Correlation of the Federal Motor Vehicle Safety Standard 225 (FMVSS225) Requirement of an Automotive Seat System Using LS-DYNA

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ABSTRACT

The National Highway Traffic Safety Administration (NHTSA) has issued a final rule for a new safety standard related to child seats and their anchorage systems in vehicles. FMVSS 225 – Child Restraint Anchorage Systems (CRAS) requires that motor vehicle manufacturers provide a new method for installing child restraints that are standardized and independent of the vehicle seat belt. The requirements for CRAS can ensure their proper location and strength for the effective securing of child-occupants in an automotive seat system.

There are four pull tests for FMVSS 225 - forward pull with top tether, forward pull without top tether, lateral pull to the right, and lateral pull to the left. The tests are performed by applying a specified load to the child seat anchorage system using Static Force Application Devices (SFAD), mandated by NHTSA. The regulation requires that the displacement of the load application point on the SFAD, along the horizontal plane, should be less than 125 mm and there should not be any structural separation [1][2].

LSDYNA is widely used for the "quasi-static" simulation of the automotive seat systems and plays a key role in improving design and saving cost. Due to the dynamic effects in quasi-static simulations, correlating the displacement for FMVSS 225 using LSDYNA becomes a challenge. At Lear Corporation's test lab, physical tests were conducted on number of different seats and the results were correlated by simulating the tests in LSDYNA. Based on the knowledge and data collected over a period of 3 years, the authors have established a methodology to simulate FMVSS 225 and correlate accurately with the physical test.

INTRODUCTION

New car buyers not only are looking for attractive styling, better performance and power, but also are concerned about safety. During the last decade, lot of safety devices such as air bags, advanced seat belts and CRAS have been introduced. FEA has played and continues to play an important role in the development of such safety systems. However, much more still needs to be accomplished to satisfy the increasingly stringent legislation and public demand.

Non linear FEA code such as LSDYNA is widely used to predict the structural response of the automotive systems. FE simulation plays an important role in determining the correct stress levels and deformation modes of the critical components. Increasing demand from the OEMs has accelerated the study of CRAS and has helped evolve a good working FE methodology that works for all the seats irrespective of their stiffness and functionality.

Mathematical Interpretation of Displacement Response

The physical tests mandated to meet the FMVSS225 requirements are static in nature. Since LSDYNA is an explicit solver for dynamic analysis, the static test condition is simulated as quasi-static.

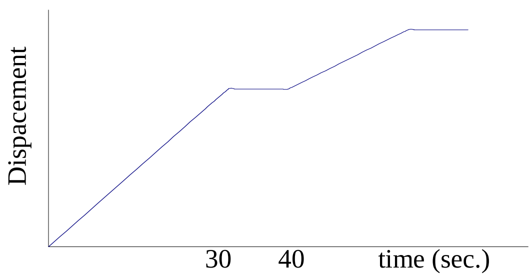

Figure 1. Physical Test Displacement-Time Curve

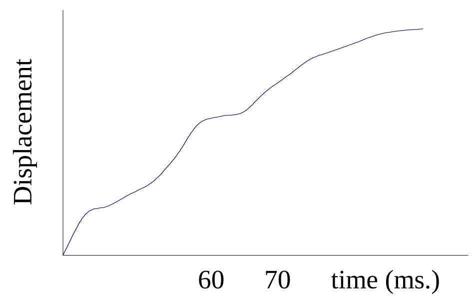

Figure 2. FEA Displacement-Time Curve

Figure 1 shows the displacement vs. time plot of a typical static test. The displacement increases when load is increased, and stabilizes during the holding period of the load. In the FE analysis using LS-DYNA, the very explicit nature of the solver compels us to attain the load in a fraction of the static case. Figure 2 illustrates a typical displacement-time output of a quasi-static LSDYNA run. Though the load is held constant between 60 and 70 ms, the displacement does not stabilize. This phenomenon can be described by the mathematical formulation of the Duhamel's integral for dynamic response [3].

