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Verification of Automotive Monopost Seat Strength through Dynamic and Quasi-Static Simulations

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Abstract: A monopost seat is a novel, lightweight seat developed to utilize most of the interior space of vehicles. The space under the seat can be utilized by inserting a monopost columnar structure between a monopost seat rail and the floorboard. This design increases the perceived spaciousness of the vehicle and imparts passengers with a higher degree of freedom, because the seats can be adjusted more easily than standard seats. Meeting these requirements will require the seats to be sufficiently strong and sturdy in order to maintain passenger safety. Compared to traditional seats, it is more likely that a monopost seat will shift under the mass of the passenger, and these seats are more vulnerable to external vehicle collisions. Passenger safety is further compromised if an operational function is added. Therefore, further research on monopost seats is required. This study performed quasi-static and dynamic simulations to determine if the attachment of monopost seats to a vehicle meets international safety requirements in collision events. With a focus on clarifying the dynamic simulation process, the outcomes of quasi-static simulations were compared with the results obtained from dynamic simulations.

Keywords: automotive monopost seat; strength analysis; collision simulation; seat belt anchorage test; LS-DYNA

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1. Introduction

As the number of vehicles on the road increases, environmental and energy problems increase because of exhaust emissions and excessive oil use. In recent years, electric vehicles have steadily replaced traditional vehicles with internal combustion engines. The floor space of an electric vehicle is more extensive and stable than a standard internal combustion engine vehicle because of the absence of drive shafts. Despite this, the internal space cannot be fully utilized because the seat frame structure, which occupies most of the internal area, is unchanged.

The total weight of an electric vehicle has a significant influence on its mileage. Hence, a change in the internal structure is required to utilize the internal space better and reduce its weight. Automotive seats occupy a significant amount of interior space and account for 3–5% of the vehicular weight [1]. Therefore, improvements to standard seats are required.

In standard automobile seats, a square-shaped frame closely connects a cushion part to a floorboard. The space under the cushion cannot be utilized, and the seat structure occupies most of the space inside the vehicle. The limited internal space of a vehicle can be innovatively improved by increasing the openness and spaciousness by applying a monopost columnar structure instead of the traditional square frame.

By setting a columnar monopost structure between the rail and the floorboard of a vehicle, cushions can be separated from the floorboard, and the space under the seats can be used, increasing passengers' perception of openness and spaciousness. The National Highway Traffic Safety Administration (NHTSA) website provides vehicle collision models, and the 2019 Honda Odyssey model is freely downloadable [2]. Figure 1 presents a seat in the 2019 Honda Odyssey and the space available under a monopost seat. Monopost seats are thinner and lighter than standard seats because they use novel materials.

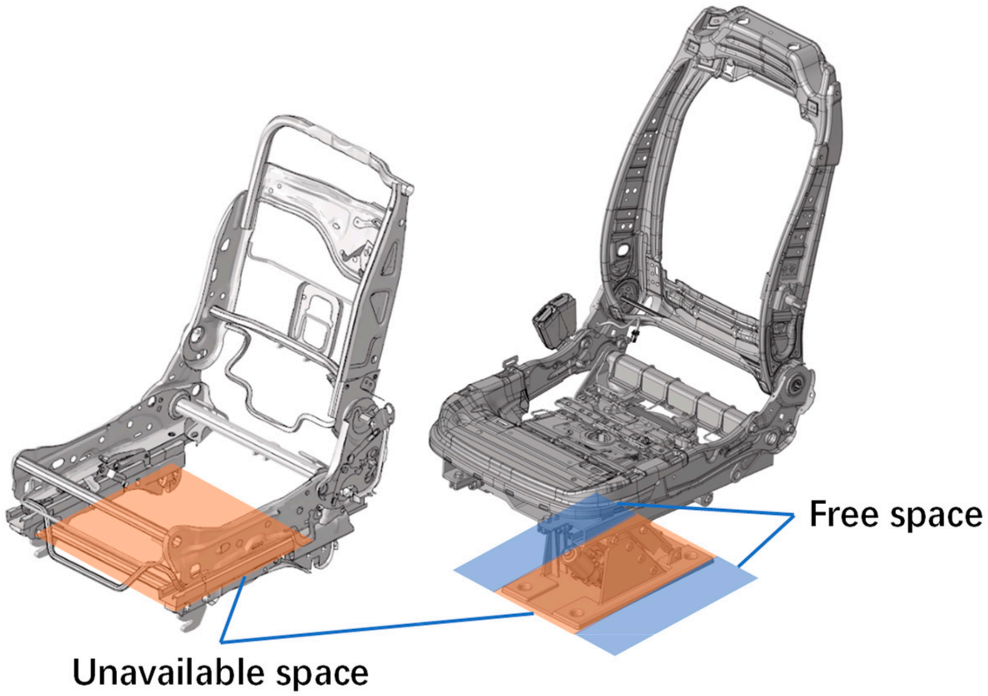


Figure 1. Comparison of a 2019 Honda Odyssey seat and a monopost seat with the available space underneath.

Vehicle seats provide passengers with ride comfort and safety in collision events. Nevertheless, they should be sufficiently sturdy and lightweight, and should provide increased freedom of movement.

Haining Chen et al. (2014) evaluated the passenger protection capacity of seats in front- and rear-end collisions using LS-DYNA. The simulation results indicated that structural modifications were necessary to ensure passenger safety. Four improvements were made to the seat structure based on the seat stress analysis, the seat side panel, center hinge, seat bottom frame, and backrest lock. A passenger model sustained fewer injuries when the re-designed seats were re-simulated [3].

Peicheng Shi et al. (2017) examined an automobile seat with a focus on seat belt fastening and sliding parts, using LS-DYNA, in accordance with GB14167-2013 national standards [4]. The re-designed and finally optimized seat met regulatory standards [5].

