A FE Modeling and Validation of Vehicle Rubber Mount Preloading and Impact Response

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Abstract

A variety of rubber mounts are being used for vehicles as isolators/dampers between body and frame, on the engine cradle, etc. It has been the prevalent CAE practice in the auto industry to evaluate the mounts' high-speed vehicle crash response by the means of nonlinear spring/beam models. However, the simplified models carry a risk of generating incomplete and erroneous results, especially under very complex crash loadings due to the absence of component contact and failure criteria. To alleviate the shortcomings of the simplified mounts, this paper presents a FE representation of a detailed vehicle rubber mount coupled with failure criteria and initial bolt wrenching (preloading) using LS-DYNA, as well as test validation of those mounts.

Introduction

The vehicle flexible mounts, made of mainly rubber materials and housed in a metallic tube, are indispensable components affecting the quality of the vehicle ride, noise and vibration. In the auto industry, the usual practice when designing vehicle flexible mounts is to minimally reflect impact considerations in the mount design features. However, in most high-speed vehicle crash events where the mounts fail, the crash responses, including occupant injury severity, are known to be very different from the responses of non-failure cases. Even in low-speed vehicle impact cases, excessive deformation of the flexible mounts could cause significant variance in the compliance of the vehicle acceleration level to the air-bag firing and timing threshold requirements. Therefore, flexibility and failure of the flexible mounts need to be accurately evaluated for their crash responses, and fully considered for their effects on the full vehicle impact responses, as well as for subsequent decisions on impact performance improvement direction.

Recently, with the need to comply with the enhanced U.S. government vehicle safety regulations and with the advancement of computer technology, vehicle safety design development practices using CAE tools have become very common within the auto industry because it provides better insights into structural response/behavior, early resolution of problems and considerable savings in design time and cost, all while upgrading quality. However, typical CAE methods for representing flexible mounts are limited to modeling with rigid connections or assigning springs of an unrealistic stiffness. As a result CAE models inadequately predict failure modes and can misguide design improvement and optimization. During vehicle crash events, the mounts are subjected to complex loadings including a combination of compression, shear, bending, and torsion loading. More importantly, since they are fastened to the vehicle body by a torque application on the fastener bolt, a tension preloading of 50K~70K Newtons is already applied on the bolt, causing the rubber isolator to become compressed [1, 2]. This preloading generates residual stresses on the bolt, and accelerates or decelerates the bolt stress concentration induced by the vehicle impact loading. Thus, if a CAE model for the mount can not simulate the preloading phenomenon properly, its results could lead to erroneous failure predictions. This is why the mounts need to be properly modeled and bolt preloading should not be neglected.

This paper, considering the above mentioned shortfalls in the current CAE modeling practice for the flexible mounts, has created a CAE rubber mount model which contains the bolt preloading and bolt separation failure due to stress concentration during vehicle impact. For this study, LS-DYNA [3, 4] was used as the FE solver and the results have been validated through component-level bench tests. The valuable findings of this study will be:

- Creation of a more realistic CAE modeling method for the flexible vehicle mounts,
- Best estimates of the mount material properties, including rubber, bolt, sleeve, and plates,
- Understanding of the importance of proper Pre-Loading modeling,
- Weld integrity check during impact loading, and
- Possibility of applications to other types of rubber mount impact models.

The benefits of employing the validated rubber mount FE model for full vehicle crash models include enabling:

- Control of parameter sensitivities affecting bolt separation failure,
- More reliable Full vehicle crash evaluation with flexible mount effects,
- Identification of the rate hardening effect of rubber and bolts on the mount response to crash loading

