Structural Topology Optimization of Multilink Suspension System Using ATOM

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Abstract: A multilink suspension offers a good balance between ride and handling performance and packaging space efficiency. It is also complex in design due to changes in link loading and compliance at high articulation travel. Therefore, geometric and material non-linearity behaviors are important to consider when designing these types of suspension components.

Structural topology optimization has been applied in linear structural design for many years. It is a proven method for developing concept designs to meet design requirements. However, most techniques of this type in use do not comprehend geometric and material nonlinearities. This may lead to suboptimal designs for components where these effects are important, such as multilink suspensions.

GM Chassis CAE has used Abaqus for many years. We have been exploring new simulation-based design methods to reduce development time and provide mass-efficient vehicles to our customers. ATOM is one tool that offers the ability to optimize our designs while comprehending material and geometric nonlinearities. This study is an example of our recent efforts.

First, this study demonstrates a simulation of an integrated multilink suspension system model in Abaqus. This model includes both finite element models of the links as well as connector elements. Next, the model is assessed in Abaqus to determine the suspension strength and fatigue life of each individual link. Finally, topological design optimization is executed for this multilink suspension model using ATOM to determine the critical load path, alternative concept designs, and locations for mass reduction in order to meet the performance requirements.

Keywords: Abaqus Topology Optimization Module (ATOM), Design Optimization, Fatigue Life, Geometrical Nonlinearity, Material Nonlinearity, Multi-Bodies Dynamic (MBD), Multilink Suspension, Ride and Handling Performance, Topology Optimization

1. Introduction

Chassis suspension type and design determine how a vehicle handles under varying road conditions encountered while driving. Multi-link suspension represents an assembly of linkages and/or control arms, shock absorbers and springs that connects a car body to the wheel. Recently, many commercial vehicles have adopted independent multi-link suspension systems because they

offer a good compromise between packaging space efficiencies and ride and handling performance.

However, unlike a traditional strut or Short-Long Arm suspensions which have clearly defined kinematics, a multi-link suspension kinematics change as the suspension articulates through its ride motions. Depending on the particulars of the design, this may cause links that are designed for tension-compression loading to be in bending. And since link is flexible, compliance of the whole system can change with suspension travel.

Using optimization techniques to achieve lower mass and costs has become a common practice in today's automotive engineering. Structural topology optimization has been applied to linear structural design since its first introduction in 1988 [1]. In addition, nonlinear structural analysis has also become very popular in the past ten years. Lately, topology optimization of nonlinear structures has focused on both theoretical and commercial software developments. Haug and Choi [2] derived design sensitivity of nonlinear analysis. Pedersen et al. [3] studied compliant mechanisms for maximizing output work and path generation by incorporating geometrical nonlinearity. Gea and Luo [4] studied topology optimization with geometrical nonlinearity and showed the solutions of linear analysis may differ from that of nonlinear analysis. Jung and Gea [5] studied the effect of material nonlinearity using different material models in topology optimization of a compliant mechanism. However, industry examples of topology optimization with both geometrical and material nonlinearities are still very limited in literature. ATOM [6] provides a realistic design tool for nonlinear structural analysis.

The purpose of this paper is to demonstrate a suspension system modeling technique and topological design synthesis of a multi-link suspension system using ATOM.

1.1   Current Structural Design Process

Figure 1 shows a common design process in the current chassis structural design. The process starts with defining design requirements and the hard points of geometry, establishing design loads and a design envelope for each component. Each component is then analyzed and optimized linearly, based on the design load and proper boundary conditions. One advantage of this process is each structure component can be designed in parallel by separate teams.