In compliance with ECER1414 requirements, Ömer Osman DEVECİ et al. (2019) examined the effects of the material type, thickness, and cross-sectional symmetry on the strength of an automobile seat slider, where the material type demonstrated the most significant effect. The increase in material strength compensated for the decrease in strength caused by the thinner cross-section when S700MC material was used. In addition, the symmetry/asymmetry of the cross-section had a negligible effect [6].

Ömer Osman DEVECİ et al. (2021) assessed a design method for a lighter front seat rail. A built-in stand pipe that can replace a single set of existing stands for an automobile seat rail was developed. The final model passed a crash test and was 26.7% lighter than a standard seat [7].

Kyu-Chun Cho et al. (2018) performed a strength test on a motor seat frame made for commercial vehicles weighing one ton, in order to identify its vulnerable regions. The experiment conducted on the seat frame strength followed the FMVSS210 test standard and was conducted using ANSYS software. The results showed that the seat support was a vulnerable component. The experiment and simulation results were compared, and there was a 5–10% difference, confirming the validity of the experiment results [8].

A seat belt serves to restrain a passenger to a seat in a crash or rollover event. It prevents or mitigates collisions between passengers and internal compartment components. A M Manea et al. (2022) constructed two simplified seat structure models that were simulated using finite element simulation software. The simplified models reduced the complexity of the automobile seat modeling and finite element simulations [9].

The safety of existing automobile seats has been verified in numerous vehicles, but vehicles that use monopost seats are uncommon. The application of a monopost seat in the Tesla Model X, which is an electric vehicle, led to the mass production of monopost seats. On the other hand, although the second-row monopost seat in the Tesla Model X has tilt and sliding functions, it was not designed to be lightweight, owing to its steel-based frame. Most alternative monopost seats have been designed for future concept vehicles that are yet to be mass-produced. While previous research on existing general seats is highly advanced, studies on monopost seats are required because of their scarcity.

2. Monopost Seat

This study selected the monopost seat currently under development by DAS, which is composed of upper and lower sections. Figure 2 presents its composition. The upper section has a similar structure to a standard seat available on the market, whereas the lower section is an integral component of a monopost seat. Figure 3a presents the composition of the lower section. The monopost part is comprised of a sliding rail, screw, electric motor, and high-strength bolt. The electric motor moves the screw, and the sliding rail that connects the upper and lower sections controls the forward and backward movements of the seat. In contrast, the riding rail controls vertical movement. Figure 3b–d show the dimensions of the bracket and slide rail. A monopost seat is equipped with a three-point seat belt; one of the three seat belt fixtures is placed on the seat, whereas the other two are placed on the vehicle frame.

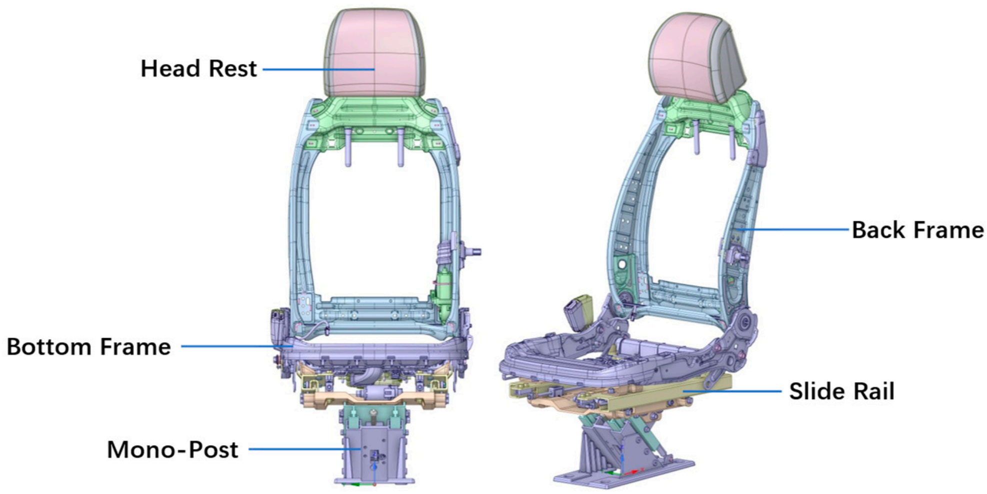


Figure 2. Composition of a monopost seat.