Response to a Step Function Load with a Rise Time

For an undamped system, the Duhamel's integral for a ramp function is

$$u(t) = \frac{1}{m\omega}\int_0^t \frac{Po\,\eta}{t_1}\sin\omega(t-\eta)\,d\eta \tag{1}$$

Assuming Young's Modulus remains constant, Equation (1) simplifies to

$$u(t) = \frac{Po}{K}\left(t/t_1 - \frac{\sin\omega t}{\omega t_1}\right) \quad \text{, for } t \le t_1\text{, where} \tag{2}$$

u(t) = Displacement
Po = Force applied to the system
K = Stiffness

ω = Natural frequency of the system
η = Time variable
t_1 = Ramping ends

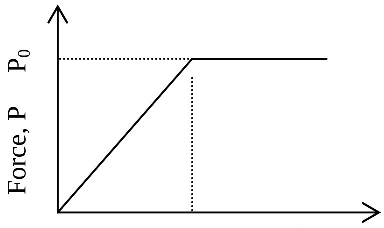

Figure 3. Input Function

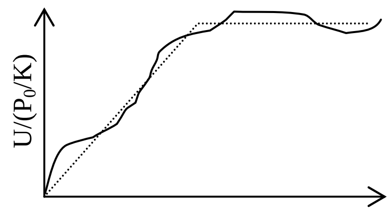

Figure 4. Response of the Input Function

Figure 3 represents input function load to a system. The required load P_0 is attained in time, t_1. Figure 4 is response to the input function. From equation (2), the response to a step function applied at time $t = t_1$ is

$$u(t) = \frac{P_0}{K}\left\{\frac{t-t_1}{t_1} - \frac{\sin\omega(t-t_1)}{\omega t_1}\right\} \quad (3)$$

Subtracting equation (3) from equation (2)

$$u(t) = \frac{P_0}{K}\left\{1 - \frac{\sin\omega t}{\omega t_1} + \frac{\sin\omega(t-t_1)}{\omega t_1}\right\} \text{ For } t > t_1 \quad (4)$$

The maximum value of the response can be obtained by differentiating equation (4). Substituting the value of t from du/dt = 0 in equation (4)

$$u_{\max} = \frac{P_0}{K}\left\{1 + \frac{2\sin(n\pi - \frac{\omega t_1}{2})}{\omega t_1}\right\} \quad (5)$$

The value of integer n should be chosen such that the second term within the braces in equation (5) is positive.

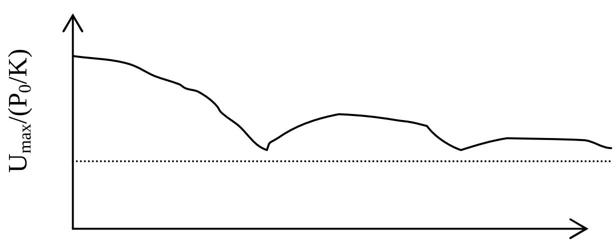

Figure 5. Response Ratio vs. Time

The response ratio, $U_{max}/(P_0/K)$ is plotted as a function of $\omega t_1/2\pi = t_1/T$, where T is time period. It is evident from equation (5) and figure 5 that as t_1/T increases, the maximum response tends to a value close to the static displacement under load P_0. So, if the load is applied very gradually, the response is essentially static.

FMVSS225 Physical Test Set Up

For the FMVSS225 test, seats are tested on a rigid fixture with foam and trim. Figure 6 shows the CRAS setup, which includes a top tether and two lower anchorage hooks. The tether runs from the top of the child seat to the attachment location. The lower anchorage hooks, located at the seat bite line, are used to connect the child seat to the seat system. The new CRAS is totally independent of the vehicle seat belts and will only have the anchorage hooks. In both physical tests and FE simulations, the SFAD2 fixture (Figure 7) represents the combined mass of the child seat and the child. SFAD1 is used to test a child seat system without CRAS, and is a subject of a different discussion.