Next, each optimized component is assembled in a system model to test the vehicle performance and exercise what-if and/or trade off studies. If the system level vehicle performance cannot be achieved through what-if and trade-off studies, the critical components will be redesigned with a new design requirement until the vehicle performance meets all requirements.
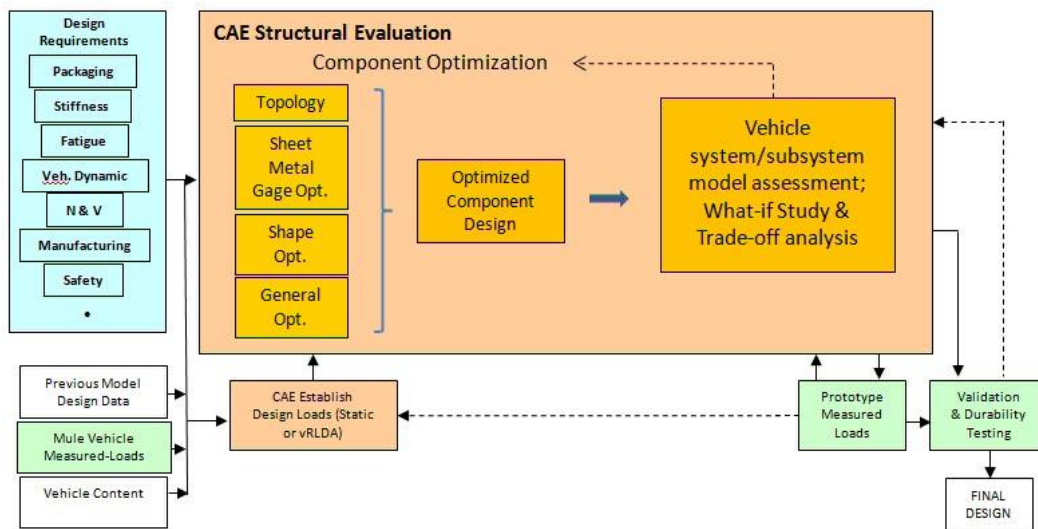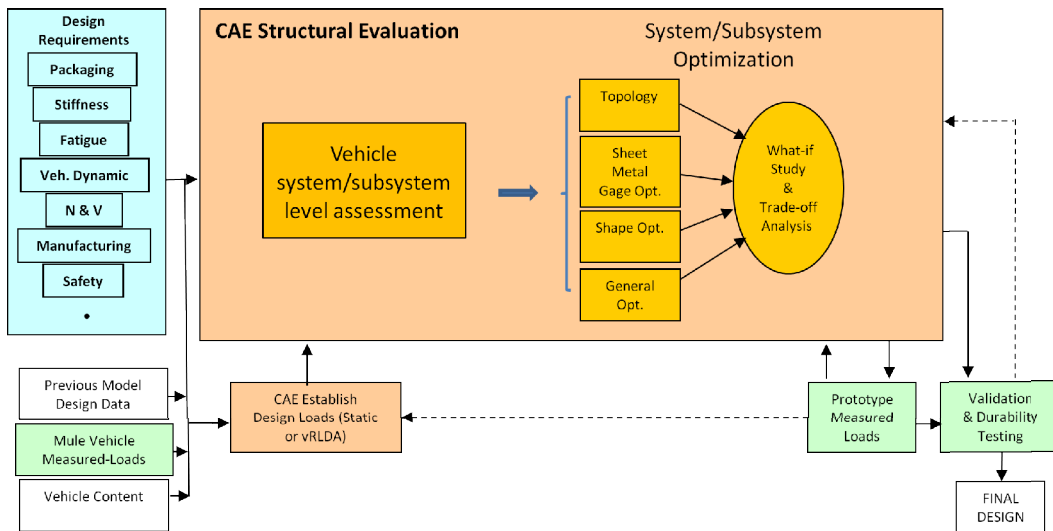
Figure 1. Current Structural Design Process.

1.2   Proposed Structural Design Process

Figure 2 shows the proposed structural design process. The process still starts with the same step as the current design process by defining design requirements and hard points geometry, establishing the design loads and design envelope for each component to. Through CAE structural evaluation, the engineer will begin to build and validate the vehicle system model instead of just the component design synthesis in the current process. Notice that building a system model does require vehicle level information & requirements, and the effort may not be trivial. Some assumptions or experience from the previous program will help streamline the modeling effort. Once the model is validated, the system level nonlinear structural optimization, what-if study, and trade-off analysis can then be performed.

