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The Optimal Design of Biaxial Compression Test Fixture for Solid Propellant Under Dynamic Loading

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Abstract

In order to solve the problem that the test cannot be carried out normally due to the bending of the clamping end at the bottom of the fixture in the biaxial compression test under dynamic loading, the bottom clamping end was designed optimally, and the I-shape structure was adopted, which could greatly improve the stiffness of the fixture. Firstly, the finite element software abaqus was used to check the stiffness of the original fixture with the simplified long plate configuration, and the deformation cloud diagram was obtained. The maximum displacement change in the y-axis direction was selected as the evaluation index to quantitatively analyze the simulation results. Secondly, the dynamic biaxial compression test of solid propellant was carried out under corresponding conditions. Finally, the stiffness of the optimized I-shape fixture was checked and verified by finite element method and experiment. The results show that the relative error between the simulation value and the experimental value was only 6.09%, which verified the rationality of the model simplification and the correctness of the simulation conclusion. The optimized I-shaped fixture could bear up to 100 KN load in the vertical direction, which could meet the design requirements of the test fixture. Finally, by analyzing the characteristics of the loading-time curve obtained from the biaxial compression test under dynamic loading, the effectiveness of the optimized fixture design was verified.

Keywords

Test Fixture Design; Structure Optimization; Finite Element; Biaxial Compression.

1. Introduction

In the process of ignition and pressure build-up of solid rocket motor, the stress state of solid propellant grain is complex, which is not a simple one-dimensional stress state [1]. In addition, Jeremic [2] pointed out that solid rocket motor will bear high-speed loading at the moment of ignition, and the real loading strain rate is in the range of $1\sim100s^{-1}$. Therefore, it is necessary to carry out mechanical property tests under complex stress loading such as biaxial compression under dynamic loading.

At present, in order to study the mechanical properties of solid propellant under biaxial tensile loading, many scholars have designed biaxial tensile clamps and carried out a large number of experiments [3-5]. However, there are few experiments on the performance of solid propellant under biaxial compression, especially under dynamic biaxial compression. In order to study the strength criterion of solid propellant under biaxial stress state, Zhang [6] carried out biaxial compression tests on cuboid specimens under different loading rates based on quasi-static biaxial testing machine and self-designed rectangular block clamp. However, due to the limitation of loading rate of conventional biaxial testing machine, dynamic loading cannot be realized. In the early stage, high strain rate hydraulic servo testing machine was widely used in the dynamic test of solid propellant materials due to its advantages of stable and high-speed loading [7-9]. However, it is necessary to design a specific test fixture for dynamic biaxial compression test based on this testing machine. At this time, the design of the test fixture is very critical, and the specimen mainly depends on the cooperation of the fixture and the testing machine, which will directly affect the accuracy of the mechanical property test of the specimen [10, 11]. Therefore, it is necessary to design an effective test fixture which can successfully carry out biaxial compression under dynamic loading.

In this paper, the finite element numerical simulation method was adopted to optimize the weak part of the original fixture and a new fixture configuration that could meet the dynamic loading conditions was proposed. The biaxial compression test of solid propellant under dynamic loading was carried out based on the high strain rate hydraulic servo testing machine to verify the effectiveness of the optimized fixture.

2. Fixture structure design requirements

In order to successfully realize the mechanical performance test of double axial compression under dynamic loading of solid propellant, the test fixture should meet the following design requirements.

1) During the compression loading process, the overall strength of the fixture meets the requirements;

2) In the process of dynamic loading, the stiffness of the weak part meets the demand;

3) According to the loading principle of biaxial compression fixture [12], the fixture always moves in one dimension in the vertical direction;

4) Fitting well with the upper and lower fixed ends of the high strain rate hydraulic servo testing machine testing machine.

3. Finite element numerical simulation analysis (FEA) of original fixture

3.1 The establishment of the model

According to the original wedge-shaped lower clamping fixed end of Instron 160/100-20 high strain rate hydraulic servo testing machine, the maximum size of the bottom surface of the clamping area is $5\text{mm} \times 30\text{mm}$, so the bottom fixed end of the original fixture was designed with long plate structure, the specific size was $5\text{mm} \times 30\text{mm} \times 100\text{mm}$. In view of the thin long plate structure at the bottom, it was initially regarded as a weak part, and the key point is to check whether the part meets the design requirements. In order to highlight the loading situation of weak parts and reduce the amount of calculation, this paper simplified the non-weak parts. In addition, in the process of dynamic compression loading, the quality of the fixture was an important factor that cannot be ignored, so using the mass equivalence, the upper part of the bottom clamping end was equivalent to a cuboid with the same mass and the same bottom section.