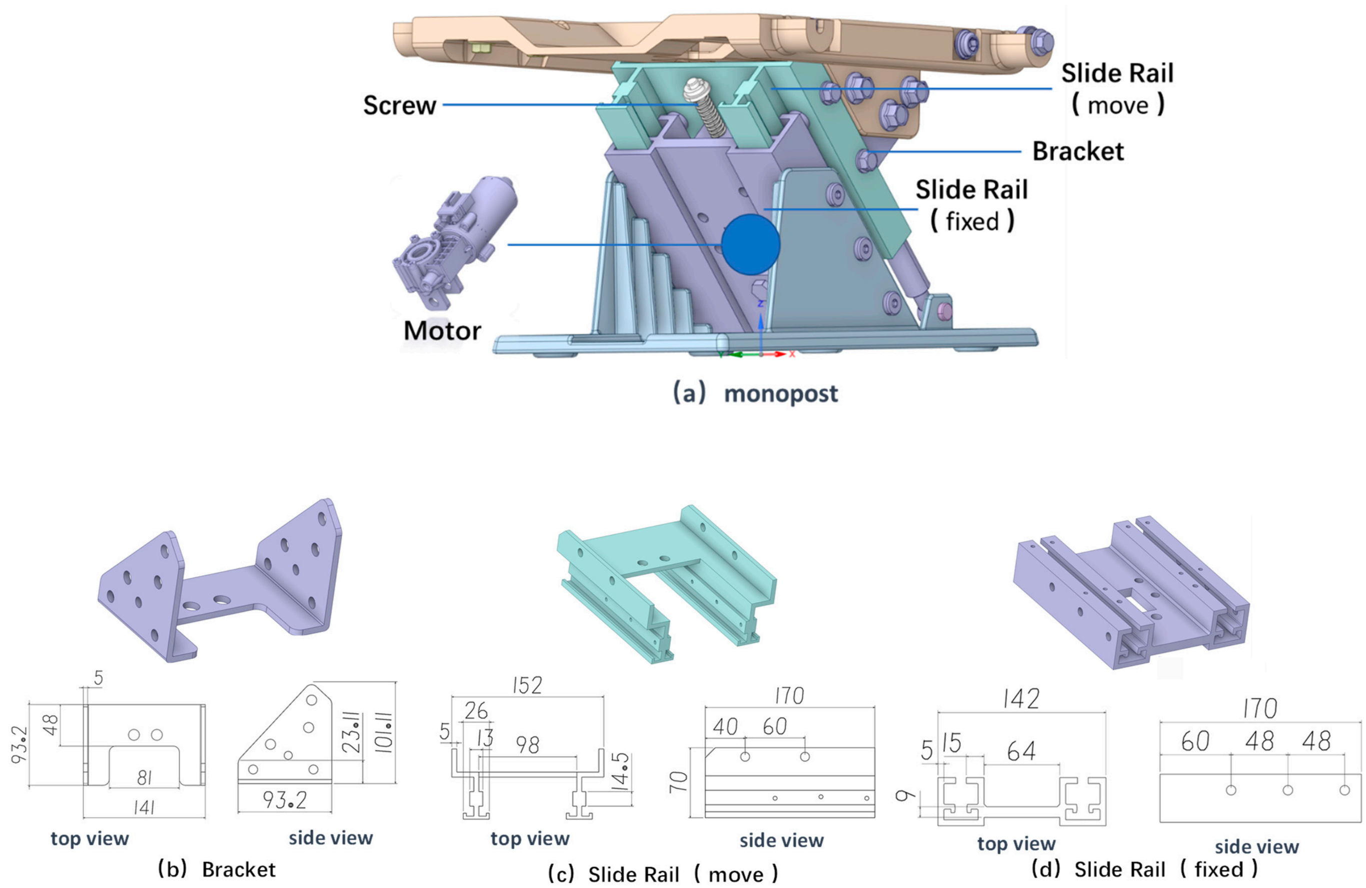


Figure 3. Composition of the lower section of the monopost seat (unit: mm).

Figure 4 presents the differences in height between a 2019 Honda Odyssey seat and a monopost seat. The 2019 Honda Odyssey seat has a height of approximately 750 mm, whereas the monopost seat has a height of approximately 970 mm. When a passenger is seated, the monopost seat has a higher center of gravity than the 2019 Honda Odyssey seat, rendering it more susceptible to fractures in a crash, given that the lower section is subject to greater torque. Therefore, its safety should be validated by measuring the strain modulus of the seat in the instant of collision.

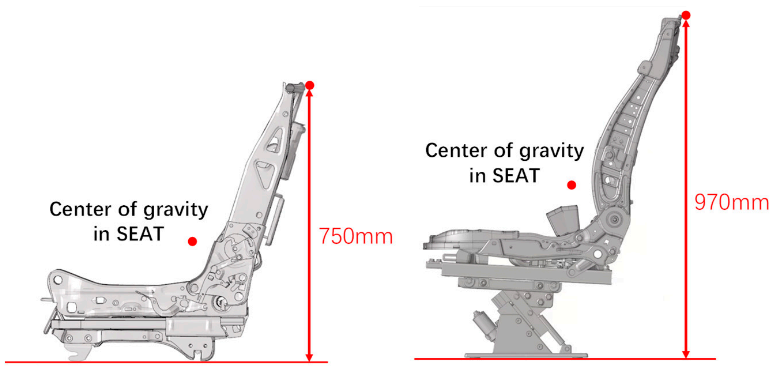


Figure 4. Differences in height between a 2019 Honda Odyssey seat and a monopost seat.

3. Safety Performance Standard

The safety performance tests of the vehicle seat include a dynamics test and a quasi-static test. Multiple countries have set standards for seat strength. Such seat requirements require manufacturers to connect the components and seat belt anchor in order to minimize the likelihood of fracture due to crash forces.

Table 1 lists the safety standard used in this research The standard allows permanent seat deformation during the specified period, while the fixed and peripheral areas are not destroyed.

EUR ECE R14 and American FMVSS 210/207 regulate the force exerted on the lap and shoulder blocks at 13,500 N and 13,345 N, respectively. The force exerted on the center of gravity of the seat needs to be set 20 times greater than the seat mass.

Regarding the safety performances of EUR ECE R14 and FMVSS 210/207, the angle at which a load is applied and its magnitude are similar. On the other hand, the speed at which a load is applied and the holding duration are different. EUR ECE R14 requires a load to be increased from 0 at the maximum speed, and the maximum load should be sustained for a minimum of 0.2 s. FMVSS 210/207 requires a gradual increase in load from 0 to the maximum within 30 s, with the maximum load sustained for a minimum of 10 s.

Therefore, a test with a low load application rate and a long maximum load holding duration, such as the North American FMVSS 210/207 test, can be considered quasi-static testing [10].

Based on a literature review and accident analysis, the requirements of the European ECE R14 and the North American FMVSS 210/207 differ. Nevertheless, they provide significantly high safety levels for passengers, and are equivalent because they ensure seat safety [11].

Table 1. Comparison of car seat belt anchorage tests in different countries.

Regulation Name			EUR ECE R14 [12]	North America FMVSS 210/207 [13,14]
Loading angle			10 ± 5°	10 ± 5°
Load	3-POINT	SHOULDER	13,500 ± 200 N	13,345 N
		LAP	13,500 ± 200 N	13,345 N
	Inertial load		Seat weight × 20	Seat weight × 20
Holding time for load			>0.2 s	>10 s

4. Monopost Seat

4.1. Dynamic Simulation

The three-dimensional (3D) model simulation was first planned to reduce the time required for the simulation and to enhance the model accuracy. In accordance with safety performance standards, the actual testing device comprised two body blocks that are used to apply loads. The body blocks consist of shoulder and lap blocks that replace the passenger chest and torso, respectively, as shown in Figure 5.

