STATIC STIFFNESS ANALYSIS OF CAR SEATS BASED ON EXPERIMENTAL AND NUMERICAL INVESTIGATION

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Abstract - The static stiffness of the car seat can reflect the hardness of the seat and vibration attenuation of the seat cushion and backrest. Therefore, the research on static stiffness is an important aspect of dynamic comfort of car seats.Based on the finite element method, a finite element model of seat frame is established, and the reliability of the model is verified by modal test. Then the seat is tested by static load in accordance withstandards, and the static stiffness and hysteresis deformation rate of the seat cushion are obtained. The simulation analysis of the seat model with cushions is carried out, and the results are compared with the experimental data.It is found that of the simulation results correlate well with experimental data on static stiffness, but the hysteresis deformation rate has a certain error. This study provides a reference to simulate polyurethane materials of cushions, and simulation methods for the study of seat dynamic comfort.

Keywords - Car Seat, Modal Analysis, Seat Static Stiffness, Finite Element Method, Polyurethane.

I. INTRODUCTION

Car seats are essential parts for providing passenger safety and comfort and have been important for riding experience, whichinvolvesergonomics, vibration, and control engineering[1]. The main functions of car seatsare to support the occupant's body, buffer and attenuate the shock transmitted to the human body due to road roughness and vibration of engine.

The static stiffness of a car seat not only directly reflects the hardness, but also the ability of the seat cushion and the backrest to attenuate vibration. A car seat is subjected to various loads during vehicle's operation. If the stiffness of the structure is small, larger deformation occurs. If the deformation exceeds the range in which the structure is normally used, the functions of the seat are affected. The seat cushion and backrest of a car seat are mainly made of polyurethane material which has a significant influence on the riding comfort. If the foam is too hard, the passenger might feel seating on a wood plate. On the other hand, if the foam is too soft, the passenger feels that the body is trapped in the seat, causing inconvenience to movement and fatigue for the passenger after a long time.

A lot of detailed research has been done on the static stiffness of the seat. The finite element method was applied for the study of the seat comfort and the polyurethane material to obtain the nonlinear elastic compression property [2]. The simulation analysis of a car seat was carried out by using the multi-body dynamics analysis software MADYMO, and the advantages and disadvantages of multi-body dynamics analysis and finite element analysis were described[3].From the perspective of the proportion of polyurethane raw materials, the static and dynamic comfort of the seat were studied, and the proportion of raw materials which affect the rebound and hardness of the foam was determined[4].A detailed seat model was analyzed by ABAQUS with the human model CASIMIR and it provided a possible optimization for the seat structure[5].The modal and vibration of automotive seat frame are obtained by Ansys Workbench, and the response values under the condition of harmonic response and random vibration were analyzed [6].In the traditional research on the dynamic characteristics of vehicles, the structure of whole vehicle is usually simplified to a linear system. However, with the increasing requirement for higher performance of vehicles, the nonlinear characteristics of the rubber rings and the polyurethane of seat cushion for riding comfort have attracted more research efforts. Recent studies showed that the nonlinear hysteresis characteristics of system must be considered when conducting kinetic studies [7].Despite a lot of research has been done in this area, it is still a challenge that the modeling process of the whole seat system is complicated and difficult to be applied in engineering.

1.1. Test regulation

According to the China automotive industry standard "Test Method for Dynamic Comfort of Car Seats"(QC/T55-1993), the purpose of the test is to determine static stiffness and hysteresis deformation rate of seat cushion and backrest [8]. This is a quasi-static test which is usually carried out on a continuously loading test machine with low speed. The shape of loading plate for the cushion is shown in Fig.1. and the loading direction and position are shown in Fig.2.With reference to the standard, the seat needs to be loaded and unloaded twice as preloading. The preloading value for seat cushion is 700 N. The speed during the loading and unloading process is specified to be 150~300mm/min and the maximum load cannot exceed the preloading value. At the same time, the transition time from loading to unloading cannot exceed 2s. The load applied on seat

cushion is specified to be 500 N for the test of seat static stiffness. The slope of tangency corresponding to the load point on the loading curve is the static stiffness of the seat. Because this research focuses on the application of the finite element method, only the static stiffness of the seat cushion is studied.