There are four physical tests associated with FMVSS225 as described in detail in Table 1. For each of the tests, the displacement of SFAD2 in the horizontal plane cannot exceed 125 mm. For Test1 and Test2, the SFAD2 is pulled at 10^0 to the horizontal axis. For lateral pulls (Test 3 and Test 4), the load is applied in the horizontal plane, 75^0 to the forward pull direction [4].

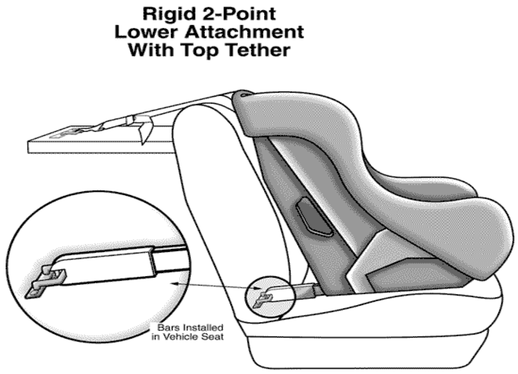

Figure 6. Child Restraint System

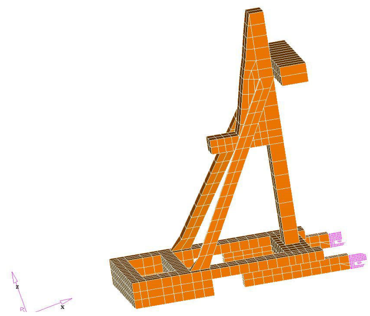

Figure 7. SFAD2

Previous Methodology

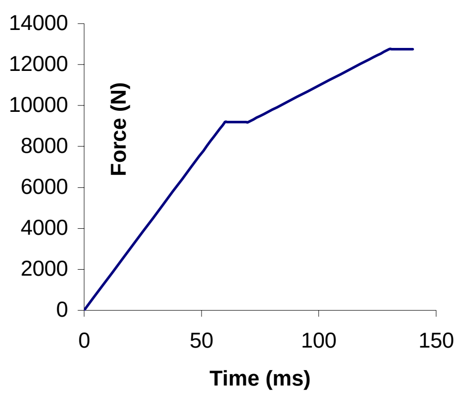

Figure 8. FE Load Curve for Test 2

For Test 1 and Test 2, a load of 9200N (8KN + 15%) was applied to SFAD2 (Figure 7) in 60 ms. The load was held for 10 ms. The displacement was reported at 60 ms. For the ultimate loading, the 12750 N (11KN + 15%) load for Test 2 was attained at 130 ms and was held for 10 ms. The entire simulation was a two step loading, similar to the physical test set up, as shown in Figure 8. The maximum stress/strain were looked into at 130 ms to predict the behavior of the system at ultimate load. As described earlier in the mathematical interpretation of dynamic response, the displacement did not stabilize between 60 and 70 ms. FE loading is much faster than the physical test loading. Dynamic effect is significant in some seat simulations using LSDYNA explicit code, and that makes the simulation look much more severe than the physical test.

As a result of discrepancy between the FEA and physical test, a new methodology was developed to improve the accuracy.

Table 1. Load Conditions of FMVSS225

Test Description	Load Profile				Requirement
		Test (sec.)	F (KN)	FEA (ms)	
Forward pull with top tether and lower anchorages (Test1)	Initial	0	0.5	0	Displacement of the X_point (< 125 mm) is measured at 8KN and no structural separation at 15 KN.
	Intermediate	27	8	60	
	Hold	29	8	70	
	Ultimate	41	15	130	
	Hold	43	15	140	
Forward pull with lower anchorage only (Test 2)	Initial	0	0.5	0	Displacement of the X_point (< 125 mm) is measured at 8KN and no structural separation at 11 KN.
	Intermediate	27	8	60	
	Hold	29	8	70	
	Ultimate	41	11	130	
	Hold	43	11	140	
Lateral pull to the right & left with isofix only (Test 3 & 4)	Initial	0	0.5	0	Displacement of the X_point (< 125 mm) is measured at 5KN and no structural separation at 5 KN.
	Peak	29	5	60	
	Hold	40	5	70	