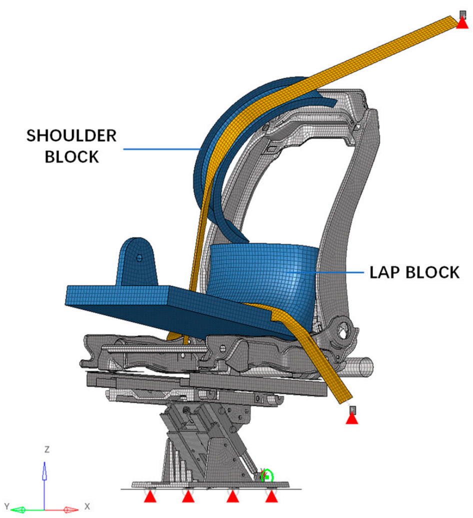


Figure 5. Finite element model (FEM) model.

HyperMesh finite element software was used to generate meshes and simplify the model. The mesh size of the elements was set to approximately 8 mm to ensure the efficiency of the analysis. The size of certain parts needed to be set smaller to improve the reliability of CAE analysis in some key areas [6,15]. The shell elements were divided using quadrilateral and triangular meshes, while hexahedral mesh elements were used mainly for the solid parts.

Given that the upper section of the monopost seat is insignificant for the simulation, a solid model was converted to a shell to reduce the simulation time and simplify the design. The critical components of the monopost seat upper section, including the back frame, bottom frame, and seat belt buckle, were all made from high-strength steel. An LS-DYNA's MAT_24 material model was used for modeling, with a Young's modulus of 219 GPa, a density of 7850 kg/m^3, a Poisson's ratio of 0.3, a tensile strength of 845 Mpa, and a yield stress of 550 Mpa. The back frame and bottom frame have a thickness of 3 mm, while the seat belt buckle has a thickness of 2.6 mm. The seat belt buckle was set as a rigid body and connected to the seat through rigid elements to prevent local over-deformation during loading.

In automotive seat dynamics analysis, the shoulder and lap blocks are components used to apply loads. They are modeled as rigid body elements with a shell element type.

The bolts around the slide rail are important, and were modeled using solid elements. Because bolts are typically made of high-strength metal and have very small deformations, they can be treated as rigid bodies and modeled using rigid body elements. In LS-DYNA analysis, rigid elements do not participate in finite element calculations, so the size of rigid elements does not affect the analysis time required. The size of these solid rigid bolt elements was set to approximately 2 mm to ensure that the bolts are accurately represented in the finite element model. In addition, bolt pre-tension was not considered in this case. The contact type between rigid bolts and the slide rail was set to frictionless. Other fasteners were simulated using beam elements connected to the parts to be fastened through rigid body 1D elements.

The seat belt is a primary restraint system that controls the occupant's motion inside the car during a car crash [16]. The car seat belt is typically made of synthetic materials, such as polyester, nylon, or a combination of both, which have high strength, durability, and abrasion resistance. These materials can withstand high tensile forces without breaking or overstretching, which is crucial for ensuring passenger safety during a collision. This study used a combination of 1D and shell elements to model the seat belt, and rigid body connections were employed to link the two. The shell element was connected to the 1D element and the seat belt buckle on the seat. The shell elements used the material model MAT_34 in LS-DYNA, with a density of 1.3 g/cm^3 and a Young's modulus of 40 GPa. The seatbelt elements used the material model SB_MAT in LS-DYNA. The seat belt had a width and thickness of 50 mm and 1.2 mm, respectively, with an element size of approximately 8 mm. Static and dynamic friction coefficients of 0.2 and 0.1, respectively, were assigned to model the interaction between the seat belt and the shoulder and lap blocks.

In LS-DYNA, a variety of contact algorithms are available. This study used the automatic single surface (CONTACT_AUTOMATIC_SIGLE_SURFACE) contact algorithm, with advantages such as high computational efficiency and stability.

For the monopost seat, different alloys were used to decrease the mass and increase its strength overall. Figure 6 and Table 2 present the materials for the panel, bracket, air cylinder, and sliding rail of the monopost seat. The main focus was the sliding rail and bracket sections, which were constructed using SPFC980Y and simulated using the MAT_3 material model in LS-DYNA. A solid mesh consisting primarily of hexahedral elements, with a mesh size of approximately 3.5 mm, was used to ensure accurate observations of the strain and stress changes in these components. Two elements were used to model the thickness direction of each component.

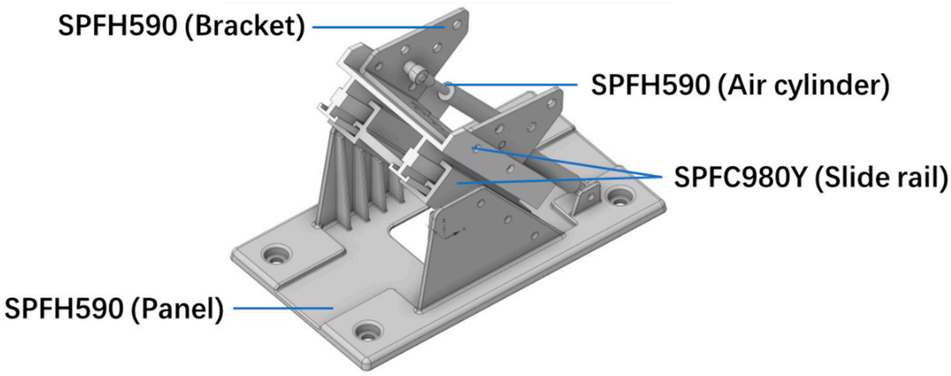


Figure 6. Material of the lower section of a monopost seat.

Table 2. Mechanical properties of steel materials.