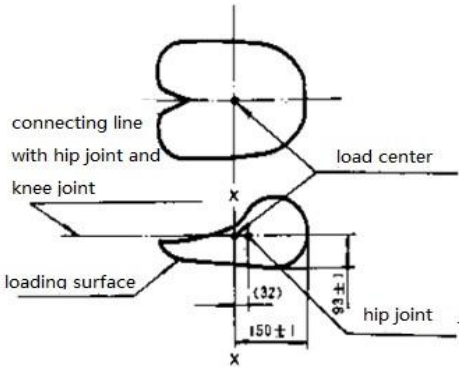


Fig.1. Loading plate for seat cushion

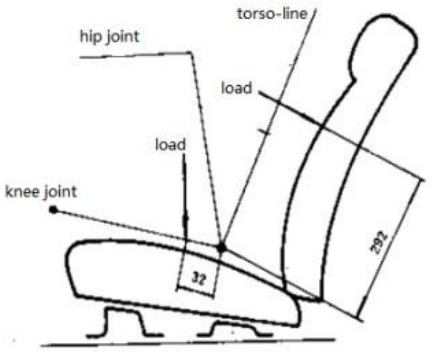


Fig.2. The loading direction and position of seat static load

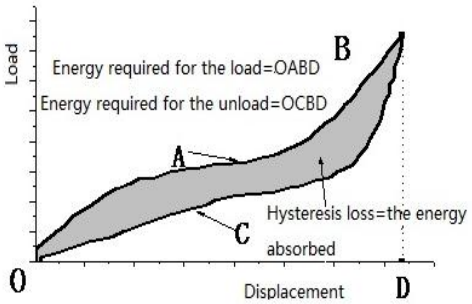


Fig.3. Schematic of hysteresis loss

$$\text{Hysteresis - factor} = \frac{S_{OABD} - S_{OCBD}}{S_{OABD}} \times 100\% \quad (1)$$

1.2. Polyurethane material

The cushion, backrest and headrest in the car seat are made of highly elastic foam, which is one of the flexible PU foams in the polyurethane categories. This material has good resilience, comfortable ride and simple production process. When the foam is subjected to external pressure, it is found that the segment of hydrogen-bonded urea phase zone is slipped, and the hydrogen bond is broken and rearranged to cope with this compression state with a new conformation. During unloading process, the foam gradually recovers to a near-original form, and there is also a break and rearrangement of hydrogen bonds with energydepleted, which results in hysteresis loss. A schematic of hysteresis lossis shown inFig.3.The shaded area in the figure represents the hysteresis loss, which is the difference between the energy required by loading and the energy required by unloading (the area between curve OABDO and curve OCBDO) [9]. The definition of the hysteresis factor is as shown in equation (1). The hysteresis factor is also called hysteresis deformation rate in the automotive industry. Related applications show that as the hysteresis deformation rate increases, the compression deformation and hardness loss for dynamic fatigue increases, resulting in poor fatigue resistance. On the other hand, the foam with low hysteresis deformation rate can also effectively buffer the vibration of vehicle during driving, so that a better riding experience can be obtained.

1.3. Objectives and hypotheses

The object of this research is a passenger car seat with detachable headrest, frame-type backrest, and half-basin-shape seat cushion frame. The main material of the seat frame is alloy steel. The inside of the seat cushion, backrest and headrest is made of polyurethane material which is a viscoelastic material with good resilience and high compression ratio. So it can absorb energy during vibration and shock.Due to the particularity of polyurethane,the three parts of seat with foam are removed during modal test. Amethod combined test with simulation is used for the static stiffness analysis of the seat. Firstly, the free modal test of the seat frame iscarried outby the method of roving impact hammer (Müller-BBM).Considering experimental frequency might lead to underestimating the resonances, which was attributed to difficulties in reproducing theoretical boundary conditions in the laboratory environment[10],the finite element model of the seat frame is established and the numerical simulation of the seat frame is carried out with the finite element software HyperWorks (AtairHyperWorks 13.0). The accuracy of the finite element model of the seat frame is verified by comparison with the experimental modal. In addition, according to the China automotive industry standard, the static stiffness and hysteresis deformation rate of the seat can be obtained. In the simulation analysis, due to the nonlinear characteristics of the polyurethane material, the feasibility of using the Law70 (Radioss material modal) is analyzed. The finite element model of the foam was constructed and combined with the seat frame model for the static stiffness analysis of car seat. According to the experimental conditions,the boundary conditions are determined and the static stiffness simulation of the seat is solved. Finally, the feasibility of using the finite element method to analyze the static stiffness of the car seat is discussed by comparing with the experimental results.