1. Functional Review of Vehicle Flexible Mount

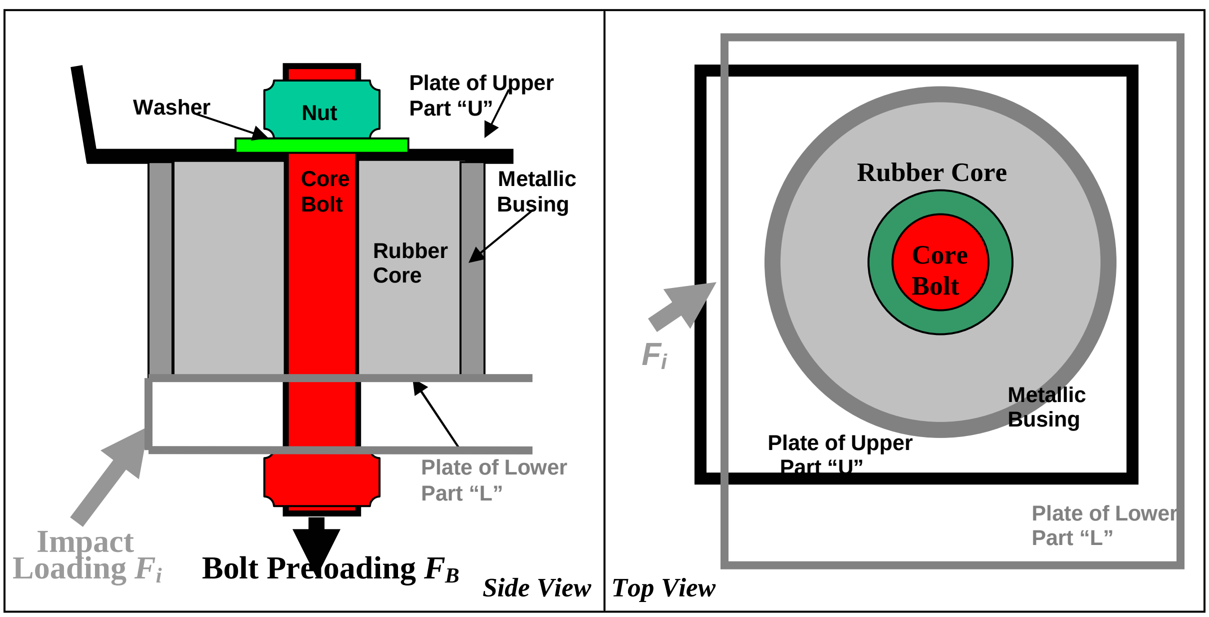


Figure 1 Schematic section view of a sample vehicle rubber mount model

Figure 1 illustrates a schematic view of a typical vehicle flex mount in which the core bolt works as a fastener for connecting the upper part "U" and the lower part "L", and the rubber core constitutes a vibration isolator between them. The rubber core, covered by a metallic bushing, becomes compressed by the fastener preloading $\boldsymbol{F_B}$ application during installation, so the initial rubber property will remain stiffer than that of its unloading state. This is also one of the reasons for the preloading process to be included in the CAE modeling. Once the impact loading $\boldsymbol{F_i}$ acts on the lower part L during vehicle crash, the core bolt and rubber begin deforming against their inner friction and strain resistance, and this causes a relative displacement and rotation of the part L with respect to the upper part U. If the impact loading passes over the bolt's ultimate strength, the bolt will yield to separation. Otherwise, the rubber can be torn off the bushing if the impact force reaches the rubber's ultimate strength,

2. FE (LS-DYNA) Model of a Flexible Mount Study Sample

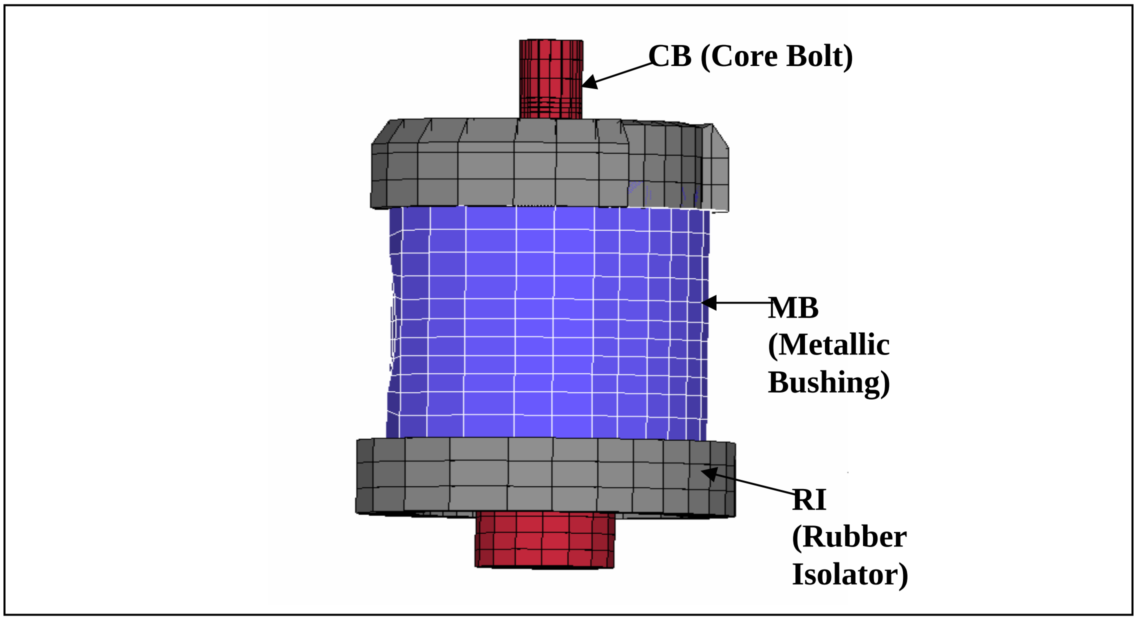


Figure 2. FE (LS-DYNA) model of a sample Flexible Mount

Table 1. LS-DYNA Model Contents of the Sample Model in Figure 2

Code	Part Name	FE Form	LS-DYNA Material Models	
			Mat'l #	Material Title
MB	Metal Bushing	Shell	MAT24	Piecewise_Linear_Plasticity
RI	Rubber Isolator	Solid	MAT27	Mooney_Rivlin_Rubber
CB	Core Bolt	Solid	MAT24	Piecewise_Linear_Plasticity

A FE model of a vehicle flexible mount was prepared for this study purpose as shown in Figure 2. The mount's components and LS-DYNA model contents are listed in Table 1. Strain versus stress test curves, provided by the rubber suppliers, were used for defining the load curves required by the LS-DYNA Mooney-Rivlin Rubber formulation [4].