Since the travel, deformation, and attachment joint force of each component are the resultant of overall system displacement, the system model eliminates the uncertainty of applying force control or displacement control in component design synthesis. Moreover, the iterative process between component suboptimal design and system level what-if and trade off study can be avoided. Even though the system modeling effort is not trivial, moving system model synthesis upfront will improve vehicle design quality and reduce the overall study time.

Figure 2. Proposed Structural Design Process.

2.   Multilink Front & Rear Suspensions

New multi-link front & rear suspensions were developed for the all new 2013 compact luxury sports sedan. The front suspension has a multi-link double pivots MacPherson strut with a direct-acting stabilizer bar. The rear suspension is a first five-link independent suspension using lightweight, high-strength steel and efficient straight link designs.

Figure 3. 2013 Compact Luxury Car

2.1   Suspension System Model

The first step in this project was to build a multi-link suspension model, which included finite element components joined by connector elements. The Abaqus connector library is applied to model suspension connection such as ball joint, bushing, and cylindrical joint. Each connector element will have linear or nonlinear spring rate and damping properties to represent bushings, mounts, strut, jounce bumper and energy absorption component. The front and rear suspension designs and the corresponding system model are shown in Figs. 4 and 5, respectively.

One of the most time consuming steps in building a suspension system model is to collect suspension data and define the connector properties. Suspension data such as jounce bumper free height, spring and bushing preloads are all important in trimming the vehicle to match suspension design position. Also, jounce bumper rate, energy absorption component behavior, bushing rates and stops, and shock damping need be described and defined through connector properties. In general this information may already exist in ADAMS models of the same vehicle.
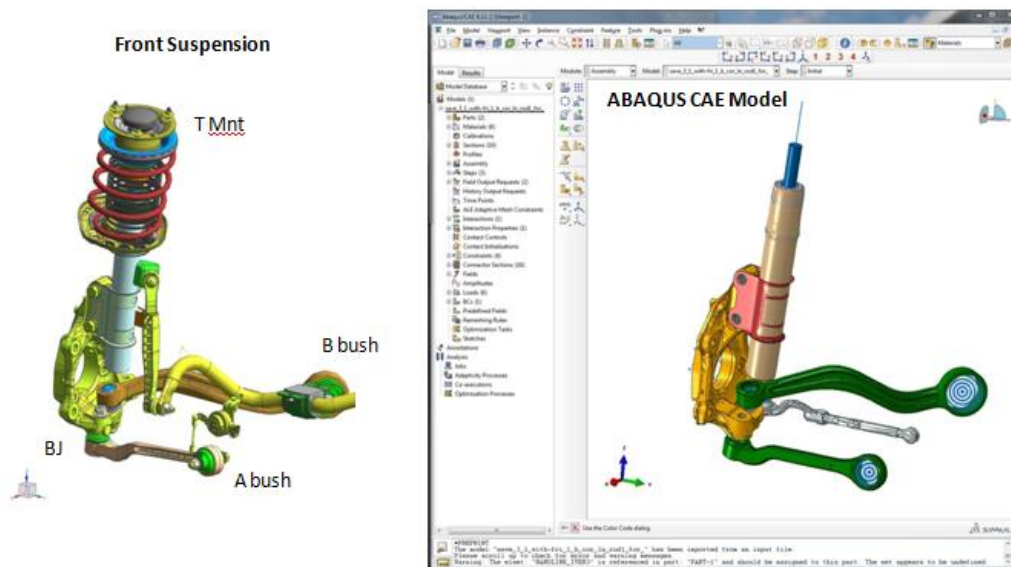