II. METHODS

2.1. Establishment of finite element model of car seat frame

The seat frames are divided into three categories referring to geometrical characteristics: the bar structure, the sheet metal structure, and the solid structure.The geometric model of the seat frame is shown in Fig.4.Bars such as bolts and spring structures are meshed by beam elements.

The sheet metal structure is meshed by shell elements with a mixture of quadrilateral and triangular elements. The solid structuresare meshed by tetrahedral elements. For welding, rigid elements are used for simulation. Based on the characteristics of the seat structures and the accuracy requirements of the solution, the element size is selected to be 3 mm. The finite element model of the car seat skeleton is shown in Fig.5.

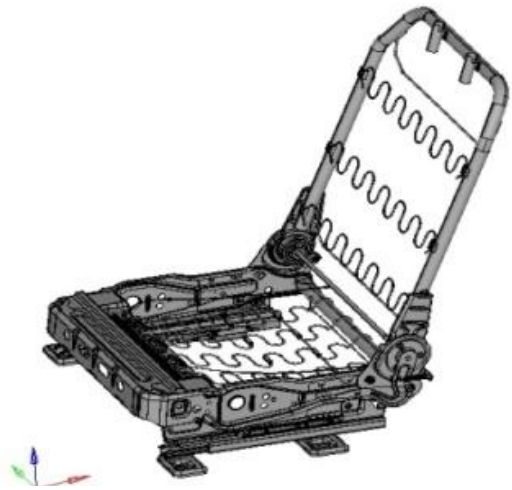


Fig.4. The geometric model of the seat frame



Fig.5. The finite element model of the seat frame

2.2. Numerical modal analysis and experimental modal analysis

Through the free-free mode analysis, the modal results of the seat skeleton in the frequency range of 1~70Hz are obtained. The first two modes are shown in Fig.6. and Fig.7.

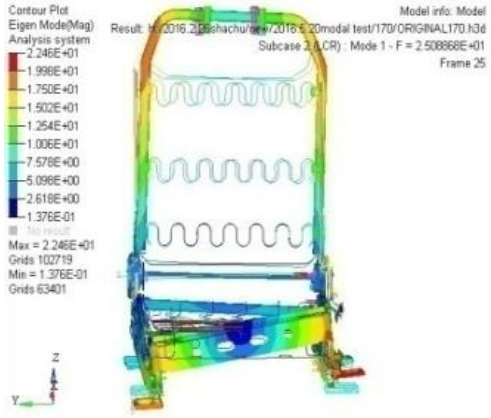


Fig.6. First-order torsion of the seat frame as a whole (1st order)



Fig.7. Left and right reverse vibration ofseat slide assembly (2nd order)

Comparing the natural frequencies and vibration modes obtained by numerical modal analysis and experimental modal analysis, it is found that except for the first-order modal error reaching 11%, the errors of other orders are within 5%. In addition, the vibration modes obtained by the two methods are consistent. Furthermore, since the third order and fourth order are local modes of the seat springs, the test data of the seat springs are not obtained, so no comparison is made with them.

The natural frequencies and modes obtained by numerical modal analysis and experimental modal analysis are shown in Table 1. The accuracy of the finite element model is verified by comparison with experimental modal results.

