained optimization problem. Finally, the multilayer TPS with optimal dimensions was obtained. The procedure of multilayer TPS optimizer is illustrated in Figurer 4.

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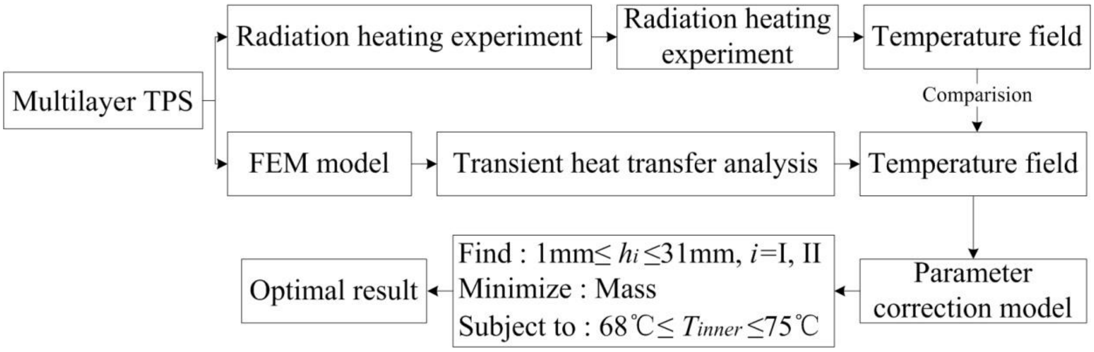

Figure 4: Optimization flowchart for typical multilayer TPS

3.1 FEM model correction

The FEM model of typical multilayer TPS is established by using the Abaqus. In order to simplify the calculation, considering the symmetry of the typical multi-layer TPS components, 1/4 of typical multilayer TPS was analyzed. An 8-node linear brick diffusive heat transfer element is used to mesh the typical multilayer TPS. The FEM model consists of 22771 nodes and 12190 cells, as is shown in Figure 5. The components of each layer was bonded by using mesh tie constraints, and the thermal resistance between the contact faces is ignored in the thermal conduction analysis.

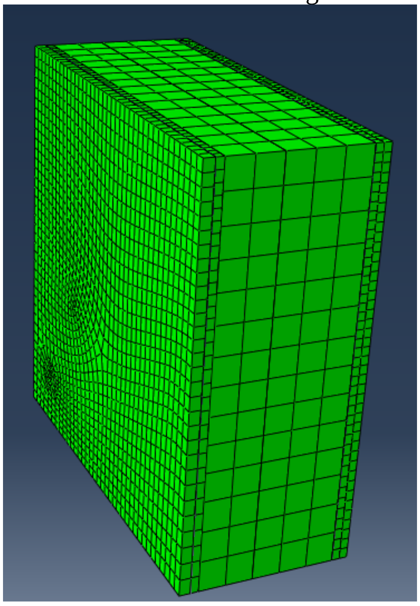

Figure 5: The FEM model of typical multilayer TPS

The purpose of this step is to correct the FEM model. Then the transient heat transfer for the FEM model of typical multilayer TPS was analyzed with the thermal load which is obtained through heating test. The temperature and time history curve of the external surface of the typical multilayer TPS was consistent with the temperature measuring point data, and the highest temperature in both cases was 1200℃at 500s. But there was a difference in inner surface temperature which means that the FEM model was not accurate enough.

Parameter correction is one of the most important works in this paper which is the premise of the next step. Therefore, the FEM model is corrected by adjusting the relevant parameters mainly through comparing the inner surface temperature field between heating test data and numerical analysis data. It is clearly that the boundary condition is one of the most important factor. And the boudary conditon of heating test and FEM analysis was different, as for heating test which was natural convective and the FEM analysis was adiabatic wall. Therefore the key factors are the convective heat transfer coefficient.

Finally, the modified FEM model was obtained by adjusting the convective heat transfer coefficient to be 2.25. It was shown that the inner surface temperature obtained by the two methods agree well, as is shown in Figure 6. And the

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temperature curves follow the same trend.. The highest temperature of the FEM analysis was 68.3 ℃ at 3620s and the highest temperature of the heating test was 68.1 ℃ at 3550s and the relative error between the two is 0.29%. Figure 7(a) shows the temperature distribution of the typical multilayer TPS at 500s, and Figure 7(b) shows the temperature distribution of the typical multilayer TPS at 3620s.

