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An investigation in crashworthiness evaluation of aircraft seat cushions at extreme ranges of temperature †

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Abstract

This paper obtains a Mathematical Dynamic Model (MADYMO) for occupant lumbar load evaluation under CFR Part 23 and 25 at extreme ranges of temperature. The validation of results is performed by full scale sled test results. Aircraft industries are using visco-elastic polyurethane foams as seat cushion. Visco-elastic foams bring not only more comfort to the passengers in long term sitting but it also maintains more safety during unpredicted crashes and hard landings. Aircraft seat cushions are exposed to varying temperature ranges during their life time. This fact has motivated aircraft industries to evaluate the seat cushion dynamic behavior at extreme ranges of temperatures in addition to what is mentioned in Federal Aviation Administration (FAA) Regulations at room temperature. This research provides a methodology based on simulation and modeling to eliminate, or at least, minimize the number of full scale dynamic sled tests defined by regulations for aircraft seats at extreme ranges of temperature.

Keywords: Aircraft crashworthiness; Dynamic model; MADYMO; Seat cushion

1. Introduction

Visco-elastic polyurethane foams are the most type of foams used as seat cushions in aircraft and automotive industries. They are semi-open cell foams which introduce fairly high rate sensitivity during a dynamic deformation. The crashworthiness enhancement of aircrafts is primarily provided by seat cushion, which is part of seat structure, restraints, fuselage and landing gear [1, 2]. As a matter of fact, they bring more safety to the passengers on board during any crash or hard landing. This fact has been investigated by H. Beheshti and Lankarani [3]. However, varying the temperature causes serious variation of material dynamic behavior of these types of cushion. Therefore, it can be hazardous for passengers if the dynamic behavior sensitivity of these foams to temperature is not properly understood and tested. The Federal Aviation Administration (FAA) Regulations require a dynamic sled test of the entire seat system for certifying the seat cushions which is time consuming and costly. FAA has defined the following Test-1 condition in its regulations, CFR Parts 23 and 25, as shown in Fig. 1. This has been so far for room temperature which is not most likely appropriate for the extreme ranges of temperature.

Propelling a full scale sled testing for extreme ranges of temperature of seat cushions is very difficult, if not impossible. However, providing a quasi- static testing to evaluate the material property of foams used as seat cushion is fairly feasible. Therefore, in this research, use of quasi-static results from a MTS machine and utilizing a mathematical dynamic simulation, instead of a full scale sled test, for cushions at very low and high temperatures is proposed and validated. All tests have been conducted at the National Institute for Aviation Research (NIAR) at Wichita State University (WSU).

2. Quasi-static testing for approximate material property of foams

The lumbar load response of an occupant in a seat is dependent on the combined stroking distance of the seat structure, pan and cushion. The stroking distance reduces velocity buildup experienced by the occupant prior to bottoming-out and is desirable in limiting the magnitude of the lumbar load. In the absence of a stroking seat structure, the seat pan and cushion combination determines the outcome of the spine load response. The behavior of the seat cushion depends primarily on the property of the foam material, which, in-turn, is characterized by the compressive load versus deflection response of

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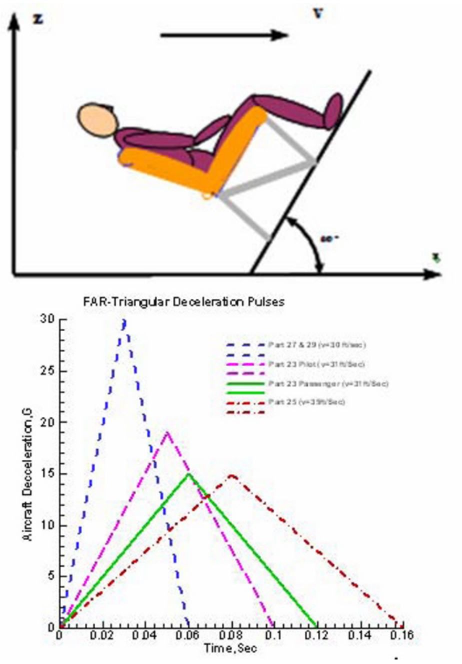

Fig. 1. FAA regulation Test-1 condition.

the material. The visco-elastic seat cushions are tested at extreme ranges of temperatures to determine their characteristics and to predict their dynamic behavior. The prediction of dynamic property of cushions is based on measurement of the load versus deflection from the quasi-static tests. A quasi-static test similar to Test B1 in the ASTM D3574-95 is performed [4]. The testing is performed at three ranges of temperature: (a) room temperature, (b) cushion heated to 50 ℃, and (c) cushion cooled to -40 ℃. The test specimen is either heated or cooled to the desired temperature. A temperature sensor is placed at the center of the cushions in order to ensure that the entire cushion reaches the desired temperature. Care was taken to avoid the contact of the cushion with the walls of the chamber. Fig. 2 shows the cooling and heating chamber used to attain low and high temperatures for testing of the cushions.