Table 1: the natural frequencies by numerical modal analysis and experimental modal analysis

Order	Numerical value (HZ)	Experimental value(HZ)	Error/%
1	25.09	28.23	11.12
2	34.88	35.46	1.64
3	35.33	36.83	4.07
4	42.21	—	—
5	46.28	—	—
6	53.46	52.29	2.24
7	59.41	58.61	1.36

Where, —indicates the local mode of the seat spring.

2.3. Static stiffness test of car seat

The static stiffness test is carried out in accordance with the QC/T55-1993. Additionally, the H-point is measured by a three-dimensional H-point device to determine the loading position, and the position of hip joint refers to the H-point. The position of the loading plate is as shown in Fig.8.Where, F=520mm, C=200mm, and the other parameters are related to the installation state of seat.

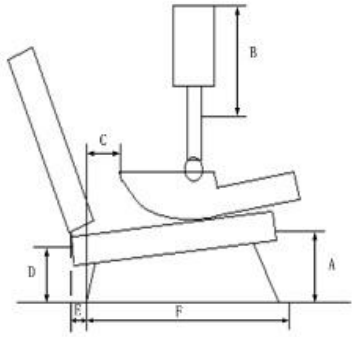


Fig.8. The position of the loading plate

The experimental system consists of a testing machine for tension and compression, a data acquisition system and the car seat system etc. The mounting feet are fixed by four bolts between the car seat and the test bench, which is the same way as the seat is fixed to the floor on the whole vehicle. In the test, the speed of loading or unloading is up to 300mm/min, and the transition time from loading to unloading is within 2s, and the total test time is 14s. The site of static stiffness test is shown in Fig.9. According to the test requirements, the test is repeated three times and the test interval is 5 minutes. During the process of three tests, the seat assembly is not damaged. The position and angle of the seat can be normally adjusted after each test, and there is also no damage at the connection between the seat and the test bench.



Fig.9. The static stiffness test

2.4. Static Stiffness Simulation of Car Seat

The polyurethane material used in simulation is the LAW70 material of Radioss which can be used to define linear viscoelastic materials. The constitutive models commonly found in linear viscoelastic materials include the Kelvin model which is obtained by connecting elastic elements and viscous elements in parallel, and include the Maxwell model, which is obtained by connecting elastic elements and viscoelastic elements in series [11] (The elastic element obeysthe Hooke's law and the viscous element obeys Newton's viscosity law). Multiple Kelvin elements in parallel or multiple Maxwell elements in series form a general line viscoelastic model. The LAW70 material can express the effect of the loading strain rate by defining stress-strain curves at different loading rates, and can also define stress-strain curves at different unloading rates if needed. There are four different unloading control algorithms for unloading behavior of the LAW70 material. The fourth algorithm is selected with load curve used for both the loading and unloading process. The stress tensor for the unloading stress isexpressed as follows:

$$\sigma=(1-\boldsymbol{D})\sigma \tag{2}$$

Where, D representsthe following equation:

$$\boldsymbol{D}=(1-\boldsymbol{Hys})\left(1-\left(\frac{\boldsymbol{W}_{cur}}{\boldsymbol{W}_{\max}}\right)^{\boldsymbol{shape}}\right) \tag{3}$$

Where, $\boldsymbol{W}_{cur}$ and $\boldsymbol{W}_{\max}$ represent the current and maximum energy values, respectively.

The mechanical behavior of the LAW70 material is controlled by the loading stress-strain curve, the strain rate during the loading process, and the scaling factor $\boldsymbol{Fscale}_{load}$ of the stress-strain curve during loading. Some other parameters such as $\boldsymbol{E}_0$, $\boldsymbol{E}_{\max}$,and $\varepsilon_{\max}$ are determined as shown in Fig.10. The material curve in the simulation analysis includes three stress-strain curves at different loading rates.