Material	SPFH590	SPFC980Y
Density (Mpa)	7.8	7.8
Poisson's ratio	0.29	0.3
Young's modulus (Gpa)	200	190
Yield stress (Mpa)	420	490
Tensile strength (Mpa)	590	980
The maximum material plastic strain/Elongation (%)	22	7

Loads were applied to the seat in accordance with ECER14 safety performance requirements during the dynamic test. The total mass of the monopost seat was 30 kg; thus, a load of 5880 N should be applied to the center of gravity of the seat. In addition, a load 1.20 times greater than the amount specified in the standard was imposed, considering safety. Therefore, as the input condition, the load applied to the lap and shoulder blocks was set as 16,200 N, and the load applied to the center of gravity of the seat was set as 7056 N. Figure 7 presents the location and direction of the loads.

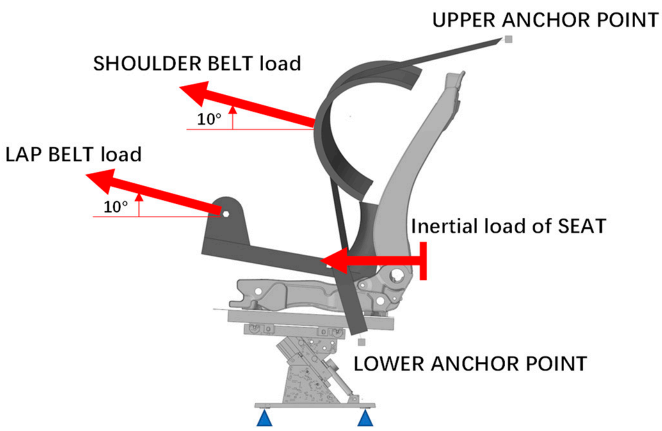


Figure 7. Load conditions of safety belt anchorage.

Figure 8 presents the change in load over time. All loads were programmed to reach a value 1.2 times greater than the regulatory standards within 0.2 s and sustained for 0.2 s thereafter.

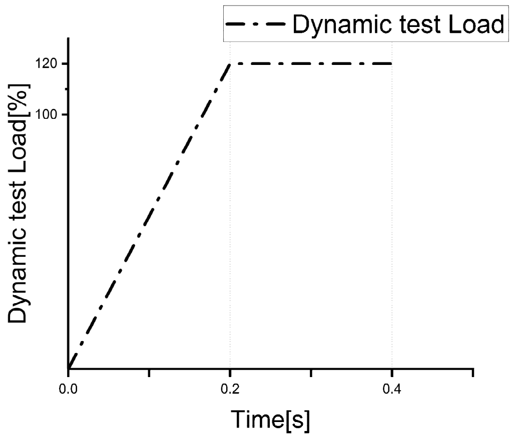


Figure 8. Dynamic test load curve.

4.2. Quasi-Static Simulation

DAS conducted the quasi-static simulation. Further information is not provided in this paper because monopost seats are currently under development. This paper only discusses the finite element boundary conditions of the quasi-static simulation. The reliability of the finite element simulation was confirmed by comparing the results of the quasi-static simulation with those of the dynamic simulation.

DAS set higher standards based on the North American FMVSS 210/207 regulations to fulfill automobile manufacturer requirements. As shown in Figure 9, the quasi-static test provided a load 1.2 times greater than the regulation. Moreover, the load reached its maximum value within 25 s, and was sustained for 10 s.

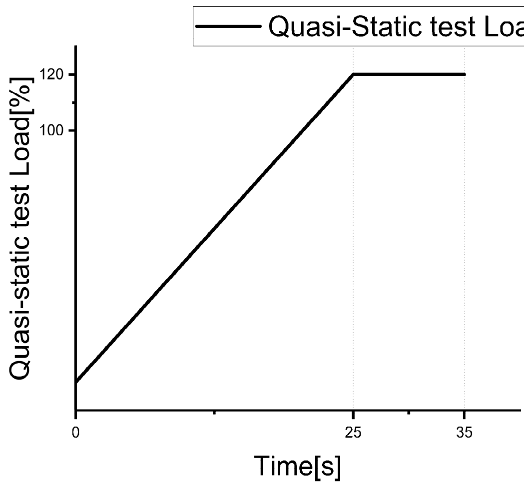


Figure 9. Quasi-static test load curve.

5. Simulation Result

5.1. Dynamics Simulation Result

Figure 10 presents an animation example at the end of the simulation (0.4 s), indicating that the monopost seat separated into two parts; this was caused by the failure of the bolts affixed to the bottom frame, and could lead to greater injury to passengers during a car collision. Therefore, the seat does not meet the safety standard of ECE R14.

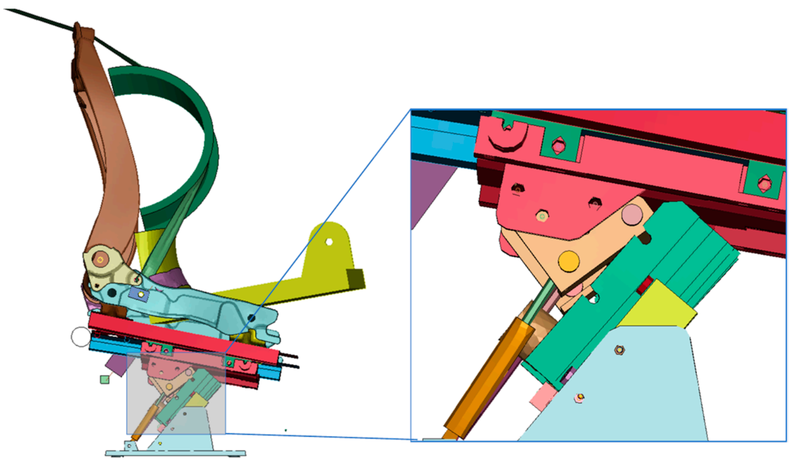


Figure 10. Simulated animation instance.