3. A FE (LS-DYNA) Representation of the Mount Bolt Preloading

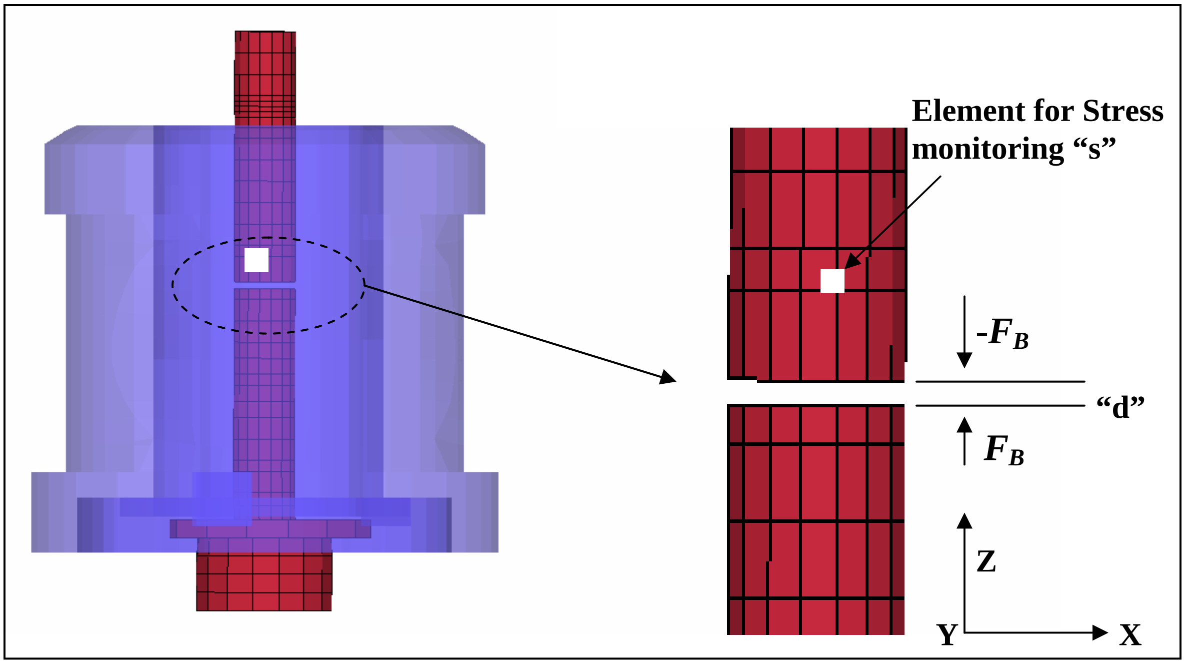
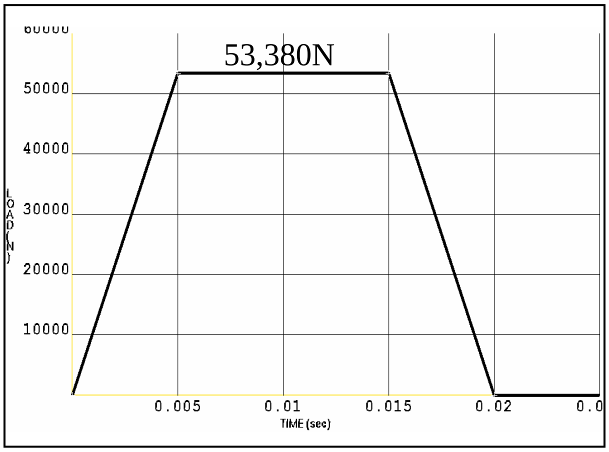


Figure 3. FE (LS-DYNA) model of Pre-Loading for Fastening Core Bolt

To simulate the mount bolt fastening to the vehicle body, a pre-loading F_B of a maximum 53,380N (12KLbs), characterized by the load curve in Figure 4, was applied to the two cut bolt faces in opposite directions, as depicted in Figure 3. As the magnitude of the preloading increases, the initial clearance of "d" which is created by cutting a piece of the bolt keeps shrinking. Finally, when the bolt tension reaches a static loading equilibrium with the rubber compression reaction, the two cut faces becomes tied by using the LS-DYNA's "Node Tied Contact" [3]. The gap "d", needs to be treated as a variable since higher pre-loadings require a larger "d" value before the cut faces are tied.