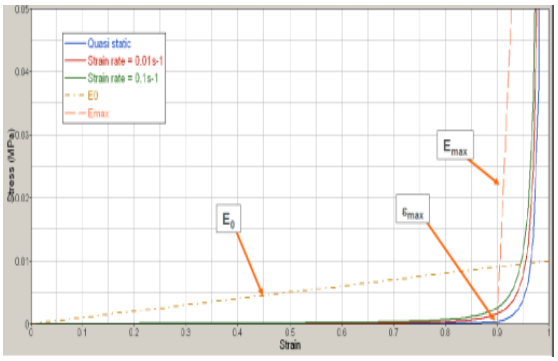


Fig.10. Determination of $\boldsymbol{E}_0$、$\boldsymbol{E}_{\max}$、$\varepsilon_{\max}$

The seat is adjusted to thesame position as in the vehiclewhile driving according to the standard and the backrest is locked at 25° of the rearward tilting position between the reference line of dummy trunk and the vertical direction. In the horizontal direction,the seat is locked to the last position as driving. The seat cushion is meshed with hexahedral elements, and which constitutes the finite element model of seat systemwith the seat frame modeltogether.

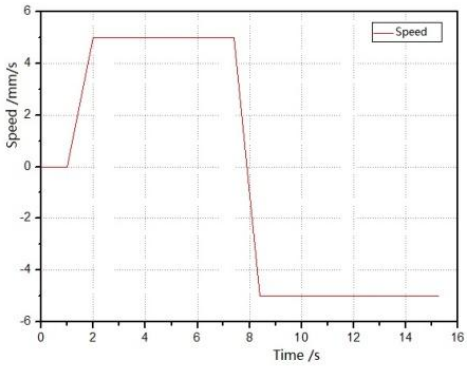


Fig.11. The speed-time load curve

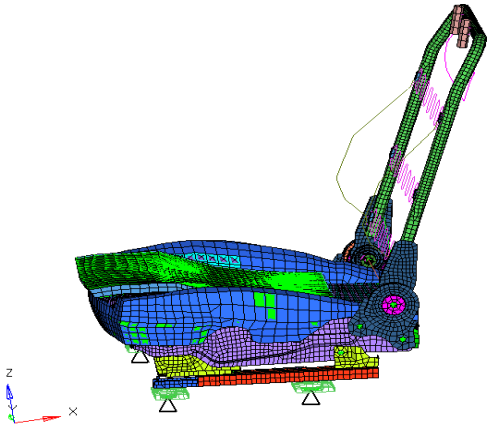


Fig.12. The finite element model for seat static stiffness analysis

In the simulation, the four mounting feet are constrained the same as the constraints in the test. In order to improve the speed of calculation, the loading plate is simplified as a rigid body with shell elements. The contact between loading plate and seat cushion is emulated as point-surface contact method, and the contact inside seat structures is defined as self-contact. Since there is the transition time required from loading to unloading, the velocity load is applied on the loading plate and output load can be converted into a load-deflection curve through the contact force and displacement.

In addition, the seat system is applied with its own gravity in the vertical direction. The loading plate is applied with a speed-time load curve containing loading and unloading conditions with a maximum rate of 5 mm/s.The speed-time load curve is shown in Fig.11. The finite element model for seat static stiffness analysis is shown in Fig.12.

III. RESULTS AND DISCUSSIONS

3.1. Test results of seat static stiffness

The load-displacement curves obtained in the three tests are shown in Fig.13. The static stiffness is calculated from the slope between loads 497N and 503N.The static stiffness and hysteresis deformation rate of the seat cushion are calculated by the three test data as shown in Table 2.

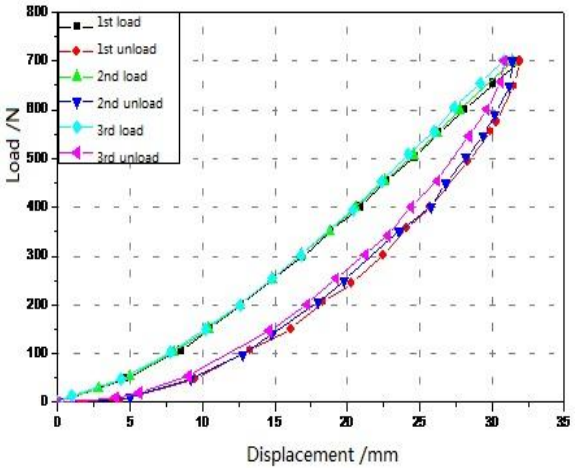


Fig.13. The load-displacement curves

Table 2: The static stiffness and hysteresis deformation rate

	Test 1	Test 2	Test 3	Average value
Static stiffness （N/m）	27.95	28.53	29.49	28.66
Hysteresis deformation rate（%）	30.1	30.6	27.7	29.5