Figure 11a,b illustrate the Von Mises stress and plastic strain nephograms, respectively, for the upper portion of the monopost seat. The maximum Von Mises stress was 725.2 MPa, and the maximum plastic strain was 2.132%, both occurring on the bottom frame. The two anchor points of the three-point safety belt are fixed on the vehicle body frame, while the other anchor point is located on the red circle of the bottom frame in Figure 11a, and no failure was observed at this point. The seat belt buckle is modeled as a rigid body, and the beam elements connecting the seat belt buckle and the bottom frame are subjected to an axial force of 8.19 kN and a tangential force of 9.12 kN.

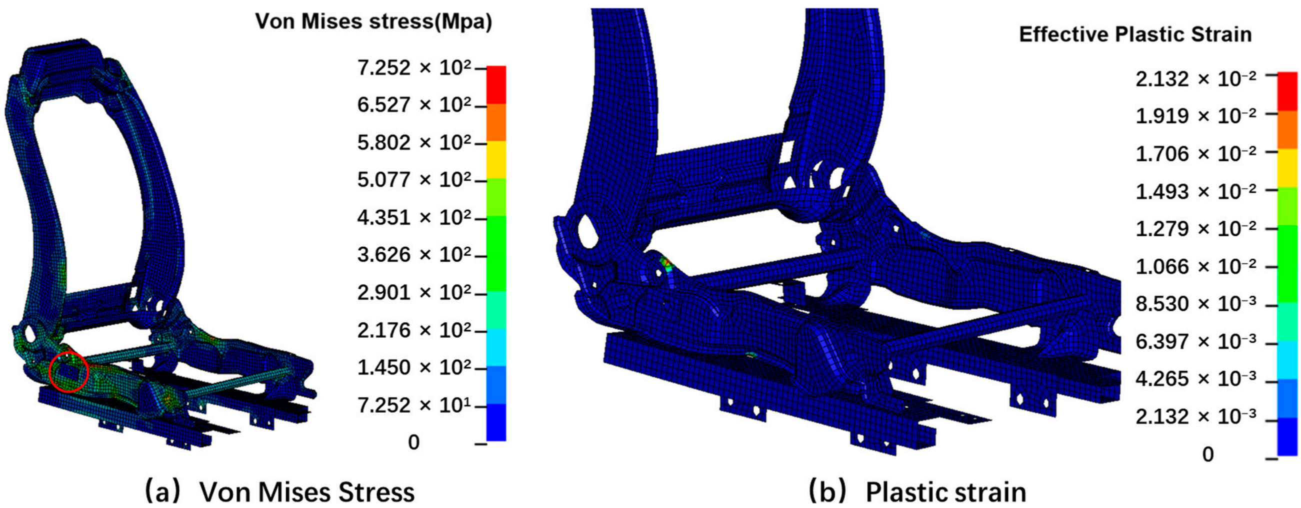


Figure 11. Strain and stress nephograms of the upper of the monopost seat.

Figures 12 and 13 show the Von Mises stress and plastic strain nephograms, respectively, of the lower part of the monopost seat. The lower part of the monopost seat experiences plastic deformation at multiple locations. The stress and strain are mainly concentrated at the bolt fixation of the slide rail, which ultimately resulted in bolt failure. Owing to the three-point seat belt system, two of the fixing points are located on the B-pillar of the car, and the third is located on the right side of the seat (Left seat of the car). Therefore, the right side of the seat experiences a higher load than the left side. The first bolt fixation point on the right side failed at 0.056 s, followed by the second and third bolt fixation points at 0.108 s and 0.116 s, respectively. The final bolt failed at 0.128 s. Figure 12a,d show the stress nephograms at the time of failure of the first three bolt fixation points and at the end of the simulation. Figure 13a shows the plastic strain nephogram at the time of failure of the first bolt fixation point, with a maximum plastic strain of 5.76%, because the element with a strain higher than the maximum allowable plastic strain of the material has already failed. Figure 13b shows the maximum plastic strain nephogram of the entire simulation, with the maximum plastic strain occurring on the air cylinder, reaching 14.36%. The monopost seat is fixed within the car by four M10 bolts at the bottom. In the simulation, these four beam elements experienced a maximum axial force of 39.47 kN and a maximum tangential force of 18.51 kN. According to ISO 898-1:2013 [17], the four bolts used to fix the seat should be of at least 8.8 grade or higher.

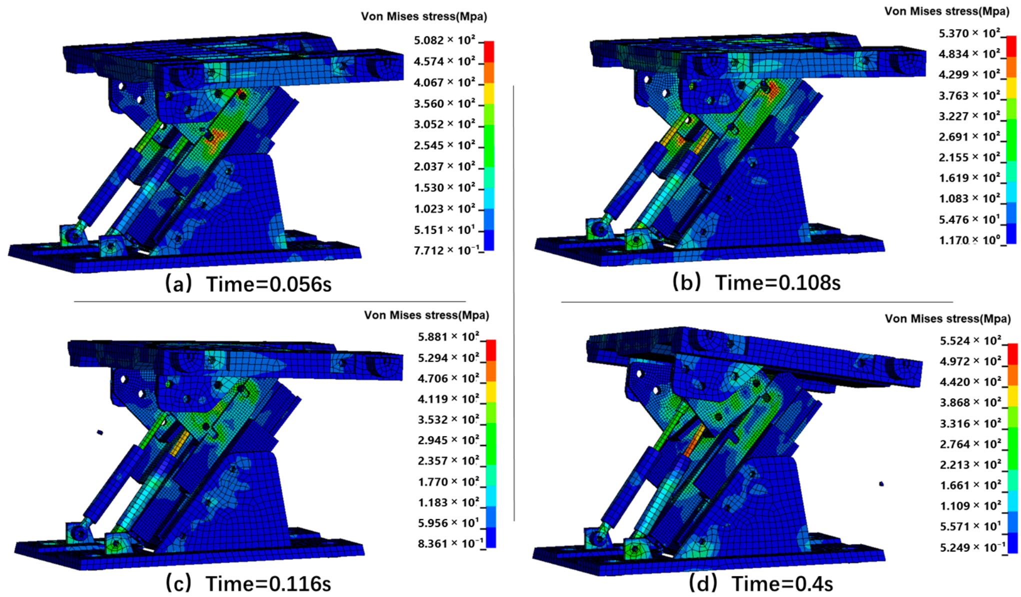


Figure 12. Stress nephograms of the lower part of the monopost seat.