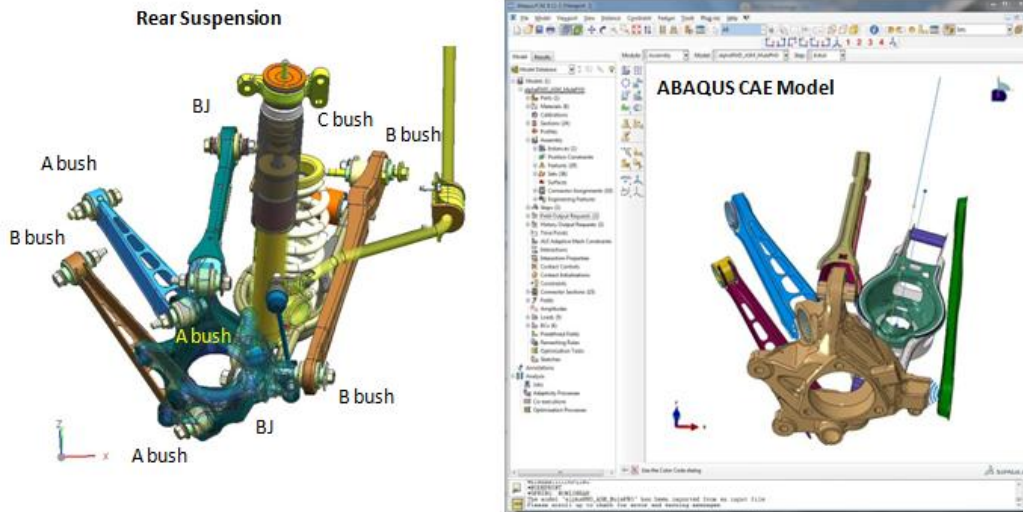**Figure 4. Front Suspension Model**

Figure 5. Rear Suspension Model

2.2 System Model Verification

To confirm that the system model was valid, two major load cases were tested. A pothole and hard forward braking event were tested, and the interface joint reaction forces were compared with the force obtained from MBD ADAMS analysis. Table 1 shows the interface joint force from the Abaqus system model analysis is consistent with the ADAMS result. Once the system model is validated, the design study can then be performed using automatic structural optimization ATOM to find out the critical load path and optimal structural design.

Load Case	Handling Bushing				Top Mount			
	Fm	Fx	Fy	Fz	Fm	Fx	Fy	Fz
	(N)	(N)	(N)	(N)	(N)	(N)	(N)	(N)
1. Forward Braking								
ADAMS Load	6592	-750	-6500	800	7972	-3400	4000	6000
Abaqus System Model	6680	-586	-6654	-17	8584	-2993	4026	6966
%	1%	-22%	2%	-102%	8%	-12%	1%	16%
2. Pothole								
ADAMS Load	15788	2000	15000	-4500	54599	9000	20000	50000
Abaqus System Model	15247	1545	15107	-1369	60065	8052	19778	56141
%	-3%	-23%	1%	-70%	10%	-11%	-1%	12%