3.2. Simulation results of seat static stiffness

The time history curves of the energy, displacement and contact force are obtained by post-processing. At the end of loading, the maximum displacement is 31.2mm, and the displacement is shown in Fig.14. Since the load applied is a forced speed, the total energy of the seat system is essentially the same as the internal energy, and they increase with loading and decrease with unloading. The hourglass of seat system can be within 10% of the total energy.The changes of energy are shown inFig.15. In order to avoid penetration, there is a slight distance between the loading plate and the upper surface of seat cushion, and the foam is soft, so that the contact force does not have a significant numerical change until 2s later after loading. It can be seen from the illustrated results that the displacement and contact force change with time are in accordance with the actual data.The curves are shown in Fig.16. and Fig.17.

With the displacement and the load are taken as absolute values, the displacement-time curve and contact force-time curve can be converted into load-displacement curve.The load-displacement curve is shown in Fig.18. It can be seen from the curve that the contact force is smaller in the unloading process than in the loading process, and the difference increases first and then decreases with the increase of displacement. These changes are related to the stress-strain curve of polyurethane material and the strain rate. According to the load-displacement curve, the simulated static stiffness is 24.93 N/m and the hysteretic deformation rate is 38.52%.

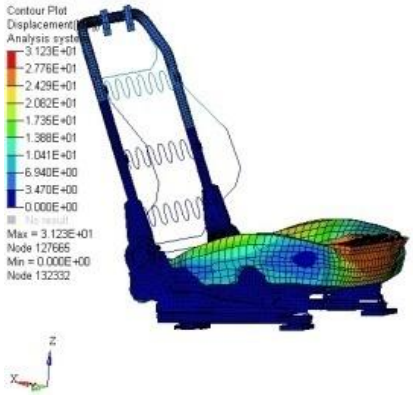


Fig.14. The displacement at the end of loading

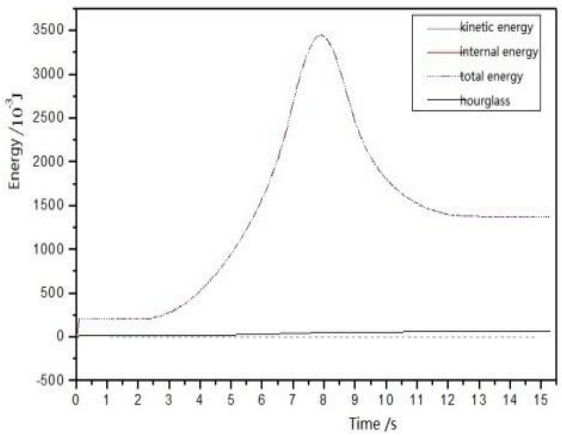


Fig.15. The changes of energy

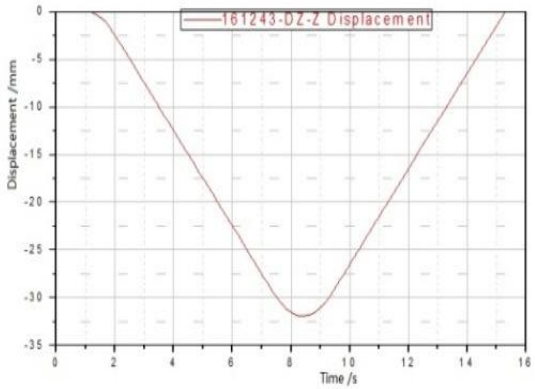


Fig.16. The displacement-time curve

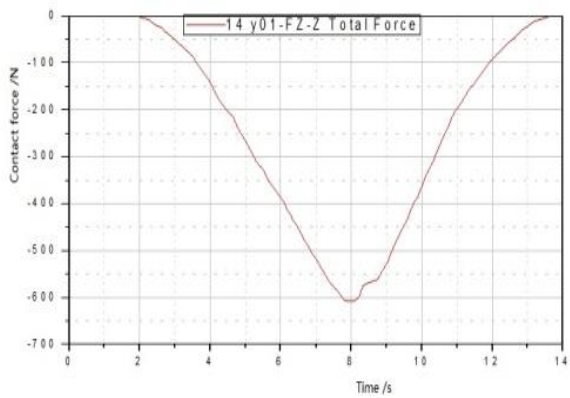


Fig.17. The contact force-time curve

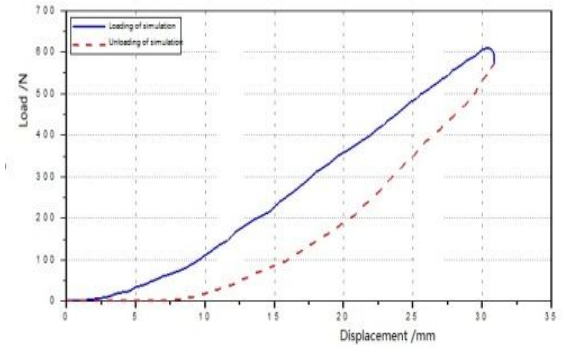


Fig.18. The load-displacement curve

3.3. Comparison between simulation and test