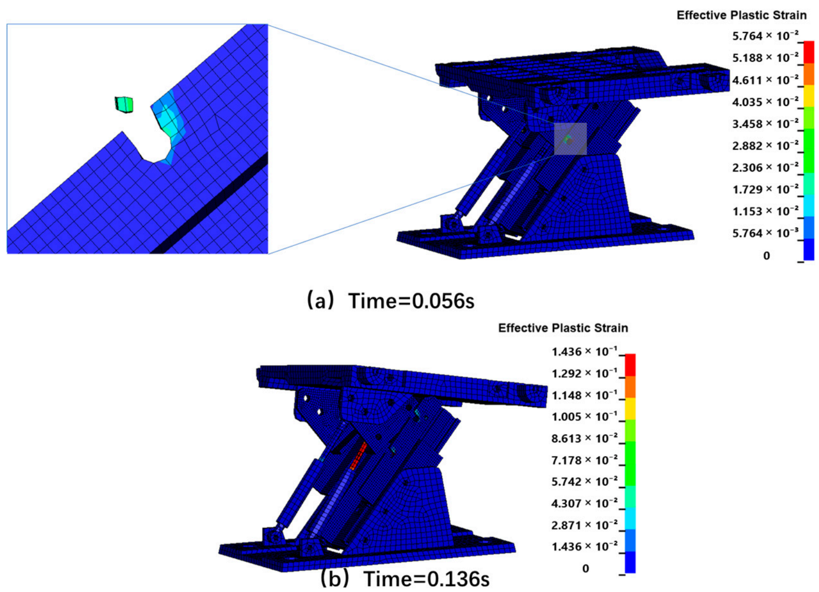


Figure 13. Strain nephograms of the lower part of the monopost seat.

Figure 14 shows the Von Mises stress nephograms of the upper slide rail (move) at 0.056 s, 0.108 s, 0.136 s, and 0.4 s. The cloud diagram showed that in addition to the bolt fixation position, damage also occurred at the chamfered section. Figure 14a–d correspond to the moment at which the first and second bolts fracture, and at which the chamfered section was damaged, as well as the final simulation time. A combination of Figures 13 and 14 shows that the maximum plastic strain of the single-column seat occurs when the upper slide rail chamfered section (move) is damaged.

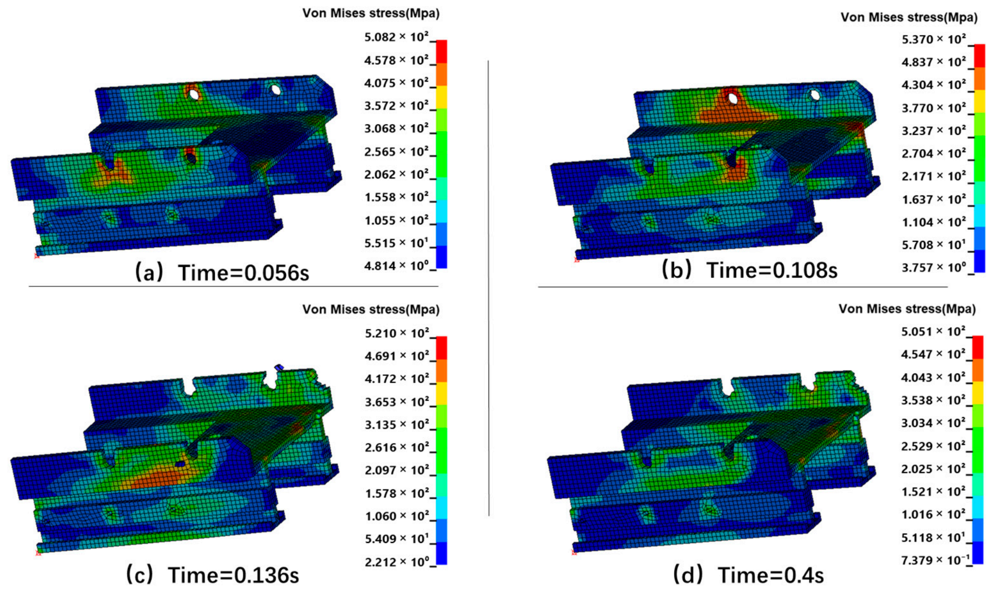


Figure 14. Von Mises stress nephograms of the upper slide rail (move).

Figure 15a,b are the maximum Von Mises stress and maximum strain nephograms of the lower slide rail. The maximum plastic strain occurred at 0.136 s, exceeding the maximum allowable strain of the material and leading to damage. On the other hand, this is not the main reason for the failure of the monopost seat, and its damage did not cause the upper and lower slide rails to separate. Figure 15c,d show the maximum Von Mises stress and maximum strain nephograms of the bracket. The maximum Von Mises stress and strain nephograms of the bracket were 512.3 MPa and 1.17%, respectively.