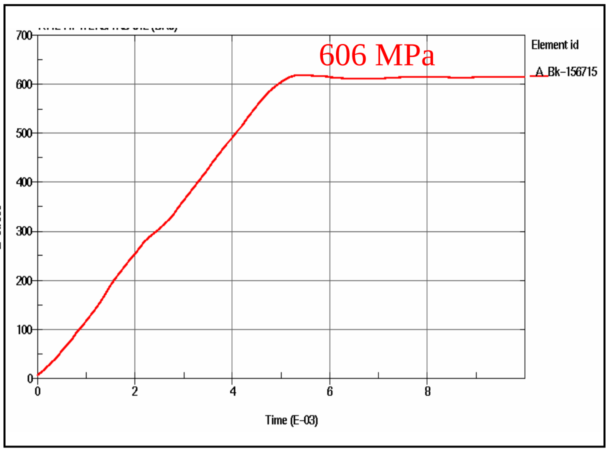


Figure 4. Pre-Loading Curve (F_B)

Figure 5. Z-Stress of Element "s"

To confirm the attainment of the afore-mentioned loading equilibrium, the z-stress of the element "s" has been monitored as shown in Figure 6. In the z-axis stress readings it can be seen that a loading equilibrium was reached at the 5 msec of loading, and a maximum stress of 606 MPa was developed during preloading. Since the maximum 606 MPa stress is equal to the stress amount computed from Loading (53KN) divided by Bolt Cross Section Area (88 mm^2), the pre-loading process is proved to have been properly defined in the CAE model.

4. Test Validation of CAE Results for the Mount Bolt Failure Model

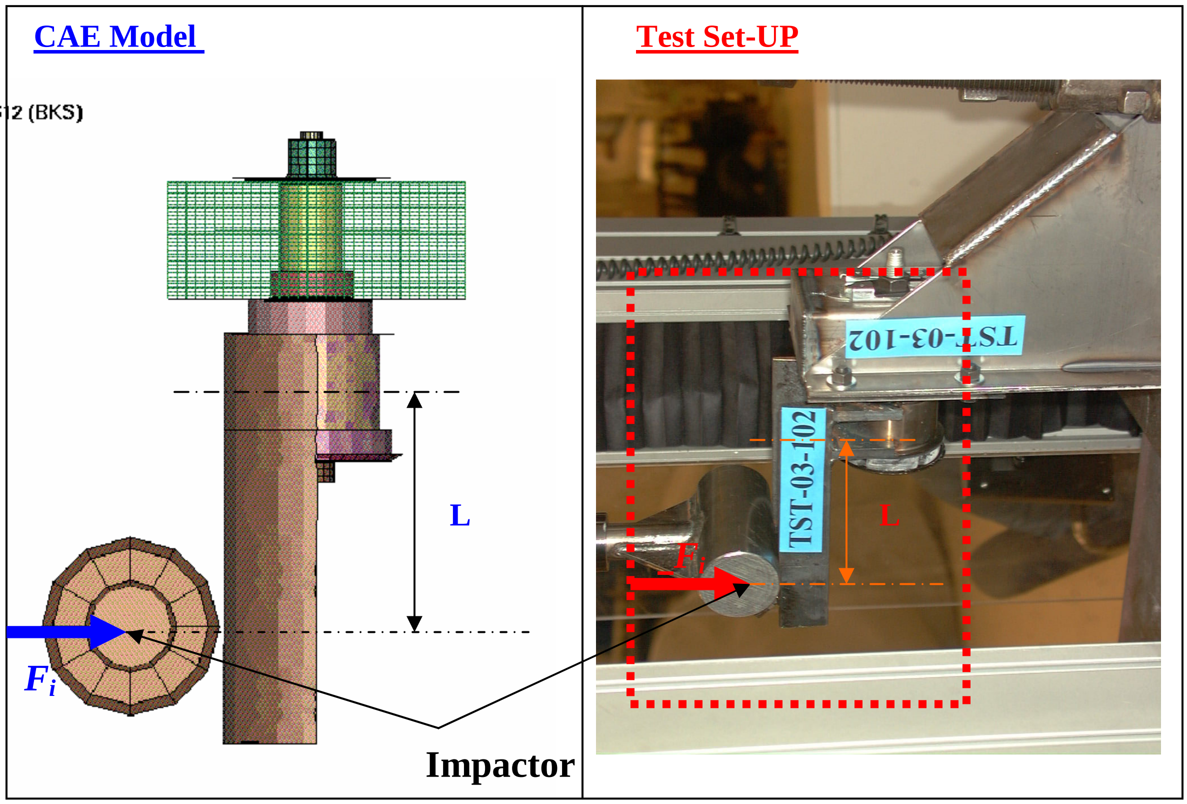


Figure 6. FE (LS-DYNA) model and Validation Test Set-UP for Mount Impact Loading

A series of component level tests were conducted with a view to validate the CAE modeling of the flexible mount impact phenomena, as shown in Figure 6. In the test set-up, an impact loading was applied to the mount through the impactor. As test design variables, the rubber hardness and the moment arm length L were varied together to measure their effects. For the CAE model, the plastic failure strain level for the bolt model was controlled for achieving better agreement in the bolt separation loadings and timings with test results. A detailed test parameter list has been provided in Table 2.