The finite element software abaqus was used to model the original fixture, and the specific geometric model is shown in Fig. 1a. Considering the strength requirements of fixture structure design, 30CrMnSi was selected as fixture material in numerical calculation, its elastic modulus is 2×10^5MPa, Poisson's ratio is 0.33. C3D8R element type was used for mesh generation, with a total of 16052 elements. The dynamic display was selected for the analysis step, the acceleration load was $v = -141.4\text{mm/s}$ applied on the upper surface of the fixture (the corresponding loading strain rate is 4s^{-1}), the analysis step time was 0.12 s, the fully fixed boundary condition was adopted for the overlapping part of the lower fixture and the clamping end of the specimen machine, and the finite element model after the constraint is applied is shown in Fig. 1b.

3.2 Numerical simulation results and analysis

The simulation results are shown in Fig. 2. It can be found that large deformation occurs in the area where no constraint is imposed on the bottom fixed end of the original fixture, which no longer meets

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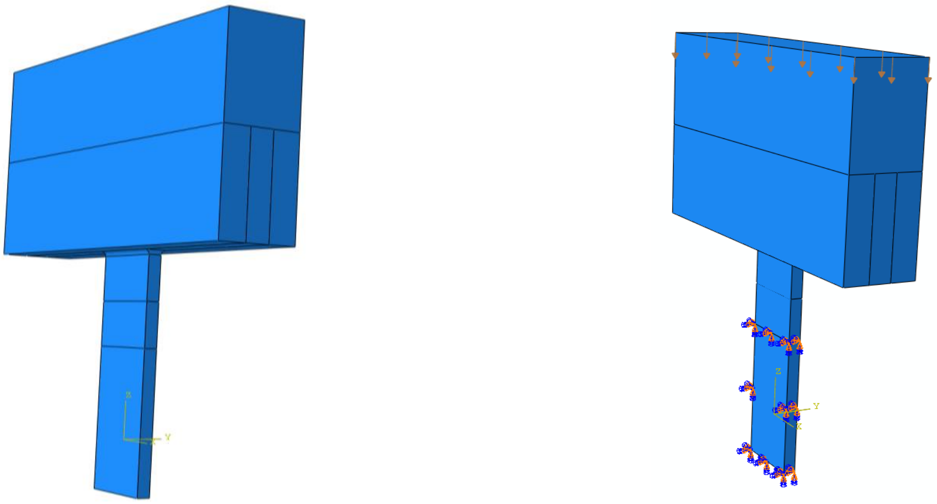
the stiffness requirements of the fixture. In order to quantitatively check the stiffness of the original fixture under dynamic loading, the evaluation index $U_{2\,max}$ was introduced to represent the maximum displacement change of the fixture in the *y*-axis direction, which is used to measure whether the stiffness of the fixture meets the design requirements. The $U_{2\,max}$ is closer to 0, the more the stiffness of the fixture meets the design requirements.



(a) Geometric model of original fixture before constraint

(b) Geometric model of original fixture after constraint

Fig. 1 Geometric model of original fixture

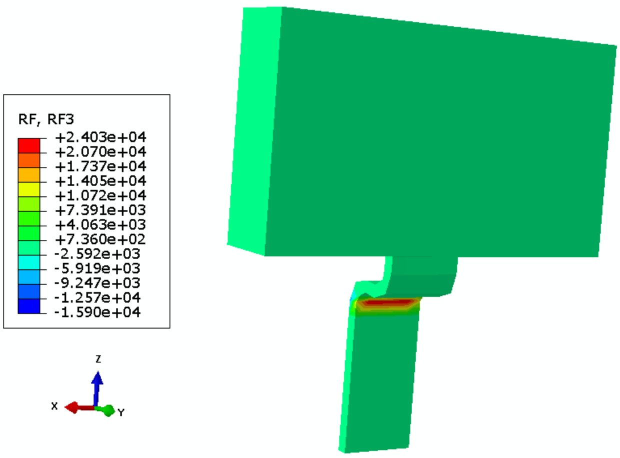


Fig. 2 Simulation results of original fixture

The region of vertical direction (*z*-axis) with support reaction force RF_3 was selected as the research region, and then the average value of support reaction force of all nodes in the region was obtained. The relationship between the average value of reaction force RF_3 and stiffness index $U_{2\,max}$ is shown in Fig. 3.

It can be seen from Fig. 3 that when the reaction force of the long plate is more than 5 KN, the stiffness index $U_{2\,max}$ is no longer close to 0, and it is considered that the stiffness does not meet the requirements. Secondly, it can be found that with the increase of the average value of the reaction force RF_3, the maximum displacement in the *y*-axis direction $U_{2\,max}$ shows a gradually increasing trend, and the increasing speed gradually increases, which indicates that the degree of insufficient stiffness of the original fixture is also deepening. In addition, when $U_{2\,max}$ is increased to 10.5 mm, the counterforce load almost does not change, and the force value is maintained at about 24.03 KN.