Table 1 Comparison between Abaqus & ADAMS Joint Forces

Bushing rate design and tuning is one of the most complicated science studies in the multi-link suspension design. A harder bushing can provide a better vehicle handling performance; however, it may cause higher fatigue damage to the suspension structure. A bushing rate sensitivity study in the system model can provide a proper tuning range and a safe structural design. As shown in Fig. 6, lower trailing link deformation and the peak stress location changed as the conical bushing rates increased.
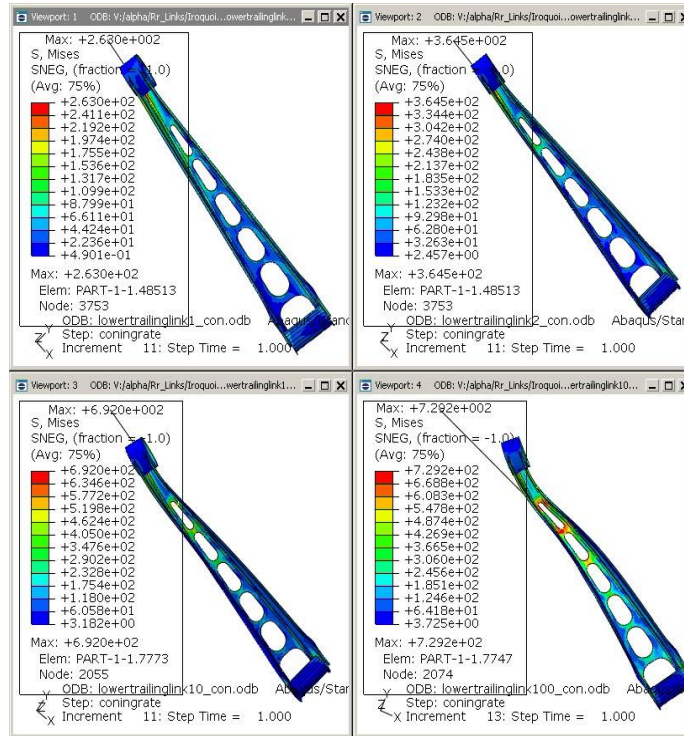

Figure 6. Lower Trailing Link Conical Bushing Rate Sensitivity

3. Topology Optimization of Nonlinear Structures

Although the minimum mean compliance design of nonlinear structures may not be the stiffest one, the mean compliance formula is sufficient for our purpose of demonstrating the effects of geometrical and material nonlinearities on the optimal solution. The optimization problem can be expressed as:

Minimize Compliance $\Pi = \int_{\Omega} \mathbf{f}_i \mathbf{u}_i \, \mathbf{d}\Omega,$

Subject to $\int_{\Omega} \rho \, \mathbf{d}\Omega \leq \mathbf{V}_0 ,$

where V_0 denotes the upper bound of the allowable material.

3.1 Example 1

One of the most well-known examples in topology optimization is the stiffness optimization of a slender beam shown in Fig. 7. Both linear and nonlinear analyses are applied in the topology study. The optimal designs using two analysis results are presented in Fig. 7. As shown in Fig. 7, the two optimal results are very different. When materials are removed from the design domain during optimization iterations, the loading in the center region changes from shear dominated to bending dominated. The linear geometry model does not sense this change, causing it to evolve into a compression member. The nonlinear geometry model creates a stable structural design. This result shows the importance in designing with nonlinear analyses for applications such as energy absorption structure and compliant mechanism.
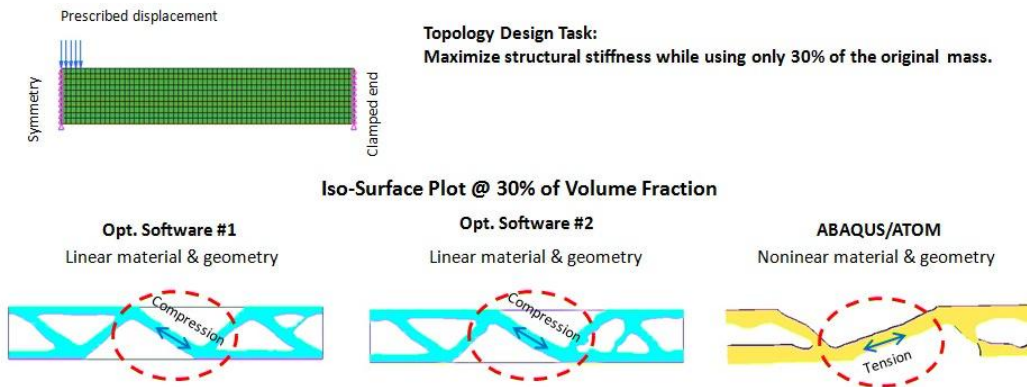

Figure 7. Slender Beam Topology Optimization

3.2 Example 2

In this example, handling link in front multi-link suspension shown in Fig. 4 is considered for a topology study. A typical topology design problem is formulated in Fig. 8. Also, volume fraction constraint of 70% or 50% and manufacturing symmetry conditions are applied to this study.