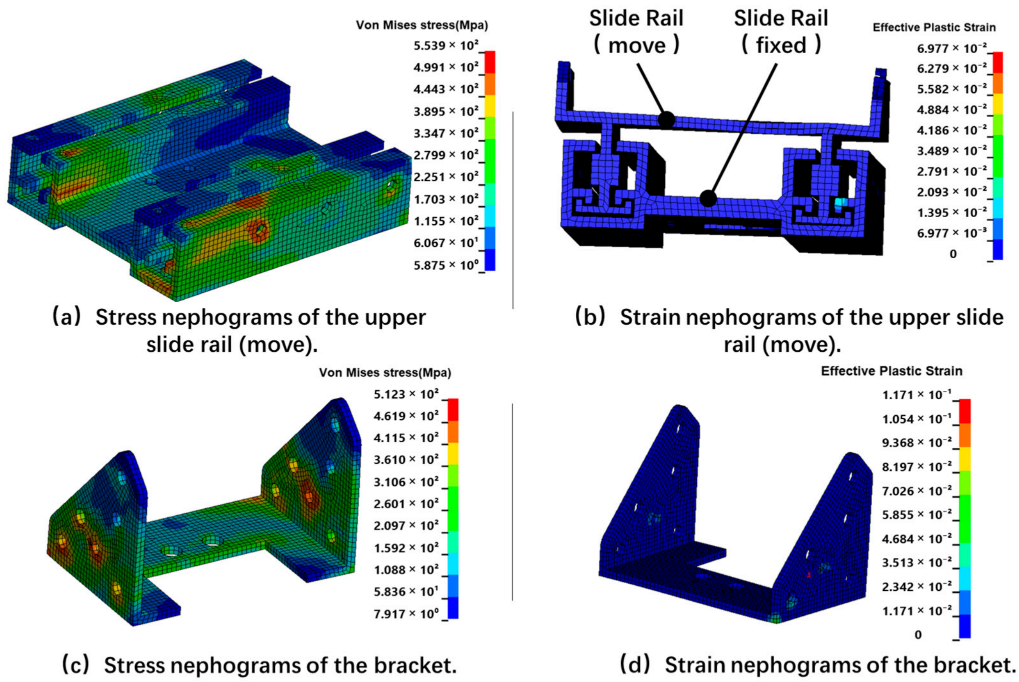
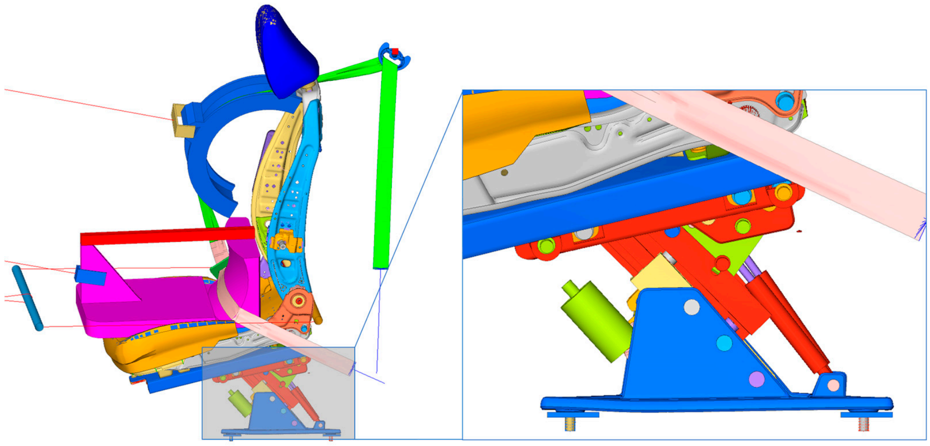


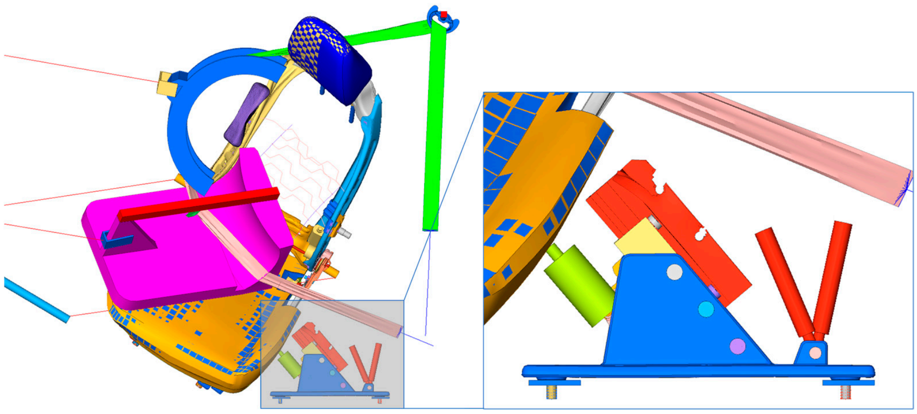
Figure 15. Strain and stress nephograms of the upper slide rail (move) and bracket.

5.2. Quasi-Static Simulation Result

Figure 16 presents the analytical results of the quasi-static simulation. Considering that one side of the seat belt fixture was attached to the seat and the other two were attached to the automobile frame, one side of the seat belt fixture tilted with the other side when the load was applied. As shown in Figure 16a, the bolt fastening part was damaged after 27 s, and all four bolt fastening areas on the sliding rail were damaged, separating the upper and lower sections of the seat, as shown in Figure 16b. The seat failed the test due to damage to the bolt fastening part.



(**a**) Time = 27 s



(**b**) Time = 35 s

Figure 16. Quasi-static simulation result.

6. Conclusions

The finite element method was used to simulate an automobile monopost seat currently under development. The results of the quasi-static and dynamics simulations were compared to ensure the accuracy of the simulation results. The simulations showed that the bottom sliding rail of a single column seat is the most vulnerable section of the seat, and the bolt fastening area is readily damaged. By comparing the results of the quasi-static and dynamic simulations, valuable insights can be provided for physical testing during the product development phase. This part requires improvements, which can be achieved by using a high-strength material, increasing the thickness, or altering the location and number of bolts.

The event of an automobile crash involves multiple factors that render a seat structure vulnerable. Shearing forces can damage the bolts beside the lower sliding rail, leading to a seat structure malfunction. Hence, more specific simulations and experiments are required prior to the manufacturing of seats.

The results of the finite element simulations conducted in this study may serve as the basis of seat development research and are critical for reducing the number of physical tests required, decreasing development costs, shortening development cycles, and increasing test pass rates.

Author Contributions: Software, D.S. and Y.H.; Investigation, D.S.; Writing—original draft, D.S. and S.P.; Writing—review & editing, J.K.; Supervision, J.K. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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Conflicts of Interest: The authors declare no conflict of interest.

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