Table 2 Test & CAE Analysis Parameters

Test Design Parameters			Additional CAE Parameters
Rubber Core Materials	Moment Arm Height (L)	Initial Bolt Loading (FB)	Plastic Fail Strains
H(Hard) Rubber	120 mm	53,380 Newtons	30%
S(Soft)Rubber			35%
Aluminum	0 mm		40%

4-1 Results for Mount Models with Different Rubber Hardness

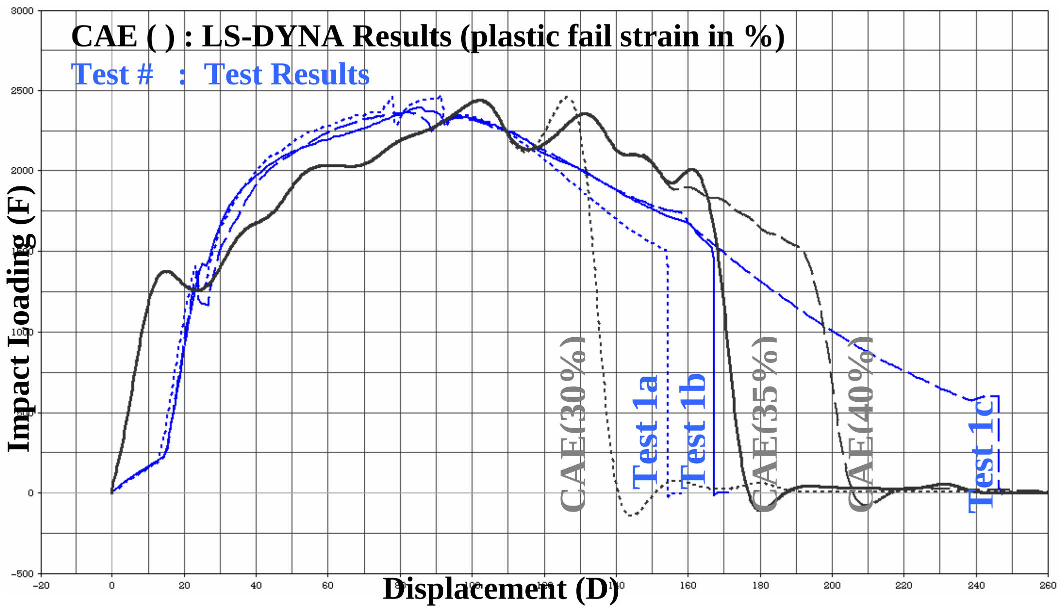


Figure 7. F-D Curves for Test and CAE analysis for Soft(S) Rubber Mount

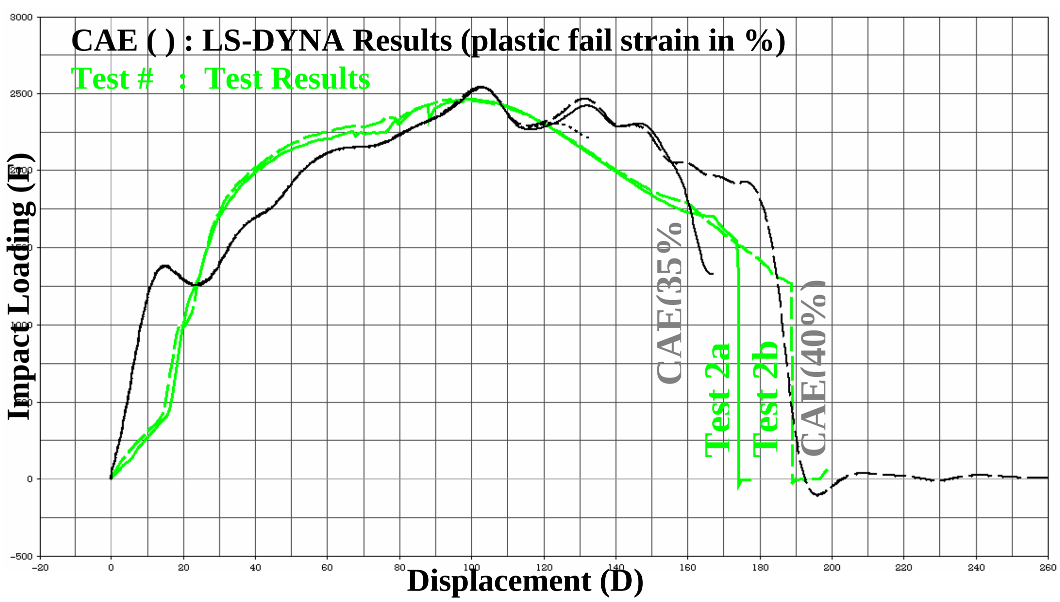


Figure 8. F-D Curves for Test and CAE analysis for Hard (H) Rubber Mount

Figure 7 represents the Force- Displacement (F-D) curves, measured from tests with soft rubber mounts and overlayed by CAE results. In contrast, the F-D's from tests with hard rubbers are shown in Figure 8. In both figures, it can be noted that the test and CAE F-D's are in good agreement in the overall loading curve shape as well as in the loading levels and timings of the peaks and bolt separation, indicated by the load plummeting at the end. The slight deviation at the inception of the CAE F-D curves with respect to the Test counterpart curves is due to the small cavities in the core rubber of the test specimen which were simply filled in the CAE models. And, the variance in the bolt separation