It was ensured that the quasi-static testing was completed within 30 minutes from the time the cushion was taken out of the chamber. Test procedure is shown in Fig. 3 and described below.

2.1 Quasi-static testing procedure

Prior to testing, the specimens were brought to required temperature. The following procedures should be followed:

a. Place the foam sample on the rigid test platform.
b. Lower and hold the 0.032 m^2 indentor directly over the center and in contact with the foam specimen. Feedback load should read 0 newton.
c. Start data acquisition.
d. Indent sample at the loading rate of 0.094 m/s until full compression is obtained.

Fig. 2. Cooling and heating chamber.

Fig. 3. Quasi static testing setup.

e. Unload the indentor at the same rate. Full compression is defined when the load versus deflection curve becomes almost vertical which is approximately 90% of the cushion thickness.
f. Stop data acquisition.

It has been observed from the various tests conducted with the seat cushion at a range of temperatures that at elevated temperature, there is very little effect on the material behavior of the visco-elastic cushion. On the other hand, at the lower temperature, the cushion becomes so stiffer and extremely brittle. Fig. 4 depicts comparison of load vs. deflection of visco-elastic specimen at room temperature, heated to 50 ℃, and cooled to -40 ℃.

3. Full scale dynamic sled testing

As mentioned before, a full-scale dynamic seat test, such as the one shown in Fig. 5, is currently required to certify the seat cushion and the seat system. Located in the primary load path between the seat occupant and the seat structure, seat cushion acts as a spring/damper. It is considered a primary component in the seat system, and must be included and certified as part of the seat system during the dynamic seat test program. It has been demonstrated that if the physical properties of the seat

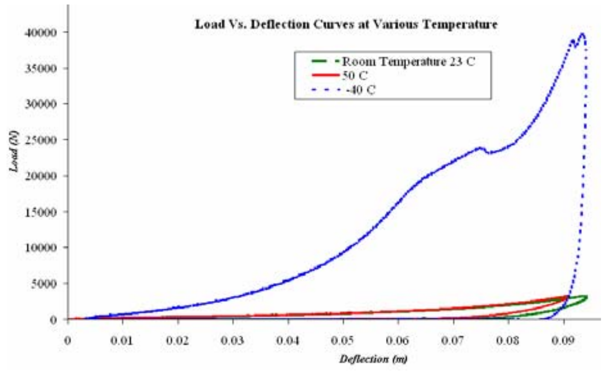

Fig. 4. Load vs. deflection characteristics of a visco-elastic foam at various temperatures.

Fig. 5. Full scale sled test for validating the mathematical dynamic model.

cushion improperly chosen, it can amplify the lumbar-column pelvic load of the seated occupant during a vertical impact [2]. The lumbar load could vary depending on the temperature at which the seat cushions are exposed to.

In this research lumbar load response obtained from full scale sled test is used to validate the mathematical dynamic model (MADYMO). Important steps in testing are as follows:

a. Incline the sled consisting of two side-by-side iron seats at 60 degrees according to the CFR Test-I condition.
b. Place two cushions on the sled seats.
c. Place Anthropomorphic Test Dummies (ATDs) on the cushions.
d. Tighten the seat belts so that just two fingers can barely pass between the belt and the dummy.
e. Propel the sled and produce a deceleration of 14 G's.
f. Obtain the lumbar load from cells connected to the ATD.

As it was performed for quasi-static testing, the exact same cushions were heated/cooled to desired temperature before it was placed on the iron seat. Care was taken to convey the cushions from heating/cooling chamber and locate it on the sled as quick as possible. Table 1 shows maximum lumbar load response from full scale sled test performed for 14 G's.

These various tests performed with the seat cushion at a range of temperatures show that at high temperature, there is merely a little effect on the dynamic behavior of the visco-elastic cushion. However, at lower temperature, the cushion becomes stiffer which lowers the lumbar load down and obtains more safety for the passenger. The small gap due to the cushion causes a secondary impact which amplifies the lumbar load. The softer cushion does not keep the body away from developing its velocity toward the seat pan so that higher velocity of impact can be existed when the cushion bottoms out [1-3]. The complication of obtaining data from a full scale sled test is obvious to all researchers who are working in the area of crashworthiness. This matter has motivated people in industry and academia to model and simulate the crash tests using mathematical dynamic models and software. This lowers the costs and eliminates a time consuming process like crash test in the most cases. In this research, particularly, since cushions are exposed to vast ranges of temperature, running an accurate sled test was more tedious.