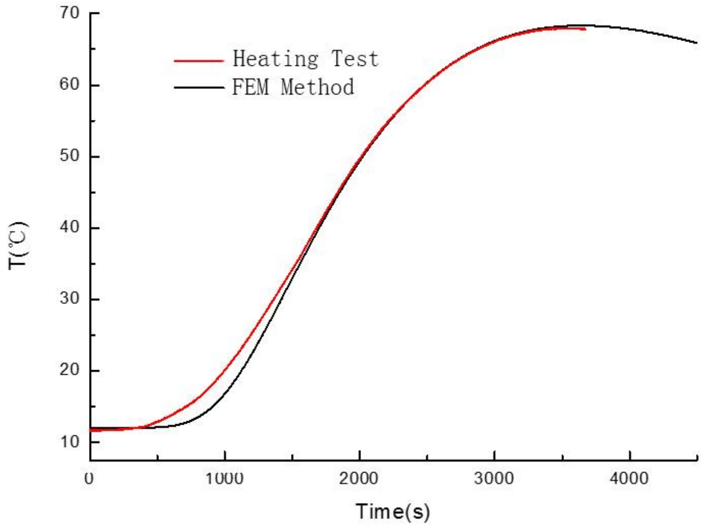
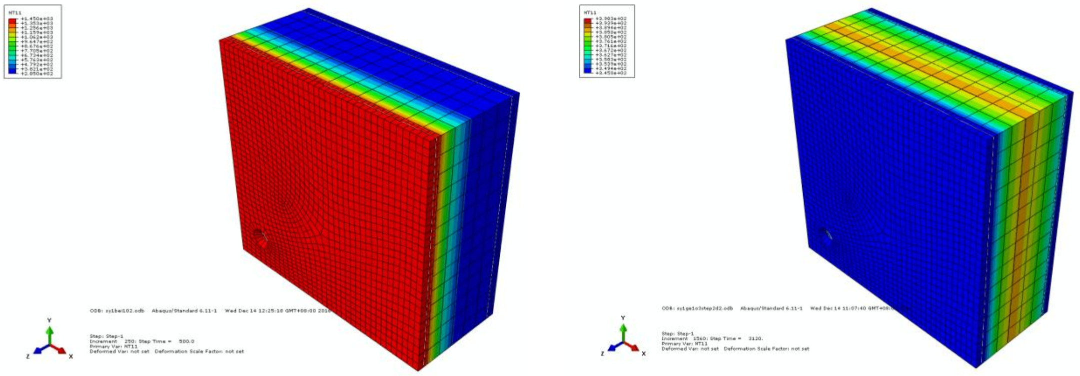


Figure 6: The inner surface temperature of typical multilayer TPS



(a) 500s

(b) 3620s

Figure 7: The temperature distribution of the typical multilayer TPS

3.2 Optimization Analysis

Based on the modified typical multilayer TPS model, the deterministic analysis under a given thermal load was carried out, and the thickness of the model was optimized to achieve the purpose of weight reduction. Considering the characteristics and process feasibility of the multilayer TPS, the thickness of insulation I and the insulation II were selected as the design variables for optimization.

The design process can be formulated as a multi-objective nonlinear constrained optimization problem, and can be written as

$$\text{Find} : 1\text{mm} \leq h_i \leq 31\text{mm}, \quad \text{i} = \text{I}, \text{II}$$

$$\text{Minimize} : \text{Mass}$$

$$\text{Subject to} : 68℃ \leq T_{\text{Bottom}} \leq 75℃$$

where h_i is the thickness of the insulation layers and T_{Bootom} is the temperature of the bottom surface.

Using the optimization process shown in Figure 4, the thermal analysis was performed based on the finite element analysis software Abaqus and Fortran self-programming. In this paper, Multi-island genetic algorithm and modified sequential quadratic program (SQP) were used for optimization analysis. The comparison of the size and inner

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temperature before and after optimization is shown in Table 1. The overall weight loss is 6.68%. Finally, the multilayer TPS with optimal dimensions was obtained. The optimization results show that the areal density of the new ITPS panel decreases by 6.68% compared with the previous one, which proves the potential of this parameter correction and optimization methods for the future spacecraft vehicles.

Table 1: The comparison of the size and inner temperature before and after optimization

	before optimization	after optimization
h_{I}（mm）	20	18
h_{II}（mm）	31	28
Temperature（℃）	68.3	74.5

4. Conclusion

In this paper, the radiation heating method was carried out for a typical multilayer TPS, and numerical optimization design was carried out based on the test data. The main conclusions are as follows:

1. In the radiation heating test, the bottom surface temperature of the the typical multilayer TPS was sensitive to the boundary conditions. In order to avoid the interference of boundary conditions and external factors and to obtain more effective measurement data, the measuring point position away from the boundary condition should be selected.
2. The optimization analysis process was established based on experiments and numerical analysis. In order to establish an effective and accurate optimization model, radiation heating experiment is used to obtain both the true temperature distribution of the multilayer TPS and the thermal load at the same time,
3. The multilayer TPS with optimal dimensions was obtained. The optimization results show that the areal density of the new ITPS panel decreases by 6.68% compared with the previous one, which proves the potential of this parameter correction and optimization methods for the future spacecraft vehicles.

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