APPROACH

New Methodology

The new methodology is based on a study done on a cantilever beam (300x40x4mm), as shown in Figure 9. The beam was subjected to a point load of 3 KN at the free end, and the other end of the beam was constrained in all degrees of freedom. SAE950 material was used for the beam. The rate of loading on the beam was varied from 15 ms to 500 ms, as shown in Table 2. The load was held till the displacement stabilized. The average value of displacement was calculated by taking the average of the displacement at peak load and the displacement at the end of the hold period (when the displacement stabilizes). Figure 10 is the plot of the displacement at the peak load, stabilized value and the average value. It can be easily inferred that as the ramping time increases, the displacement value at the peak load converges to the average value. This method is valid only if there is no structural failure during the test.

Figure 9. Cantilever Beam with Boundary Conditions

Table 2. Rate of Loading on the Cantilever Beam

3KN load attained in (ms)	Displacement at Peak Load (mm)	Stabilized Displacement (mm)
15	40	180
30	50.8	168
60	87.4	124
120	101.5	114.4
180	100	109
500	99.8	102

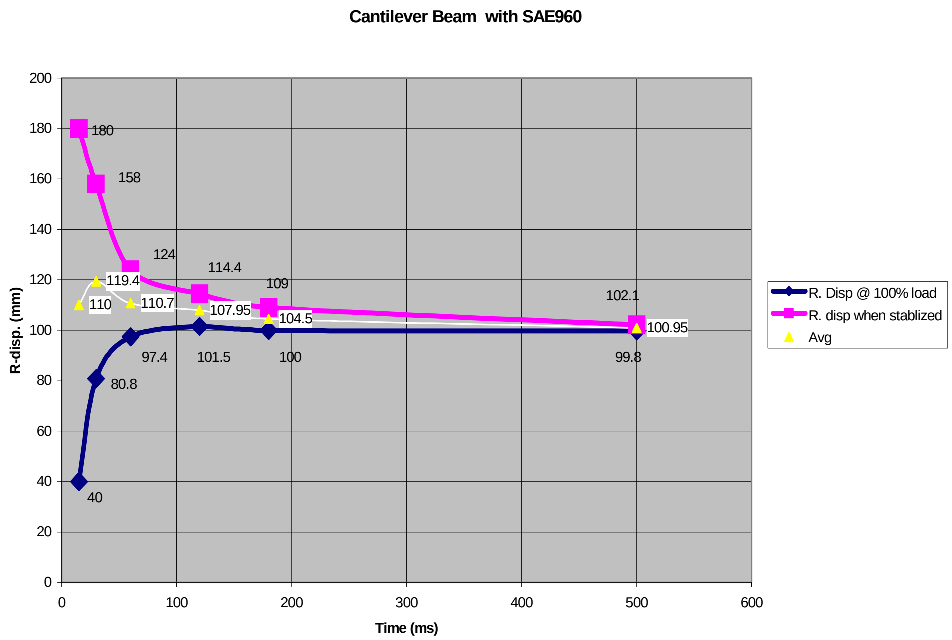

Figure 10. Displacement with Different Ramping Rates for Cantilever Beam

FE Modeling Technique

Most components of the seat structure are built from metal stampings and tubes, and were modeled using shell elements. Critical latches and strikers were modeled as solid elements using element formulation 1 and hourglass control 6 [5][6]. Bolts and rivets that attach the different parts of the seat assembly together were modeled using beam elements. Bolts and washers were modeled to connect the seat risers to the rigid fixture [7]. Pivoting action of any bolt or joint was simulated by a regular beam element with a very low value of torsional rigidity. The rigid fixture was modeled using shell elements and was assigned rigid material property. Seat cushion foam was modeled using solid elements and all the foam contours were captured accurately. *CONTACT_AUTOMATIC_SINGLE_SURFACE was used for regular contact between all components and *CONTACT_AUTOMATIC_GENERAL was used for contact between the solid isofix hooks and SFAD2. To reduce the dynamic effects of the SFADs, a very low density material (density = 1.0e-9 Ton/mm3) was assigned to them, and CONTACT_INTERIOR was used to simulate the foam's interior contact to avoid negative volume. Seat belt loading and unloading curves (Strain, Force) were stiffened using high values of strain and force to maintain the acceptable energy ratio, Total Energy/Initial energy [8].