Table 1. Lumbar load from full scale sled test at room and extreme ranges of temperature.

Temperature (℃)	Lumbar load (N)
-40	6641
23	7571
50	7624

4. Full scale dynamic sled testing

Understanding the dynamic behavior of seat, seat cushion and occupant during a sled test needs a detail study of kinematic and kinetic of all the bodies which are mathematically modeled. The body of an occupant can be divided to head, shoulders, chest, abdomen, spine, hip, femur and legs which affect the lumbar load during the compression of seat cushion and eventually its bottoming out. These bodies are connected to each other by joints which have biomechanical properties and needed to be modeled properly. Material property prediction of the bones and all the tissue compliance is one of the most challenging among all the difficulties to model behavior of the occupant during the crash. MADYMO (Mathematical Dynamic Model) is known as a versatile software which can be used to simulate dynamic behavior of mechanical systems. An explicit algorithm is employed to solve the second order time derivatives of the equations of motion for a multi-body dynamic model. The model of seat pan, back seat, sled, feet step, and the cushion are created by planes and ellipsoids. The occupant is modeled by a hybrid dummy ATD (II) validated for crashworthiness investigations.

The serious effect of seat belt on the safety of passengers has been verified to scientists in automotive and aviation community. Therefore, the accuracy of modeling the seat belt is so important in simulating the sled testing of the whole seat system and occupant. Two point constraint of seat belt configuration, as it is used for aviation purposes, has been used to keep the dummy tied to the seat. It is user's decision to choose

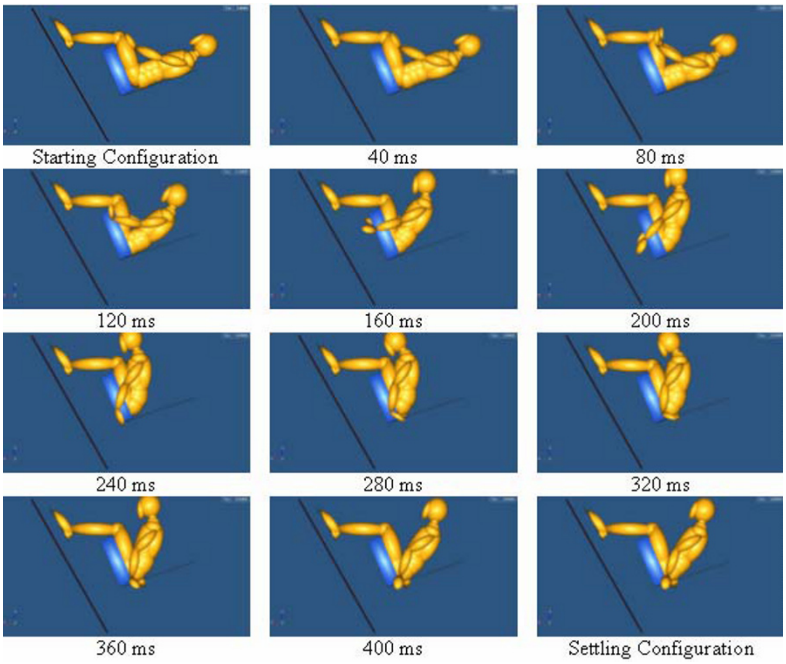

Fig. 6. MADYMO occupant kinematics subjected to 14 G's pulse.

the number of segments for the seat belt, and for the sake of simplicity of the model, it is considered five in this model. The extensive care has been taken to create the model as comparable as possible to the real life scenario of sled testing.

The contact between the belt and the body is defined with friction coefficient of 0.2 such that it can slip on the dummy.

The friction coefficients between the dummy and back seat and the seat cushion have been considered 0.3.

The friction between the legs and step has been put equal to 0.45. The contacts between the different parts of the model have been defined so that the penetration between the dummy and solid parts such as sled, seat pan and seat back do not occur. In addition, the material properties of the cushion have been utilized by taking advantages of load vs. deflection characteristics of the cushion provided from quasi-static testing.

The rate of loading used for MTS testing was 0.094 m/sec which is far below the speed at the real impact scenario; about 10.7 m/sec. It is evident that the rate sensitivity of cushion affects the lumbar load results. This issue is being taken into account by using the dynamic load factor which is dependent on the strain rate [5]. The model has been validated for bare iron seat and different seat cushion buildups at room temperature by H. Beheshti and Lankarani [6].