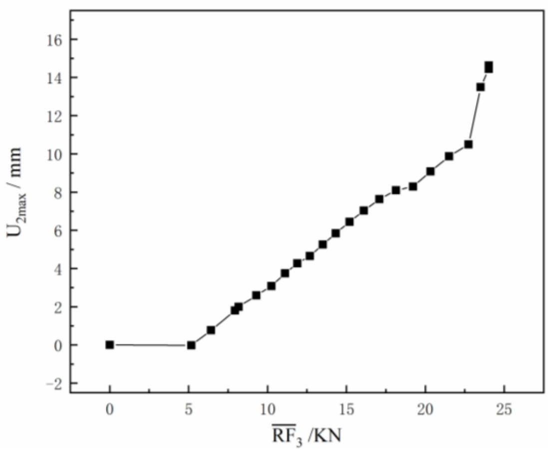


Fig. 3 Variation curve of original fixture with average value of support reaction

3.3 Test verification of original fixture

Based on the original fixture and HTPB composite solid propellant specimen, the biaxial compression test under dynamic loading was carried out. The loading speed of the test is consistent with the simulation loading speed, with the size of 141.4 mm/s (corresponding strain rate of 4 s^{-1}) and the loading time of 0.12s. Fig. 4 is the load time curve obtained from the original fixture test.

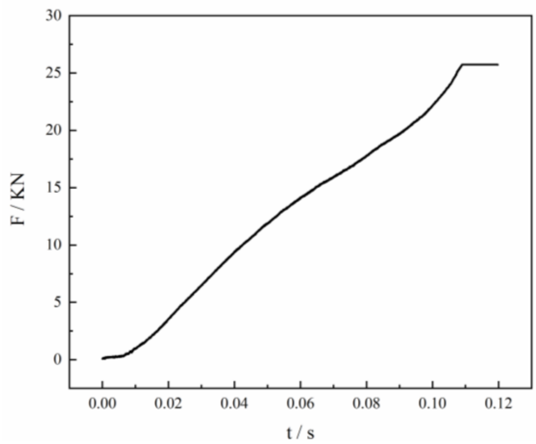


Fig. 4 Loading-time curve obtained from original fixture test

It can be seen from Fig. 4 that the load increases gradually with time, but after 0.11s, a ‘load platform area’ appears, mainly because most of the vertical force is decomposed into a rotation vector with a fixed constraint boundary as the rotation axis, which is no longer a one-dimensional vertical motion meeting the design requirements. In addition, it can be found that the load approaching value is 25.57 KN, and the relative error between the load approaching value and the simulation result is only 6.09%, which verifies the correctness of the simulation results. At the same time, it also shows that it is reasonable to simplify the non-weak part of the fixture by using the mass equivalent method.

4. Fixture structure optimization design

Based on the simulation calculation and experimental results in Section 3, it was found that the original fixture did not meet the design requirements, so it is necessary to optimize the weak parts of the original fixture. I-steel structure has good bending capacity [13], which can better solve the problem of insufficient stiffness of the original fixture. Therefore, optimized the long plate structure and selected the I-shaped structure, and the optimized new fixture structure is shown in Fig. 5.

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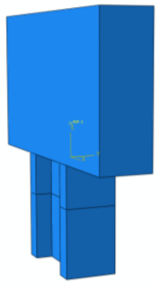

Fig. 5 Fixture structure after optimization

4.1 FEA of the optimized fixture

Using the same material parameters, mesh types and load boundary conditions as those in Section 3.1, the numerical simulation of the optimized fixture was carried out, and the calculation results are shown in Fig. 6.

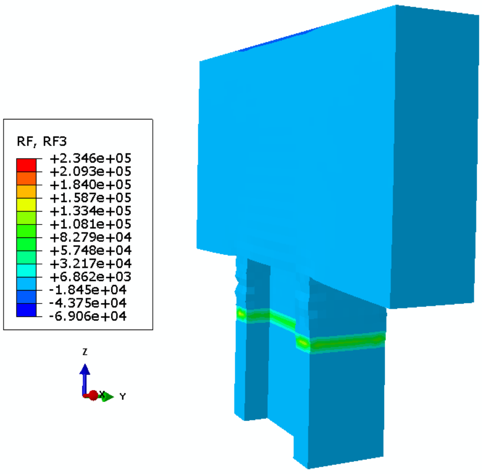

Fig. 6 Simulation results of optimized fixture

It can be seen from Fig. 6 that under the maximum load of 234.6 KN, the bottom fixed end of the optimized fixture can still maintain the structural configuration without large deformation. In order to quantitatively analyze the stiffness of the optimized fixture, the analysis method in Section 3.2 is extended. Taking the stiffness index $U_{2\,max}$ as the evaluation index, the relationship between the optimized fixture stiffness index and the average value of support reaction force is shown in Fig. 7.