Correlation of Physical Tests with FEA

To support the new methodology, Test 2 (Forward pull without top tether) was chosen and better correlation was achieved using the technique. The new method was used on various seats of different vehicle programs. Four different rates of loading were chosen to attain peak loads for a particular seat. The load was attained in 60, 120, 180, and 240 milli-seconds. In all these cases, the hold period of 60 ms was sufficient to stabilize the displacement values. The displacements at the peak load, the displacement when the curve stabilizes and the average of the two were obtained in each case. Figure 11 summarizes the results for the four different load ramping rates.

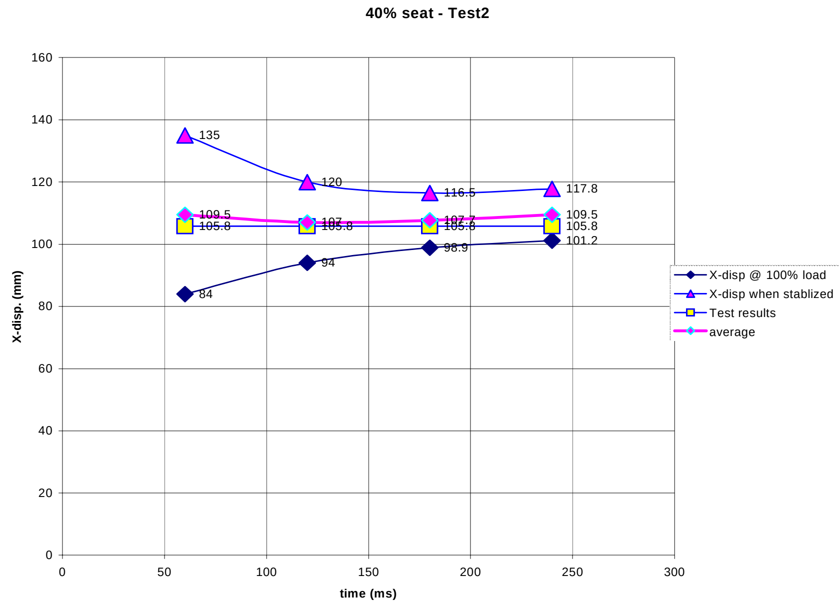

Figure 11. Results of Different Ramping Rates

From Figure 11, it is observed that displacement value at peak load is much closer to the test result, when peak load was achieved over a longer period of time. But due to computer time limitations, running a simulation for longer period is often not feasible. The observations in Figure 11 present a clear alternative, without sacrificing accuracy. In each of the four cases, the average value is very close to the test results. Hence, the simulation can be run with a faster ramping rate and peak load can be held till the displacement stabilizes.

A separate analysis was performed for the ultimate load case, which tests the structural integrity of the seat system. Since there is no displacement requirement for this loading case, the ultimate load was attained in 60 ms and held only for 10 ms. The stress and strain levels are much more reliable using this new methodology. Also, by using this new methodology, the kinematic behavior of the seat, as seen in the physical test, was captured accurately in the FE simulation.

CONCLUSIONS

- The FE displacement correlates with physical test result. The average of the displacement at 60 ms and the stabilized displacement gives the best correlation.
- To validate the structural integrity of the seat system, a separate analysis should be performed.
- Stiffer seat belt property should be used.
- Low-density foam should always be used to model seat cushions, and the model should accurately capture the foam contours.
- The mass of the SFAD should be kept minimal to reduce dynamic effects.

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