In this research, quasi-static data provided for cushions at ranges of temperature was used to incorporate material properties of these cushions in lumbar load estimation by mathematical dynamic modeling. This helps us understand the effect of temperature of cushions on lumbar load for test condition one shown in Fig. 5 without propelling the full scale dynamic sled testing. Fig. 6 shows the kinematics of the created model for different time steps. This model illustrates the movement of different part of the body at each time step.

The maximum lumbar load happens when cushion is completely compressed or is bottomed outs. There is a secondary impact involved between the buttocks and the hard surface of the seat or bottomed out cushion. At the very beginning of the deceleration of the sled whole body starts its movement toward the seat pan. Afterward upper torso bends about the hip which can affect the level of lumbar load. Finally, lower part of the body reaches its maximum stroke toward the seat pan. At this moment, a maximum amount of lumbar load is recorded. Eventually, occupant bounces back, following a little oscillation, until its settlement.

Fig. 7 depicts variation of lumbar load versus time for a visco-elastic cushion at room temperature, 50 ℃ and -40 ℃. A fairly good agreement is observed between two graphs for room temperature and foam at 50 ℃. This matter is due to the fact that cushion's properties do not vary very much by increasing its temperature. The maximum level of lumbar load for these two cushions is validated with what was measured by running a full scale sled test. A great agreement is shown between mathematical model and experimental results.

However, lumbar load is much lower for the same cushion at -40 ℃ which is not consistent with what was measured by full scale sled test. This is perhaps because of the fact that at very low temperature running an accurate full scale sled test is very difficult so that the results from MADYMO are more reliable. The important steps for performing the full scale tests explained in preceding sections.

This is obvious that these steps for running full scale dynamic tests are much more tedious and time consuming compare to quasi-static testing of the cushions mentioned in previous sections. Therefore, particularly for the cushion which is just taken out from the heating/cooling chamber, it is more

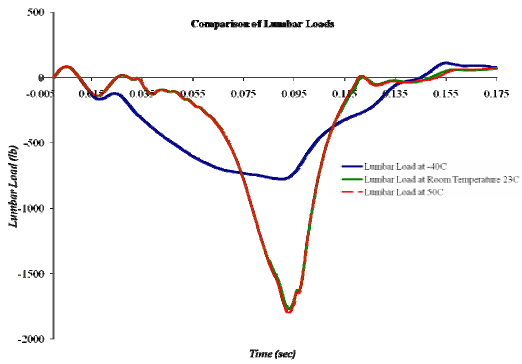

Fig. 7. MADYMO results for estimation of lumbar load for visco-elastic cushions at room temperature, -40 ℃ and 50 ℃.

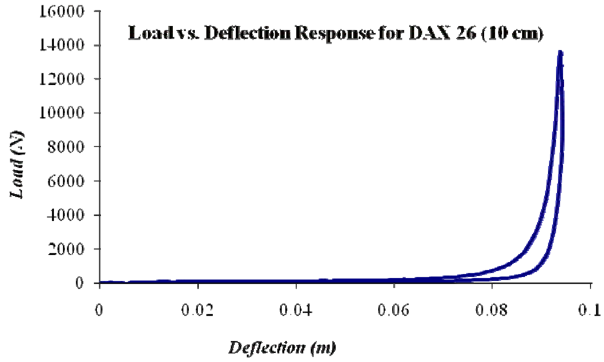

Fig. 11. Load vs. deflection characteristics of a DAX foam at room temperature.

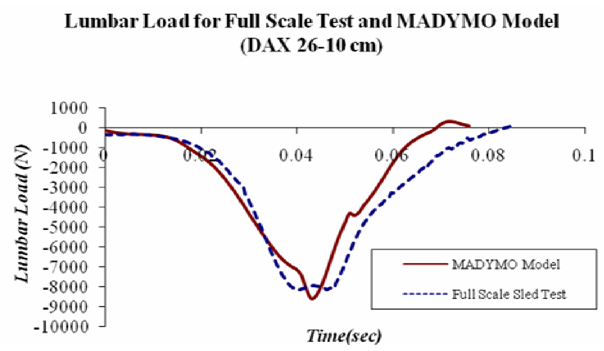

Fig. 8. MADYMO validation for a DAX foam at room temperature.