timings in the test cases is owing to variation in the mount components' material properties. Considering the test variance, the CAE models were run with the bolt's plastic failure strain changes in order to see how it affects the bolt separation timings. From the results, the bolts' failure strains are estimated at the mean of 0.35 with a 0.05 standard deviation, and the harder rubber generates greater peak loading.

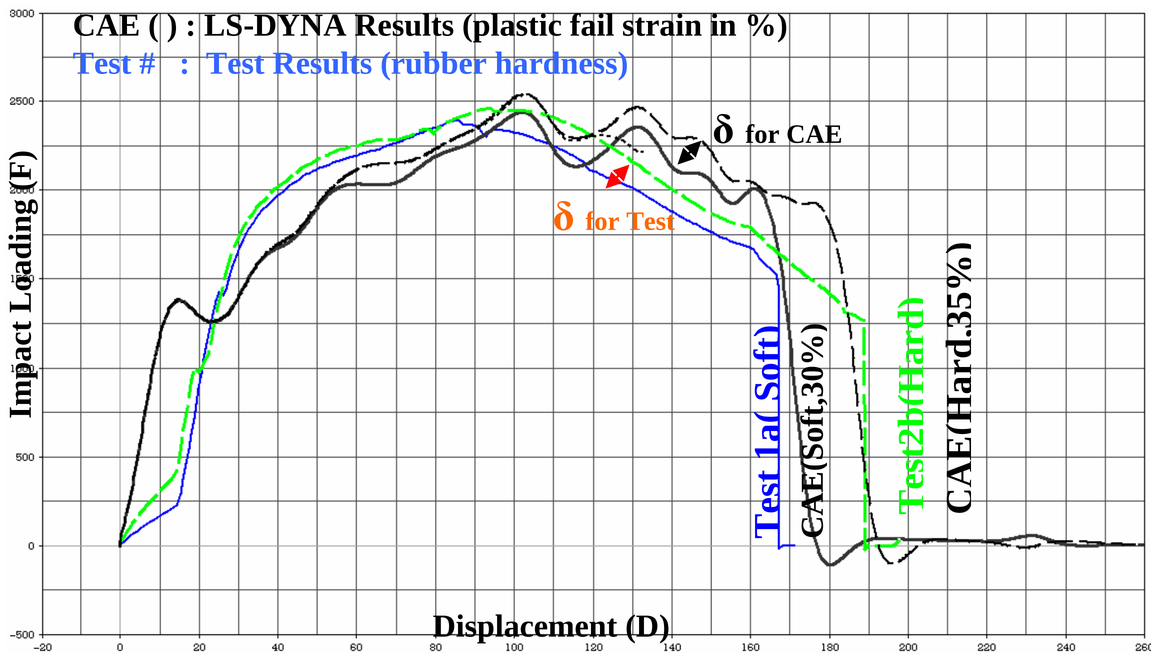


Figure 9. F-D: Test Vs. CAE and Hard (H) Vs. Soft(S) Rubber Mount

To demonstrate the rubber hardness effects on the F-D curves, all the rubber F-D curves are synthesized as seen in Figure 9. The loading difference between the test soft mounts and test hard mounts, represented as **δ,** has turned out to be close in magnitude to that of the CAE models. This proves that the CAE models of the mount system are valid for being able to represent the effects of the mount rubber stiffness difference on the physical response of the real rubber mount system under impact loading. It would be very difficult that this delicate physical phenomenon can be represented by a simplified spring models or rigid-body connection, which is the current CAE practice for the mount impact response assessment.