First, the link component is designed using linear and nonlinear analysis with the same loading and boundary conditions. Again, Fig. 8 shows very different design recommendations. Linear analysis shows an I-beam section at mid-span where nonlinear analysis prefers a more stable solid section.

Second, link topology optimization is carried out in the front suspension system model with nonlinear geometry and material options. At 70% volume fraction, the nonlinear system model removes material from link top compression surfaces, and secures bottom tension surfaces. This behavior is consistent to the last example study.

Finally, a 50% volume fraction is applied to this nonlinear system design, but optimization is terminated due to a convergence issue in nonlinear analysis. Unlike linear topology optimization which can run with any nonzero volume fraction, nonlinear optimization requires a stable plasticity model in order to get a convergence solution. This makes nonlinear optimization more challenging when solving for a compliance system.
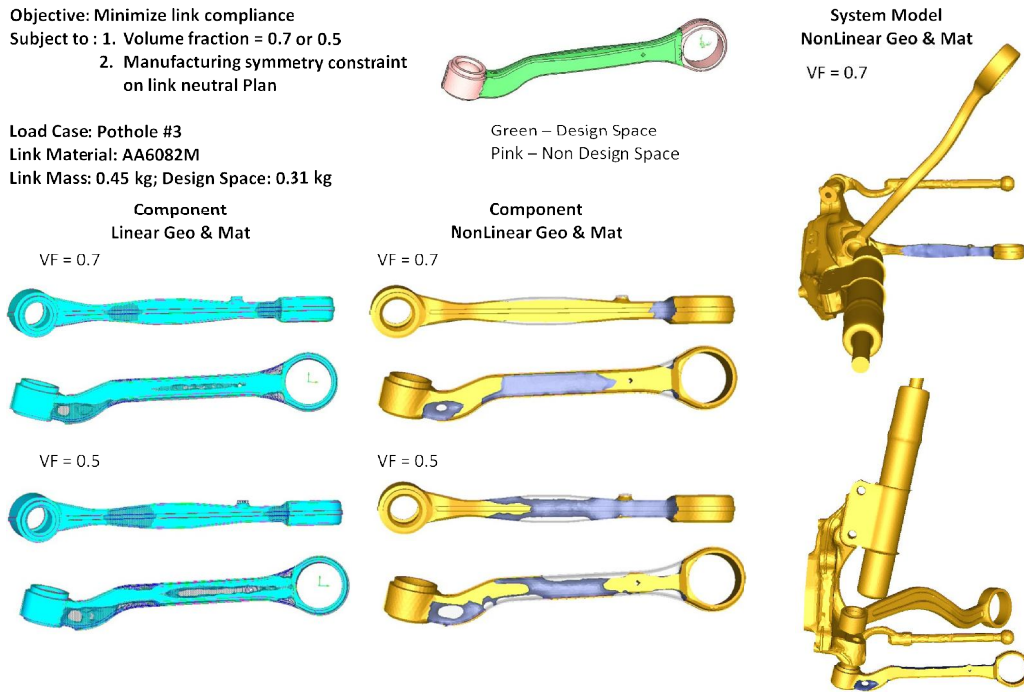

Figure 8. Front Suspension Link Topology Optimization

4. Conclusions

- It is demonstrated that Abaqus is capable of providing an accurate solution for flexible multi-link suspension models that include structural components and connectors having linear or nonlinear interface joint.

- Design synthesis with system modeling techniques can provide more reasonable design suggestions than component level design optimization. This is because the system model can better describe how components interact with each other in a compliant mechanism.

- Geometrical and material nonlinearities of multi-link suspensions have a significant effect on both performance and design optimization. ATOM shows that structural designs with and without geometrical nonlinearity could be different.

- ATOM is a rational tool to exploit the critical load paths and suggests alternative component designs in structural system under a nonlinear behavior.

- The GM Chassis CAE group is working toward further expansion of this capability to other chassis structural designs.

5. References

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