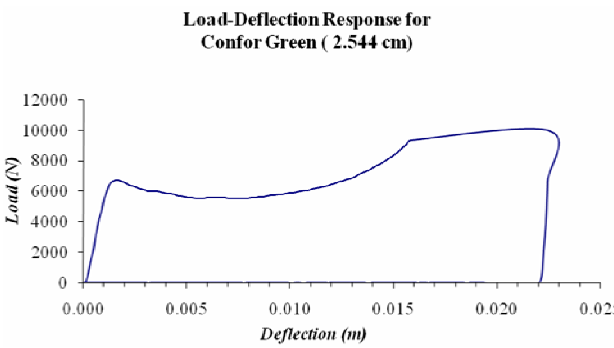

Fig. 12. Load vs. deflection characteristics of a CONFOR foam at room temperature.

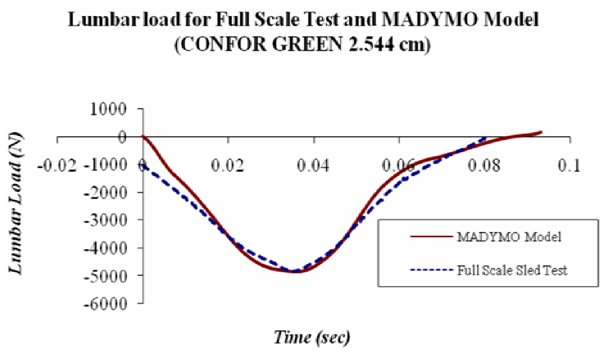

Fig. 9. MADYMO validation for a confor foam at room temperature.

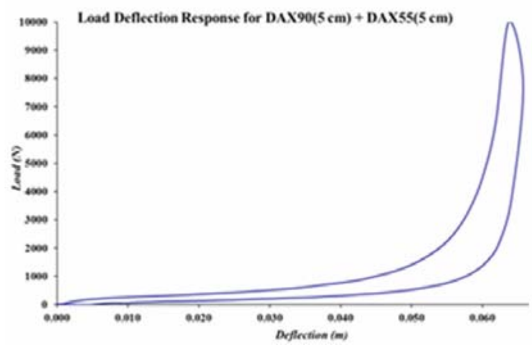

Fig. 13. Load vs. deflection characteristics of a build up foam at room temperature.

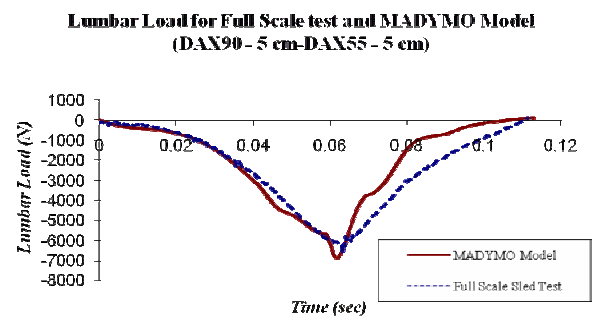

Fig. 10. MADYMO validation for a build up foam at room temperature.

accurate to run quasi-static testing than propelling full scale sled test.

Altering the temperature of the cushion for full scale tests is much more than quasi-static tests, which results in material properties disparity, so that the MADYMO results are more accurate and reliable for these cases.

The MADYMO model, itself, has been validated for so many build up and industry cushions. Figs. 8-10 show a fairly good agreement between MADYMO and full scale sled test for some cushions with load deflection at room temperature illustrated in Figs. 11-13, respectively.

The cushion at -40 ℃ becomes a very hard substance.

Humidity of the air inside the cells of the cushion freezes to the ice and makes the whole cushion like a piece of ice. This is expected to have a very low lumbar load for occupant sitting on a bare iron seat [7, 8]. This is another proof that mathematical model results have more reliability for cushions at low temperature.

5. Conclusions

This research has introduced some simulation and modeling approach to study aircraft seat cushion performance during a crash at extreme ranges of temperature. Temperature variation of the cushion affects the rate sensitivity of foams, consequently, changes the dynamic behavior of the cushion during the crash. Propelling a full scale dynamic sled test is not always possible for very low or high temperatures. The first solution to overcome this issue is to utilize a validated mathematical model to calculate the lumbar load for a typical occupant. This matter is carefully investigated in this study which depicts a fairly good output for at least two case studies. All the effort has been made to create a model similar to a real life scenario of sled testing. A fairly good agreement was observed in the maximum lumbar load for a visco-elastic cushion at room and 50 ℃. In addition, the use of a quasi-static testing instead of a full scale sled testing is also introduced in this research. This approach is very cost effective and time saving. As a matter of fact, use of quasi-static testing data in the mathematical model makes it possible to calculate the occupant lumbar load even for cushions at extreme temperatures. A visco-elastic cushion at -40 ℃ is compared with high rate sensitive foam existing in market. Therefore, such a mathematical model can be utilized as a tool either in certification process or scientific detail study of foam dynamic behavior at extreme temperature.

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