4-2 Force-Displacement Results for Mount Models with Aluminum Isolator

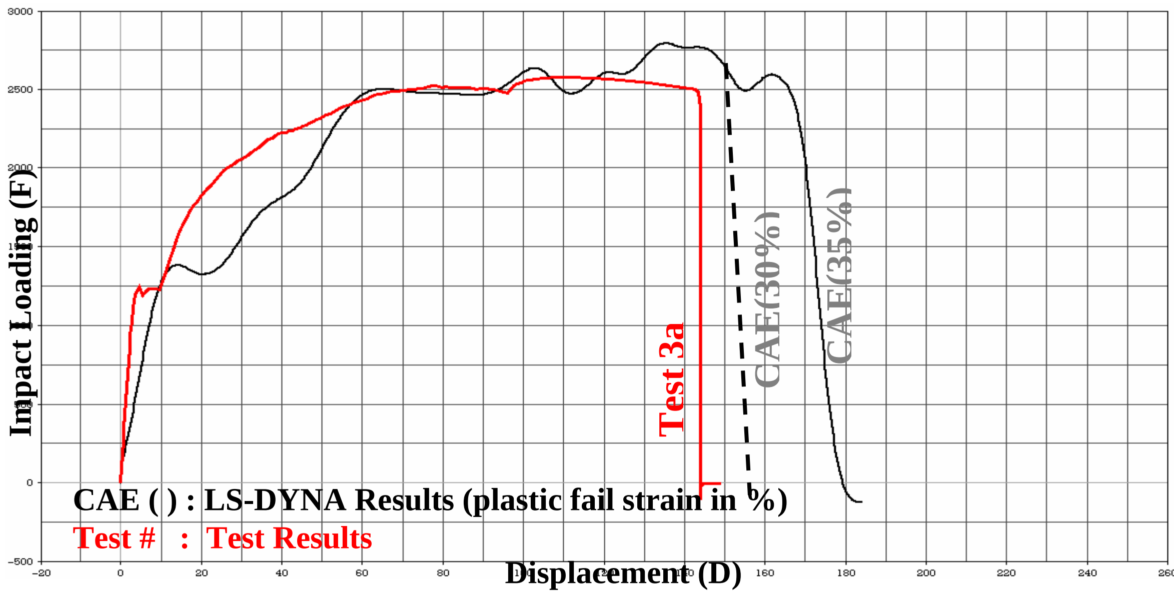
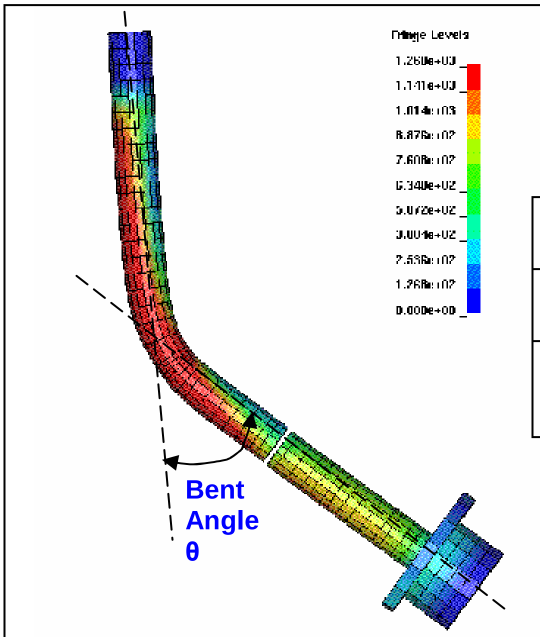


Figure 10. F-D Curves for Test and CAE analysis for Aluminum Isolator

Figure 10 represents the F-D measured from a test mount specimen with an aluminum isolator in stead of rubber. Still, the CAE results are showing good correlation with the test ones. The loading pattern of the aluminum isolator displayed a steeper load rise, followed by elevated peak loading as compared to the mounts with rubber isolators in the previous tests. In figure 11, the bolt bending angles, created at the instant of bolt separation for the aluminum isolator, are compared between Test and CAE. The two results turned out very similar with 42 º for Test and 43 º for CAE.



Model	Bent Angle θ @ fail
Test 3a	42 º
CAE, 35%	43 º

Figure 11. Bent Angle Comparison at Bolt Separation for Test vs. CAE Aluminum Isolator