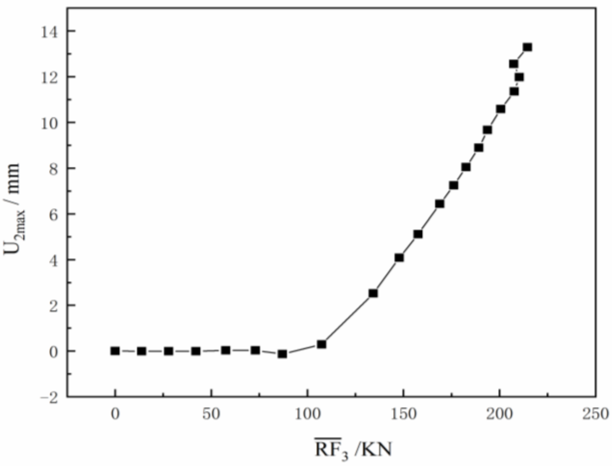

Fig. 7 Variation curve of optimized fixture with average value of support reaction force

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It can be seen from Fig. 7 that when the vertical support reaction does not exceed 100 KN, the value does not change much and is close to 0, which indicates that the optimized fixture can bear at least 100 KN support reaction and ensure that the stiffness of the lower clamping end of the fixture meets the requirements. According to the previous test data, the maximum load in the process of biaxial compression is far less than 100 KN. Therefore, from the numerical simulation results, it can be concluded that the I-shaped structure can meet the test requirements of biaxial compression under dynamic loading.

4.2 Fixture test verification after optimization

The dynamic biaxial compression test of HTPB composite solid propellant was carried out with the optimized fixture under the same loading conditions as that in Section 3.3. Fig. 8 is the load time curve obtained from the optimized fixture test.

It can be seen from Fig. 8 that the load increases with the gradual increase of displacement. And there is no load platform area. It shows that the stiffness of the optimized fixture design does not meet the design requirements in the process of biaxial compression, and further verifies the rationality of the simulation results of the optimized fixture design under dynamic loading.

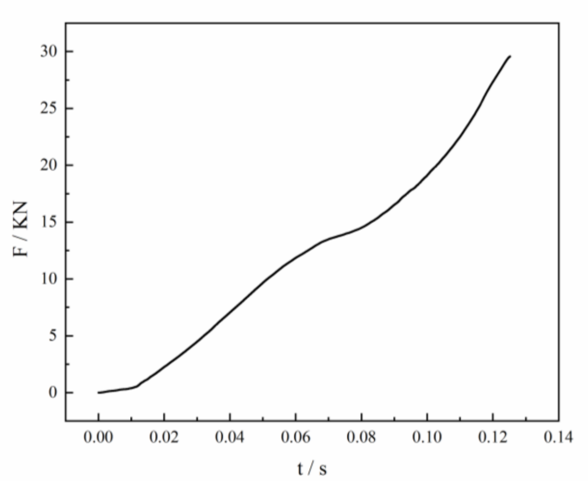

Fig. 8 Loading-time curve of optimized fixture test

5. Conclusion

(1) Based on the reasonable simplification of the non-weak parts of the original fixture, the numerical simulation calculation is carried out, and the deformation nephogram of the original fixture with long plate configuration is obtained. The results show that the bottom clamping end of the original fixture has a large deformation. The stiffness index is selected to quantitatively analyze the deformation of the fixture. It is found that the bottom clamping end of the long plate configuration does not meet the stiffness design requirements.

(2) The biaxial compression test of the original fixture was carried out under the corresponding conditions. Through the analysis of the load time curve, it was found that there was a ,'load platform area'. In addition, the relative error between the load value corresponding to the platform area and the load approaching value of the simulation results is only 6.09%, which verifies the correctness of the simulation results and the rationality of the model simplification.

(3) Based on the study of the stiffness of the original fixture, the stiffness of the optimized I-shaped fixture is checked by the finite element calculation software. The results show that the optimized fixture can withstand less than 100 KN without bending deformation at the bottom clamping end. Combined with the previous test data, it fully meets the test design requirements.

(4) The dynamic biaxial compression test of the optimized fixture was successfully carried out, and the load time curve of solid propellant under dynamic biaxial compression loading was obtained. The

analysis of the test results shows that the load increases with the passage of time, and there is no ‘load platform area’ in the original fixture test results, which verifies the rationality of the simulation results of the optimized fixture design under dynamic loading, and provides a strong support for the further systematic development of the mechanical properties of solid propellant under dynamic biaxial compression loading.

Acknowledgements

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