The load-displacement curves of the test and simulation are compared as shown in Fig.19.It is found that the trend of the load-displacement curves obtained by simulation and testare consistent, and the difference of loads at the same displacement in loading and unloading curves is small, which proves the feasibility of using the finite element model for seat static stiffness calculation. The static stiffness and hysteresis deformation rate obtained by the simulation and test are shown in Table 3. It can be found that there is a certain error in the data measured by the test and the finite element simulation, which results in lower static stiffness and larger hysteresis deformation rate in the simulation. There might be two reasons. First, in the finite element modeling process, the foam pre-stressed by the skin of cushionand the plastic baffle that supports the foam are simplified, so it is softer than the real seat cushion. Second, the relationship between strain rate and loading or unloading speed in the model of polyurethane materials is more complicated than the above defined in LAW70.

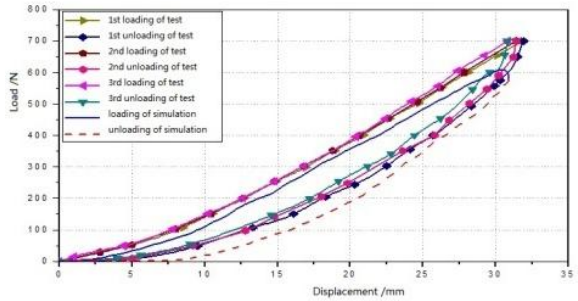


Fig.19.The load-displacement curves of the test and simulation

Table 3: The static stiffness and hysteresis deformation rate of the test and simulation

	The static stiffness (N/m)	Hysteresis deformation rate (%)
Average value of test	28.66	29.5
Value of simulation	24.93	38.52
Error	13.01%	30.56

CONCLUSIONS

In this paper, the static stiffness of car seat is studied by finite element analysis and test. The finite element model of the seat is validated by experiments, and the parameters of car seat static stiffness are obtained for seat dynamic comfort analysis. It also provides a method to simulate the material of polyurethane. Theconclusions are as follows.

1. Using the finite element analysis to perform numerical modal analysis of the seat frame, the local modes of the seat such as spring can be obtained and which is difficult to acquireby experiment.
2. In the experimental study forseat static stiffness, the hydraulic servo actuator controlledunstably and the fixed angle of mounting feet can cause lateral forces, which can generate greater experimental error. However, the finite element simulation can effectively avoid these problems.
3. In the simulation for seat static stiffness, it is a low-speed dynamic process by applying a velocity load to the seat loading plate, which can meet the requirement of transition timefrom loading to unloading. Using linear viscoelastic materials to simulate polyurethane, it mightresult in a large error in hysteresis deformation rate. This is related to the strain rate of the material model and the scaling factor of the stress-strain curve.

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