4-3 Force-Displacement Results for Mount Models under Pure Shear Loading

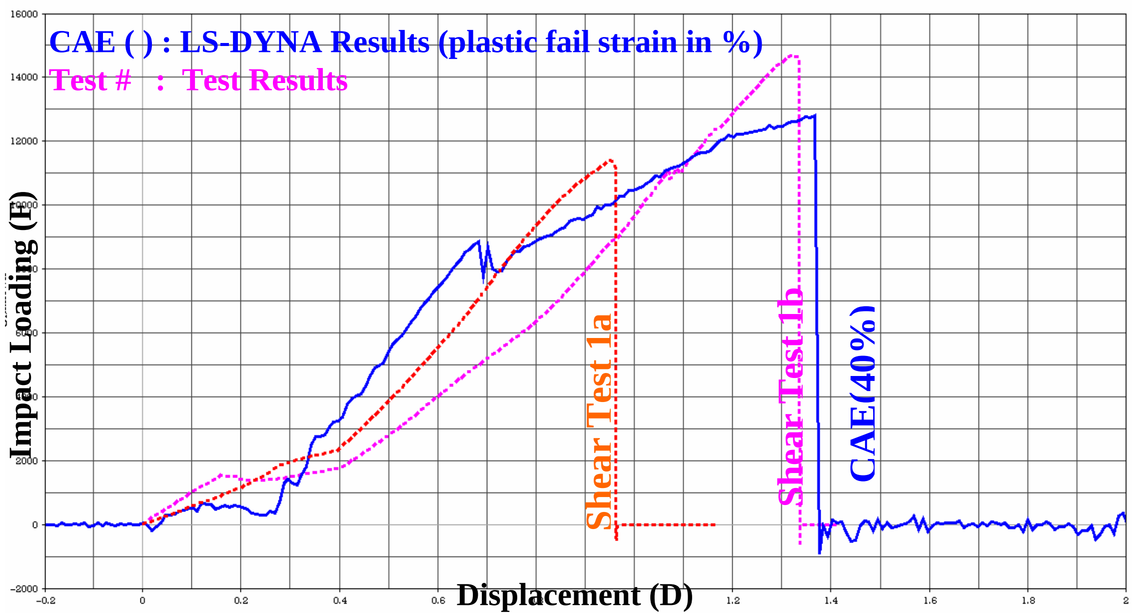


Figure 12. F-D Curves for Test and CAE analysis for Rubber Isolator under Purely Shear Loading

This time, the moment arm length L in Figure 6 is reduced form 120mm to 0mm to generate a pure shear loading on the mount by minimizing the bending moment exertion. In Figure 12, the F-D curves from the shear loading case appeared notably different from the bending driven F-D in Figure 9. Even under this pure shear loading cases, the CAE and Test model results demonstrate a good correlation. Figure 13 presents different bolt failure modes as exactly as observed in the post test examinations for the Pure Shear driven failed specimen and the Bending driven failed mount bolt specimen.

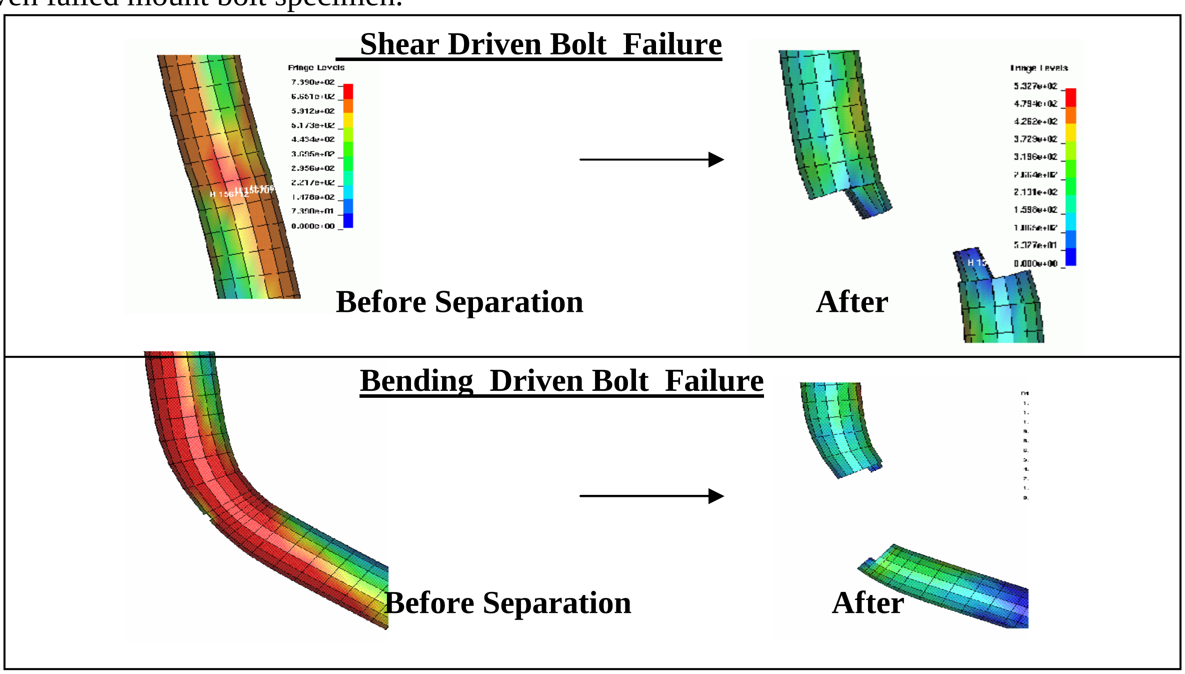


Figure 13. Bolt Separation Modes Comparison for Shear Vs. Bending Loading Cases

5. Conclusion

- CAE results showed good agreement with Test results
- A robust and realistic CAE model and method has been established, so this model/method can be applied to other types of vehicle flexible mounts such as engine mounts and body mounts on a larger scale.

- Valuable Findings from these developed LS-DYNA flexible mount models:
  1) Best estimates of Mount material properties, including rubber, bolt, sleeve, and plates became possible
  2) Importance of proper Pre-Loading application in the CAE mount modeling has been verified
  3) Weld integrity during impact loading can be assessed
  4) Development of full system vehicle impact models which enable more realistic impact response analyses/design development becomes possible with these new mount CAE models
  5) Design of Engineering (DOE) and optimization have been enabled using identified control parameter sensitivities related to the mount bolt failure

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